SRREN

INTERGOVERNMENTAL PANEL ON climate change

Working Group III - Mitigation of Climate Change

Special Report on Renewable Energy Sources and Climate Change Mitigation

SECOND ORDER DRAFT (VERSION 1)

SOD

CONTENTS

INTERGOVERNMENTAL PANEL ON climate change

June 18th, 2010

Foreword to the Second Order Draft of the IPCC Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation

Dear SRREN Authors, Expert Reviewers and Government Members,

The Intergovernmental Panel on Climate Change (IPCC) Working Group III (WG III) for the Mitigation of Climate Change is pleased to present the Second Order Draft (SOD) of the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN).

The writing of the SRREN was first approved during the 25th session of the IPCC in Mauritius in April, 2006. Since that time, the IPCC WG III has been host to a scoping meeting in Lübeck, Germany (January 2008), three lead author meetings in São José dos Campos, Brazil (January 2009), Oslo, Norway (September 2009), and Oxford, UK (March 2010) respectively and an Expert Review Meeting in Washington DC, USA (February 2010). The final approval of the completed SRREN is expected in February, 2011.

It is the goal of the Special Report to assess existing literature on the future potential of renewable energy for the mitigation of climate change. It covers six of the most important renewable energy sources, as well as the integration of associated technologies into present and future energy systems, associated environmental and social consequences, cost considerations and strategies to overcome technical as well as non-technical obstacles to their application and diffusion.

The SOD is the result of the efforts of 123 lead and coordinating lead authors, as well as a number of contributing authors. The strength of the draft can be attributed to their extensive efforts and the time they have invested on top of their daily professional commitments. We would like to extend our warm thanks for their dedication to the Special Report.

The SOD is available on the internal website of the IPCC WG III via the following link: http://www.ipcc-wg3.de/internal/srren/sod. **Please note that this is a confidential document which must not be distributed, cited or quoted**. The SOD represents work in progress that will undergo further refinements by the author teams following the Expert and Government Review and is therefore subject to change[1]. This process is completed only after acceptance by the Session of the Working Group after which it will be published. We ask all expert reviewers to closely examine this document in accordance

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[1] Placeholders have been included in the SOD text where data will be updated with information from the upcoming WEO 2010.

with Annex 1 of Appendix A to the Principles Governing IPCC Work[2] and comment on the accuracy and completeness of the scientific/technical/socio-economic content and the overall scientific/technical/socio-economic balance.

Please use the review excel sheet (available on the same website as the SOD) for your comments. Comments must be submitted in this excel format and no other. I.e. submissions in Word, PDF, self-generated Excel or other formats will not be accepted. Please note that each spreadsheet can accommodate up to 1000 comments. For individuals that anticipate submitting more than 1000 comments, please prepare separate spreadsheets for each chapter, the Technical Summary and the Summary for Policy Makers.

The expert review period will end Monday, **August 16th, 2010, Noon CET**. We kindly ask that you review the SOD and send your comments in the review excel sheet to the Technical Support Unit at comments@ipcc-wg3.de no later than that date. Please note that **all comments will be published attributable by name** following the final approval and publication of the report. A revised SRREN timetable and outline is available at the beginning of the SOD. As there have been some changes of dates for the second expert/government review period and some changes in the outline, respectively, please use these versions for future reference.

Should you have any questions, please contact the IPCC WG III Technical Support Unit at the email address provided above.

Sincerely,

Ottmar Edenhofer
Co-Chair IPCC WGIII

Ramón Pichs Madruga
Co-Chair IPCC WG III

Youba Sokona
Co-Chair IPCC WG III

Patrick Matschoss
Head of TSU of WG III

Kristin Seyboth
TSU Senior Scientist
SRREN Coordinator

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[2] http://www.ipcc.ch/pdf/ipcc-principles/ipcc-principles-appendix-a.pdf

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Timeline for the development of the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)

Date /Deadlines	Time allowed	Meeting	Action	By whom?
April 06	Process up to January 2009	IPCC Plenary Mauritius	Decision on scoping process	IPCC Plenary
			Nominations of experts for scoping meeting	Governments
			Selection of experts	Co-Chairs
November 07		IPCC Plenary Valencia, Spain	Decision on selected participants and finances	IPCC Plenary
			Invitation of experts	Co-Chairs
January 08		Scoping Meeting in Luebeck (Germany)	Scoping of report and structure	Experts
April 08		IPCC Plenary, Budapest	Decision on report and structure	IPCC Plenary
			Nominations of authors	Governments
			Selection of authors	Co-Chairs
November 08		IPCC Bureau in Geneva	Decision on author selection	IPCC Bureau WG III
			Invitation of authors	Co-Chairs
26.-30.1.2009		1st Lead Author Meeting, San Jose (Brazil)	Agree on writing assignments	All authors
Until 8.6.2009	18 weeks		Writing of ZOD, selection of reviewers	All authors
Until 6.7.2009	4 weeks		Informal review	LAs/selected experts
Until 27.7.2009	3 weeks		Collation and initial check of comments	Authors/TSU
Until 30.08.09	5 weeks		Further consideration of comments received from the internal review + analysis of mitigation scenarios*	Authors/TSU
30.08.-31.8.2009	2 days	Scenarios expert meeting	Analysis of mitigation scenarios	some LAs+experts
1.9.-4.9.2009	1 week	2nd Lead Author Meeting	Consideration of initial comments + other tasks.	All authors
Until 7-14.12.2009	13-14 weeks		Finalizing FOD	All authors
1-2.2.2010	2 days	Expert Review Meeting	Expert review with the business community	CLAs+ selected experts
Until 8.2.2010	8 weeks		Expert review	Expert Reviewers
Until 28.2.2010	3 weeks		Collation and initial check of comments	Authors/TSU
28.2 - 1.3.2010	2 days	Scenarios expert meeting	Follow-up to the analysis of mitigation scenarios	some LAs+experts
2.-5.3.2010	1 week	3rd Lead Author Meeting	Consideration of expert comments.	All authors + Review Editors
Until 31.5- 7.6.2010	12-13 weeks		Finalizing SOD	All authors
Until 16.8.2010	8 weeks		Ex/gov review	experts/governments
Until 20.9.2010	5 weeks		Collation and initial check of comments	Authors/TSU
20-24.9.2010	1 week	4th Lead Authors Meeting	Consideration of exp./gov. comments.	All authors + Review Editors
Until 15-22.11.2010	7-8 weeks		Finalize report	All authors
Until 24.1.2011	8 weeks		final gov distribution	Governments
Until 11.02.2011	3 weeks		collate and consider gov comments on SPM	Authors/TSU
19-20.02.2011	2 days	CLA Preparatory Meeting	Final consideration of gov. comments on the SPM	CLAs
21-23.02.2011	3 days	WG3 Plenary Session	Approval of SPM and acceptance full report	WG3 Plenary + CLAs

AUTHORIZED VERSION, 1 June 2010

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INTERGOVERNMENTAL PANEL ON climate change

Working Group III (WG III) – Mitigation of Climate Change

SPECIAL REPORT ON RENEWABLE ENERGY SOURCES AND CLIMATE CHANGE MITIGATION (SRREN) - AMENDED TABLE OF CONTENTS

1. Background

This document contains the latest table of content (TOC) of the Special Report on Renewable Energy Sources and Climate Change (SRREN) as discussed at the 2nd Lead Author Meeting (LA2) of the SRREN in Oslo, 1-4 September 2009, and approved at the 31st session of the IPCC Plenary in Bali, 26-29 October 2009.

Further changes were discussed at the 3rd Lead Author Meeting (LA3) of the SRREN in Oxford, 2-5 March 2010 and were approved at the 41st session of the IPCC Bureau in Geneva, 19-20 May, 2010. They will be finalized at the 32nd session of the IPCC Plenary in Busan, 11-14 October, 2010. These changes in the TOC are highlighted in light blue.

2. Current Version of the SRREN Table of Contents

0.1. Summary for Policy Makers

0.2. Technical Summary

1. Renewable Energy and Climate Change (3-5%)

(Section 1.6 Methodology (resource assessment, life-cycle assessment, setting boundaries for analysis, measures of sustainability, definitions, units qualitative and quantitative, integration methods) will be shifted to the conclusion of the report as Annex II.)

1.1. Background

1.2. Summary of renewable energy resources

1.3. Meeting energy service needs and current status *(energy need, energy deficits, energy efficiency trends and renewable energy potential)*

1.4. Barriers and issues *(in using renewable energy for climate change mitigation, adaptation and sustainable development)*

1.5. Role of policy, R&D, deployment, scaling up and implementation strategies

WMO UNEP

2. Bioenergy (15%)
    - 2.1. Introduction *(traditional and modern use)*
    - 2.2. Resource potential *(within limits of sustainable forestry and agriculture, different feedstocks and impact of climate change on resource potential)*
    - 2.3. Technology *(e.g. biological and thermo-chemical conversion) and applications (electricity, heat, transport and cooking)*
    - 2.4. Global and regional status of market and industry development
    - 2.5. Environmental and social impacts *(food security, biodiversity, competition with water, fodder, fiber, and land use, role of sustainable forestry and agriculture, health impacts from air pollution, GHG emissions)*
    - 2.6. Prospects for technology improvement, innovation and integration
    - 2.7. Cost trends
    - 2.8. Potential deployment

3. Direct Solar Energy (10%)
    - 3.1. Introduction
    - 3.2. Resource potential *(impact of climate change on resource potential)*
    - 3.3. Technology *(solar thermal, photovoltaics, concentrating solar power)* and applications *(heating and cooling, lighting, cooking, electricity, fuel)*
    - 3.4. Global and regional status of market and industry development
    - 3.5. Integration into broader energy system
    - 3.6. Environmental and social impacts
    - 3.7. Prospects for technology improvement and innovation
    - 3.8. Cost trends
    - 3.9. Potential deployment

4. Geothermal Energy (3-5%)
    - 4.1. Introduction
    - 4.2. Resource potential
    - 4.3. Technology and applications *(electricity, heating, cooling)*
    - 4.4. Global and regional status of market and industry development
    - 4.5. Environmental and social impacts
    - 4.6. Prospects for technology improvement, innovation and integration
    - 4.7. Cost trends
    - 4.8. Potential deployment

5. Hydropower (5-10%)

5.1. Introduction *(large and small hydro)*

5.2. Resource potential *(impact of climate change on resource potential)*

5.3. Technology and applications *(run-of-river, storage, multi-purpose)*

5.4. Global and regional status of market and industry development

5.5. Integration into broader energy system

5.6. Environmental and social impacts *(displacement of people, GHG emissions)*

5.7. Prospects for technology improvement and innovation *(The title of 5.7 will be changed from 'Prospects for Technology Improvement and Innovation, and multi-purpose use of reservoirs')*

5.8. Cost trends

5.9. Potential deployment

5.10. Integration into water management systems

6. Ocean Energy (3-5%)

6.1. Introduction

6.2. Resource potential *(impact of climate change on resource potential)*

6.3. Technology *(wave, tidal, ocean thermal, osmotic)* and applications

6.4. Global and regional status of market and industry development

6.5. Environmental and social impacts

6.6. Prospects for technology improvement, innovation and integration

6.7. Cost trends

6.8. Potential deployment

7. Wind Energy (5-10%)

7.1. Introduction

7.2. Resource potential *(impact of climate change on resource potential)*

7.3. Technology and applications *(onshore, offshore, distributed)*

7.4. Global and regional status of market and industry development

7.5. Near-term grid integration issues

7.6. Environmental and social impacts

7.7. Prospects for technology improvement and innovation

7.8. Cost trends

7.9. Potential deployment

8. Integration of Renewable Energy into Present and Future Energy Systems (15%)
    - 8.1. Introduction *(potential role of renewable energy in future energy systems and climate change mitigation)*
    - 8.2. Integration of renewable energy into supply systems *(electricity grids, heat distribution networks, gas distribution networks, liquid fuels; load management, grid management, energy transport, interactions with conventional systems, necessary back-up and storage for intermittent sources, distributed versus centralized deployment of renewables, relation to energy efficiency) (to be differentiated regionally)*
    - 8.3. Strategic elements for transition pathways *(transportation, buildings and households, industry, agriculture, interactions among demand sectors, urban and regional development, interregional connections) (to be regionally differentiated)*

9. Renewable Energy in the Context of Sustainable Development (10%)

(The titles of 9.3, 9.4 and 9.5 will be amended according to the structure below[*].)

- 9.1. Introduction
- 9.2. Interactions between sustainable development and renewable energies
- 9.3. Social, environmental and economic impacts: global and regional assessment *(energy supply security)*
- 9.4. Implications of (sustainable) development pathways for renewable energies
- 9.5. Policy framework for renewable energy in the context of sustainable development
- 9.6. Synthesis *(consequences of including environmental and socio-economic considerations on the potential for renewable energy, sustainability criteria)*
- 9.7. Gaps in knowledge and future research needs

10. Mitigation Potential and Costs (10%)

(The titles of 10.2, 10.3, 10.4 and 10.7 will be amended according to the structure below.)

- 10.1. Introduction
- 10.2. Synthesis of mitigation scenarios for different renewable energy strategies
- 10.3. Assessment of representative mitigation scenarios for different renewable energy strategies
- 10.4. Regional cost curves for mitigation with renewable energies *(regional, sectoral, temporal; impacts of climate change on mitigation potential)*
- 10.5. Costs of commercialization and deployment *(investments, variable costs, market support, RDD&D)*
- 10.6. Social, environmental costs and benefits *(synthesis and discussion on total costs, and impacts of renewable energy in relation to sustainable development)*

11. Policy, Financing and Implementation (10-15%)
    - 11.1. Introduction

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[*] These changes have not yet been brought to the IPCC Bureau. As applies to all other amendments in this document, they will be brought to the 32nd session of the IPCC Plenary in Busan for final approval.

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[*] These changes have not yet been brought to the IPCC Bureau. As applies to all other amendments in this document, they will be brought to the 32nd session of the IPCC Plenary in Busan for final approval.

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Summary for Policymakers

Chapter:	00				
Title:	Summary for Policymakers (SPM)				
(Sub)Section:	All				
Author(s):	CLAs:				
	LAs:	Dan Arvizu, Jean-Michel Devernay, Ottmar Edenhofer, Andre Faaij, Manfred Fischedick, Barry Goldstein, Gerrit Hansen, John Huckerby, Arnulf Jaeger-Waldau, Susanne Kadner, Dan Kammen, Arun Kumar, Tony Lewis, Oswaldo Lucon, Patrick Matschoss, Lourdes Maurice, Catherine Mitchell, Bill Moomaw, Jose Moreira, Alain Nadai, Lars J. Nilsson, Ramon Pichs, Atiq Rahman, Jayant Sathaye, Janet L. Sawin, Roberto Schaeffer, Tormod Schei, Steffen Schloemer, Kristin Seyboth, Ralph Sims, Youba Sokona, Aviel Verbruggen, Christoph von Stechow, Ryan Wiser, Francis Yamba, Timm Zwickel			
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COMMENTS ON TEXT BY TSU TO REVIEWER

Turquoise highlighted – inserted comment text from Authors or TSU e.g. [AUTHOR/TSU:…]

Summary for Policy Makers

CONTENTS

1. Introduction

The Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation focuses on new literature on the scientific, technological, environmental, economic and social aspects of the contribution of renewable energy (RE) sources to the mitigation of climate change, supplementing and expanding on information and analysis that was presented in the 2007 IPCC 4th Assessment Report (AR4).

This Special Report provides a technology and systems level analysis based on the technical literature to support the thesis that RE can contribute significantly within a broad portfolio of mitigation options to the goals outlined in the AR4 for limiting global mean temperature increases and stabilizing the concentration of greenhouse gases (GHGs) in the atmosphere.

1) The RE resource is widely available, and a sufficient RE technology base already exists to enable significant implementation of a low-carbon and sustainable energy economy.

2) Financial barriers exist for many RE systems to compete directly with incumbent energy systems in the short-term, but continually improving technologies, efficient use improvements, policies and cost reductions from increased experience can aid the transition to a new sustainable energy system.

3) Regulatory barriers inadvertently discourage the use of RE in many cases, but countries that have eliminated them and established supportive policies have seen RE provide a rapidly growing share of energy services.

4) Low-carbon energy systems and efficient end-use can be powerful tools to expand the cost-effective access to energy services that can meet the energy needs and improve the quality of life of the poor.

RE, in its many forms, has the potential to mitigate GHG emissions, enhance energy security, provide modern and affordable energy services to those currently without, and aid sustainable development. To put RE technologies and energy practices into an economically affordable, environmentally sustainable and social acceptable use will require:

- continued attention to the economic playing-field where new innovations compete;
- regional assessments of RE resources;
- strong research and development efforts to further develop RE technologies;
- development of policy tools that can bring low-carbon energy systems into practice; and
- vigilance to the opportunities, policy tools and institutional environments available for RE to achieve its potential to address sustainable development goals for diverse communities and societies.

The following summary is organised into seven sections after this introduction:

- Drivers for a low-carbon economy
- Solutions
- Mitigation potentials
- Renewable energy technologies
- Integration of RE into current and future energy supply systems
- Policies and instruments for advancing RE deployment
- Knowledge gaps

References to the corresponding chapter sections are indicated in each paragraph in square brackets. An explanation of terms, acronyms and chemical symbols used in this SPM can be found in the glossary to the main report.

2. Drivers for a Low-Carbon Economy

2.1 Climate Change

The IPCC's 2007 AR4 concluded that there is a 90 percent likelihood that global warming is happening and that most of it is caused by human actions. AR4 [Working Group I] projected that, by the end of this century, global annual average temperature will have risen by between 1.1° and 6.4° C depending on assumptions of future socio-economic trends. [1.1.1]

Climate change is a major consequence of the more fundamental problem of unsustainable development. The AR4 concluded that human livelihoods, from small communities to major urban complexes to regional economies, are fundamentally impacted by climate change and a cycle of unsustainable development. It went on to conclude that the impacts of climate change are initially being felt among the poor in both developed and developing nations, in many cases already with significant negative impacts.

Over 80% of primary energy[1] comes from fossil fuels, which produce the heat trapping GHGs carbon dioxide as the products of combustion and methane as an inadvertent product of drilling, mining and transporting those fuels. When measured by their comparative global warming potentials, these gases account for the majority of global warming since the start of the industrial revolution.

***Carbon emissions continue to rise worldwide with CO_2 concentrations exceeding 390 ppm in 2010.* [1.1.1]**

In order to meet targets for limiting global temperature increases, GHG emissions will need to begin declining in the coming decade. Many governments, and the Copenhagen Accord now advocate that to avoid the most dangerous impacts of climate change it will be necessary to hold temperature rises to less than 2° C below preindustrial values with small island developing states and other less developed countries advocating limiting the temperature increase to below 1.5ºC. The AR4 indicated that to achieve this goal will require global GHG emissions to be at least 50% lower in 2050 than in 2000, and to begin declining by 2020.

2.2 Sustainable, Secure Energy Services

Access to energy services is central to human health and welfare, as well as a fundamental input for economic development. "Secure energy services" refers to the assured access to energy resources necessary to provide essential energy services, and this varies markedly for those at the subsistence level in developing countries, and those living in an energy intensive economy. For the former, it involves gathering fuel wood, dung or crop waste, or the reliability of intermittent electricity supply. For the later, it may depend upon the reliability of imports or the capacity of infrastructure to meet high demand.

Sustainable energy services require the ongoing delivery of energy resources over time that are economically affordable, environmentally sustainable (low pollution and carbon dioxide emissions) and socially acceptable. In order for an energy source to be sustainable requires first that it be able to continue producing energy over time with low carbon dioxide emissions and with comparatively

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[1] Primary energy refers to the energy embodied in natural resources that has not undergone any anthropogenic conversion [SRREN Glossary].

low other environmental impacts. It must also be economically sustainable in terms of using scarce resources in the best possible way according to criteria of human-well being. Finally, to be sustainable, the technology must be socially sustainable in terms of providing livelihoods and maintaining social and political acceptance.

The systems perspective on energy development and deployment links global and local decision-making to short- and long-term societal needs. The Millennium Development Goals (MDG) provide a list of challenges and objectives where governments, multinational agencies, and civil society can exercise choices and focus attention on energy services that can address poverty, reduce hunger, increase access to safe drinking water, allow domestic lighting and electricity to enable education at home, increase security, and increase gender and social equity. Quantitative measures of energy access, sustainability, and social impact will be needed to chart progress and challenges in implementing clean energy solutions that meet development and sustainability goals [1.1.6].

3. Solutions

Economic and development goals may be pursued in conjunction with climate protection goals and related targets for GHG emission reductions, particularly by means of investment in low-carbon energy-related infrastructure *[10.1]*. To address some of the bottlenecks that have historically been barriers to their development, developing countries will need to invest in infrastructure that they currently lack, also in terms of energy infrastructure. A window of opportunity exists particularly in fast-growing developing countries planning to make large investments in new energy-related infrastructure. Developed countries need to renew their energy-related infrastructures as well. Due to the long life-cycle of infrastructure (e.g. power plants, roads and buildings), medium- and long-term climate protection goals need to be taken into account in near-term investment decisions to avoid lock-in situations [10.1].

To maintain both a sustainable economy that is capable of providing essential goods and services to the citizens of both developed and developing countries, and to maintain a supportive global climate system requires a major shift in how energy is supplied and utilized. [11.7].

There are various means for lowering GHG emissions from energy sources, while still providing energy services. [1.1.4, 10.1] The following mitigation options related to energy supply are available [10.1]:

- Shift to zero carbon primary energy sources[2], including RE technologies (See Box SPM 1).
- Shift from coal, petroleum or natural gas to solid, liquid or gaseous biomass energy that is produced and used in a low carbon-emitting manner utilizing new crops and management strategies.
- Utilize combined heat and power (CHP) technologies for thermal production of electric power from both fossil fuels and RE sources.
- Shift to lower carbon-emitting fuels such as from coal to natural gas or to uranium.
- Utilize carbon dioxide capture and storage (CCS) technology to prevent carbon from fossil fuel combustion from entering the atmosphere. CCS also has the potential to remove CO_2 from the atmosphere when biomass is utilized.

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[2] GHG emissions may occur during manufacturing processes. Therefore, ‘zero-carbon primary energy source’ does not necessarily refer to the entire life-cycle of a particular technology.

The main mitigation options related to energy demand are as follows [10.1]:

- Provide the same energy service with less energy. Increase the energy efficiencies of buildings, lighting, industrial and agricultural processes, transportation and the delivery of energy services at the point of end-use.
- Change consumer behaviours to use fewer carbon and energy-intensive products and services.

In addition to the energy-related methods for mitigating climate change, additional potentials exist in the agriculture, forestry and waste sectors [10.1].

Renewable energy technologies are diverse, and have the ability to serve a wide range of energy service needs. Though all RE technologies rely on resources that can be naturally replenished, the specific characteristics of these technologies and their potential use are varied (Box SPM 1). Electrical, thermal, transport, and mechanical energy service needs can be met with RE.

Renewable energy technologies can be near-zero carbon emitters if managed appropriately. The life-cycle GHG emissions of most RE technologies are low. Though the direct GHG emissions of RE technologies are often zero, GHGs are emitted in the materials supply, manufacture, and installation of these technologies. Additionally, the variable output of some RE technologies can affect the operational efficiency of fossil-fuel power plants that are also on the grid, yielding some increase in GHG emissions from those plants. The literature suggests that, in most cases, these impacts are small, and that the net life-cycle GHG emissions of RE technologies are low compared to fossil-fuel energy supply; moreover, in the case RE technologies with variable output profiles, the use of storage and/or the coupling of diverse RE technologies into a hybrid system may reduce any impacts that do exist. [2.5, 3.6, 4.5, 5.6, 6.4, 7.6]

Concerns are sometimes expressed about the net GHG emissions of bioenergy and hydropower. Bioenergy has a significant GHG mitigation potential, provided that the resources are developed sustainably and that appropriate bioenergy systems are utilized. Perennial cropping systems and biomass residues and wastes, in particular, are able to deliver GHG reductions of 80-90% compared to the fossil energy baseline. The GHG impacts of bioenergy are conditional, however, and can be either positive or very low or even negative depending on the situation; negative impacts can, for example, occur when carbon stocks are lost due to undesired land use changes. For hydropower, research shows that life-cycle GHG emissions are typically very low, but that methane and carbon dioxide emissions may occur for certain reservoirs in tropical environments. Research is needed to obtain more-reliable estimates of net GHG emissions in these instances. [2.5, 5.6]

Box SPM.1. Renewable Energy Resources and Technologies

Bioenergy is a renewable source of fuel that may be used in a wide variety of energy applications, while biomass also continues to be the world's major source of food, fodder, and fibre. Biomass sources include forest, agricultural, and livestock residues, short-rotation forest plantations, dedicated energy crops, the organic component of municipal solid waste (MSW), and other organic waste streams. Part of these are used as feedstocks which, through a variety of chemical and physical processes, produce energy carriers in the form of solid (chips, pellets, briquettes, logs), liquid (methanol, ethanol, butanol, biodiesel), and gaseous (synthesis gas, biogas, hydrogen) fuels. The production of energy from these carriers can be used in thermal, electric, transport, construction, and chemical applications, and can take place in a centralized or decentralized fashion. [2.1, 2.3, 2.6]

Direct solar energy technologies harness the energy produced by the solar radiation of the sun to meet electricity, thermal, and in some cases transportation demands. Solar technologies range from comparatively simple devices for lighting and heating to highly sophisticated devices for electricity production; many of the technologies are modular in nature, allowing their use in both centralized and decentralized energy systems. Though solar energy relies on naturally variable energy flows, creating inherent variability in energy output, thermal energy can be stored over short periods at comparatively low cost, allowing some technologies (e.g., concentrating solar thermal power) to offer controllable output. Even when integrated storage is not available, the temporal profile of solar energy output sometimes correlates relatively well with energy demands. [3.1, 3.3, 3.7]

Geothermal energy relies on the accessible thermal energy generated and stored in the Earth's interior, either onshore or offshore. Geothermal heat is extracted using wells that access the hot fluids contained in hydrothermal reservoirs or by artificially introduced fluids in Enhanced Geothermal Systems (EGS). Once at the surface, these hot fluids can be used to generate electricity, or can be used more-directly for applications that require thermal energy. When used to generate electricity, geothermal power plants typically offer constant (base-load) output with an average worldwide capacity factor of 71% in 2008 and with newer installations capable of achieving capacity factors above 90%. [4.1, 4.3, 4.4]

Hydropower harnesses the energy of moving water from higher to lower elevations, primarily to generate electricity. Hydropower projects vary widely in type and size, creating a continuum from small-scale (a few kW) run-of-river projects to large-scale (over 10 million kW) dam projects with a reservoir that provides the possibility of controllable output. This variety gives hydropower the ability to meet large centralized urban needs as well as decentralized rural needs, and the controllable output of many hydropower facilities can be used to meet peak electricity demands and help balance electricity systems that have large amounts of variable RE generation. Hydropower facilities are often multi-use facilities, meeting the needs of water management as well as energy supply. [5.1, 5.5, 5.10]

Ocean energy derives from the potential, kinetic, heat, chemical, and biomass energy of seawater, which can be transformed to serve electricity, thermal, transport, and potable water needs. A wide range of technologies can be used for this purpose, e.g., barrages for tidal rise and fall, submarine turbines for tidal and ocean currents, heat exchange technologies for ocean thermal energy conversion (OTEC), and new technologies for osmotic power. Some of these technologies have short-term (e.g., waves) and medium-term (e.g., swells, tidal and ocean currents) variable output profiles, while others may be capable of constant or even controllable operation (e.g., OTEC and salinity gradient). [6.2, 6.3, 6.4]

Wind energy relies on the kinetic energy of moving air masses and can be used in many ways, but the primary application of relevance to climate change mitigation is to produce electricity from large wind turbines located on- or off-shore. Because wind energy relies on the kinetic energy of moving air masses, wind electricity is both variable and, to some degree, unpredictable. Actual experience and detailed studies have concluded that there are no insurmountable technical barriers to integrating wind energy into power systems, though such integration becomes increasingly costly at higher levels of wind electricity penetration as more-active management is required. [7.1, 7.3, 7.5]

Table SPM 1 Overview of RE Technologies and Applications [1.2.3]

Renewable Energy Source	Select Renewable Energy Technologies	Energy Sector (Electricity, Thermal, Transport, Mechanical)	Technology Maturity[1]				Primary Distribution Method[2]	
			R & D	Demo & Pilot Proj	Early-Stage Com'l	Later-Stage Com'l	Centralized	Decentralized
Bioenergy	Non-Commercial Use of Fuelwood/Charcoal	Thermal				X		X
	Cookstoves (Primitive and Advanced)	Thermal				X		X
	Domestic Heating Systems (pellet based)	Thermal				X		X
	Small- and Large-Scale Boilers	Thermal				X	X	X
	Digestion	Electricity/Thermal				X	X	X
	Combined Heat and Power (CHP)	Electricity/Thermal				X	X	X
	Co-firing in Fossil-Fuel Power Plant	Electricity				X	X	
	Combustion-based Power Plant	Electricity				X	X	X
	Gasification-based Power Plant	Electricity			X		X	X
	Sugar-Cane Ethanol Production	Transport				X	X	
	Corn Ethanol Production	Transport				X	X	
	Wheat Ethanol Production	Transport				X	X	
	Rapeseed Biodiesel Production	Transport				X	X	
	Palm Oil Biodiesel Production	Transport				X	X	
	Soy Biodiesel Production	Transport				X	X	
	Jathropha Biodiesel Production	Transport				X	X	
	Lignocellulose Ethanol Production	Transport			X		X	
	Lignocelluose Synfuel Production	Transport			X		X	
	Algae Fuel Production	Transport	X				X	
Direct Solar	Photovoltaic (PV)	Electricity				X	X	X
	Concentrating PV (CPV)	Electricity		X			X	
	Concentrating Solar Thermal (CSP)	Electricity			X		X	
	Low Temperature Solar Thermal	Thermal				X		X
	Solar Cooling	Thermal		X				X
	Passive Solar Architecture	Thermal				X		X
	Solar Cooking	Thermal			X			X
	Solar Fuels	Transport	X				X	X
Geothermal	Hydrothermal, Condensing Flash	Electricity				X	X	
	Hydrothermal, Binary Cycle	Electricity				X	X	
	Engineered Geothermal Systems (EGS)	Electricity		X			X	
	Submarine Geothermal	Electricity	X				X	
	Direct Use Applications	Thermal				X		X
	Geothermal Heat Pumps (GHP)	Thermal				X		X
Hydropower	Run-of-River	Electricity/Mechanical				X	X	X
	Reservoirs	Electricity				X	X	
	Pumped Storage	Electricity				X	X	
	Hydrokinetic Turbines	Electricity/Mechanical		X			X	X
Ocean Energy	Swell/Wave	Electricity		X			X	
	Tidal Rise and Fall	Electricity				X	X	
	Tidal Currents	Electricity		X			X	
	Ocean Currents	Electricity		X			X	
	Ocean Thermal Energy Conversion	Electricity/Thermal		X			X	
	Osmotic Power	Electricity		X			X	
	Marine Biomass Farming	Transport	X				X	
Wind Energy	On-shore, Large Turbines	Electricity				X	X	
	Off-shore, Large Turbines	Electricity			X		X	
	Distributed, Small Turbines	Electricity				X		X
	Turbines for Water Pumping / Other Mechanical	Mechanical				X		X
	Wind Kites and Sails	Transport		X				X
	Higher-Altitude Wind Generators	Electricity	X				X	

Notes: 1. The highest level of maturity within each technology category is identified in the table; less mature technologies exist within some technology categories.
2. Centralized refers to energy supply that is distributed to end users through a network; decentralized refers to energy supply that is created onsite. Categorization is based on 'primary' distribution method, recognizing that virtually all technologies can, in some circumstances, be used in both a centralized and decentralised fashion.

At present, the total shares of consumer energy supplied by RE systems remains low. (See Table SPM 2). The percentages of RE in local primary energy supplies can vary substantially by region. In 2007, RE sources in sum accounted for less than 13% of the total global primary energy supply, but many forms of RE are growing rapidly.

Table SPM 2 Primary energy supply of different sources in 2007.

Primary energy source	**EJ**	**%**
Fossil fuels	411.09	85.33
Nuclear	9.81	2.04
Renewables	60.49	12.55
Bioenergy	48	9.96
Solar	0.40	0.08
Geothermal	0.39	0.08
Hydro	11.08	2.30
Ocean	0.00	0.00
Wind	0.62	0.13
Other	0.39	0.08
Total	481.78	100.00

Notes: Data for this table originates from the IEA and has in some cases been updated with IPCC SRREN values. Values have been converted to reflect the direct equivalent method for calculating primary energy that is used throughout the SRREN.

Renewable energy can supply the same energy services to users as conventional primary energy sources, and in some cases without the thermal losses to which combustible fuels are subject. The same energy services can also be provided with differing amounts of end-use energy. There is a multi-step process whereby primary energy is converted into an energy carrier, and then into end use energy (total final consumption) to provide energy services for the various economic sectors. Since it is the ultimate energy services of electronics, lighting, heating, cooling, transportation or industrial and mechanical processes, careful design can minimize the amount of energy required to accomplish those services, and extract the required energy from renewable and other low GHG emitting sources. This is illustrated in Figure SPM 1.

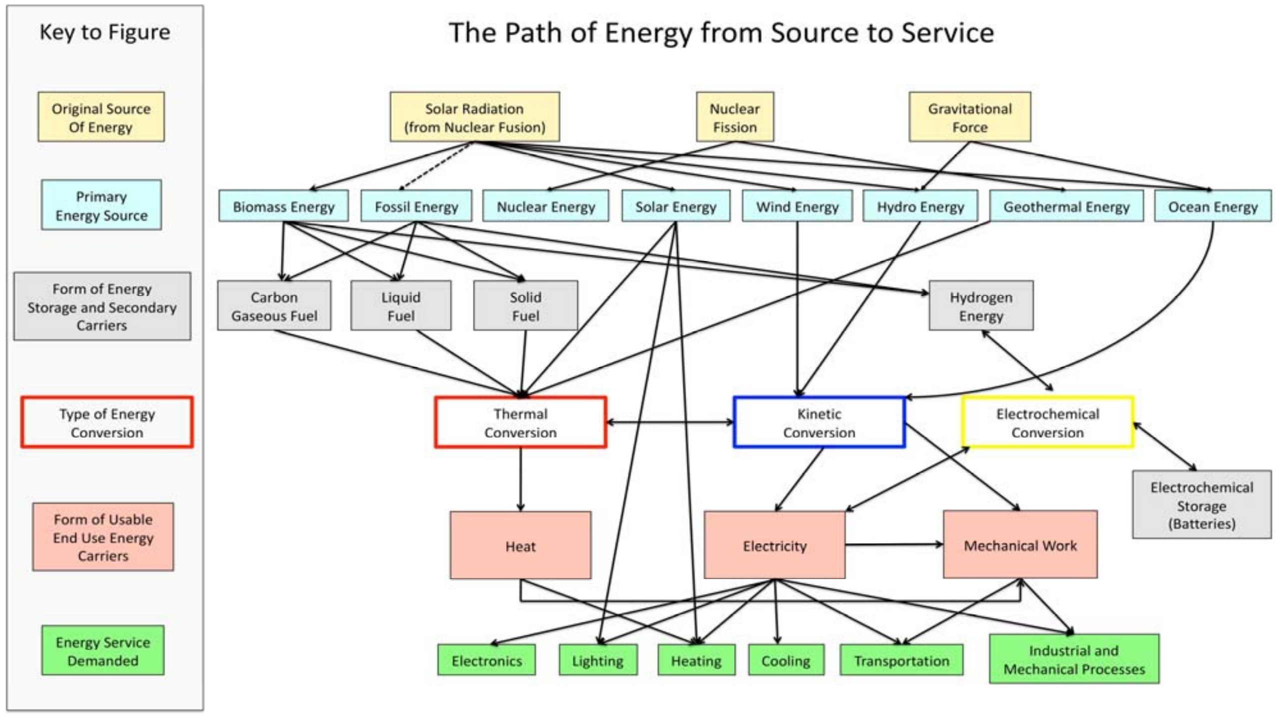

Figure SPM 1 The Path from Source to Service. The energy services delivered to the users can be provided with differing amounts of end use energy. This in turn can be provided with more or less primary energy and with differing emissions of carbon dioxide and other environmental impacts.

Thermal conversion processes to produce electricity (including from biomass and geothermal) suffer losses of approximately 50-90% and losses of around 80% to supply the mechanical energy needed for transport. Direct energy conversions from solar, hydro, ocean and wind energy to electricity do not suffer these thermal losses. See Figure SPM 2. Direct heating from geothermal, biomass and solar thermal systems can also be highly efficient processes. By comparison, CCS requires substantial energy inputs, which would increase the demand for primary energy to supply the same amount of end use energy for energy services. However, the role of RE within the overall portfolio of mitigation options requires not only an assessment of technical feasibility about also a systemic perspective which takes into account all relevant information determining economic affordability, environmental sustainability and social acceptability. [1.3.1.1]

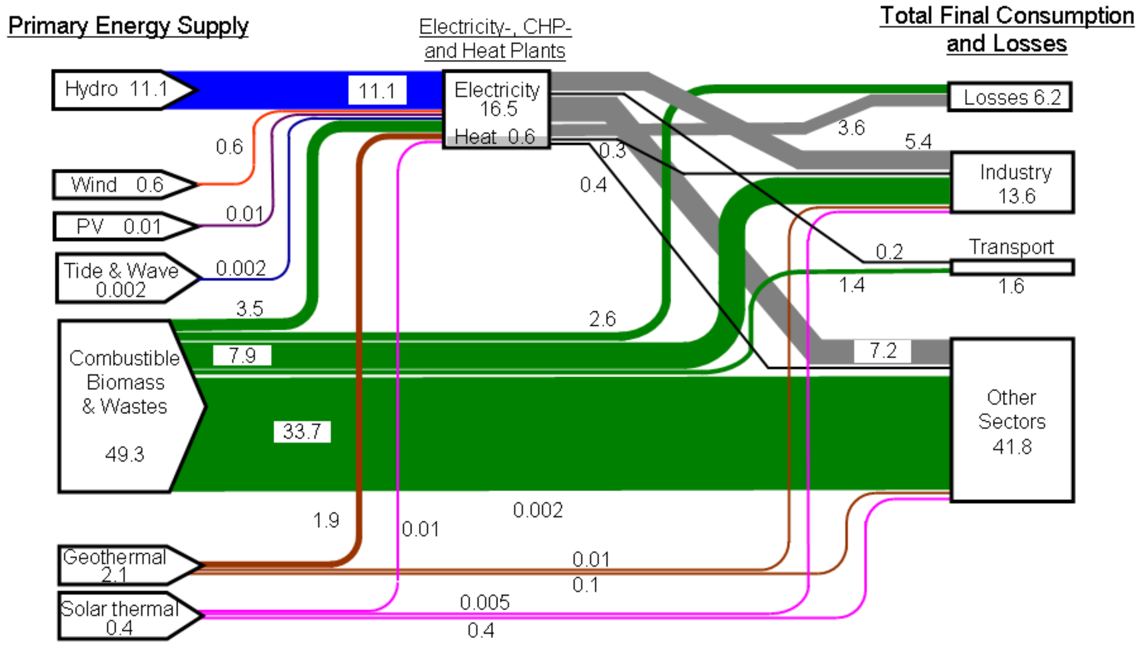

Figure SPM 2. Global energy flows (EJ in 2007) from primary renewable energy through carriers to end-uses and losses drawn with IEA data. Other sectors include agriculture, commercial and residential buildings, public services and non-specified other sectors.

Economic, social, and ecological benefits are further motivating governments and individuals to adopt RE because they offer the potential to simultaneously realise multiple goals in relation to sustainable development [11.3] The key drivers of RE policy are: climate change mitigation; enhanced access to energy services, in particular for the poor as a basic aspect of poverty reduction and achievement of the MDGs; improved health, education and environmental living conditions; higher security of energy supply at stable prices; diversity of energy sources; and economic development and domestic job creation. The relative importance of the drivers, opportunities and benefits of RE varies from country to country and over time as changing circumstances affect economies, attitudes and public perceptions [10.6, 11.3].

RE generation replaces conventional energy generation that may create local pollutants. See Figure SPM 3. For energy production technologies based on combustion, impacts and external costs arise largely from emissions of particulates and gases to air [10.6.2]. RE technologies have significant benefits for reducing air and water pollution, and damage to land from mining, subsidence and oil spills [1.1.6].

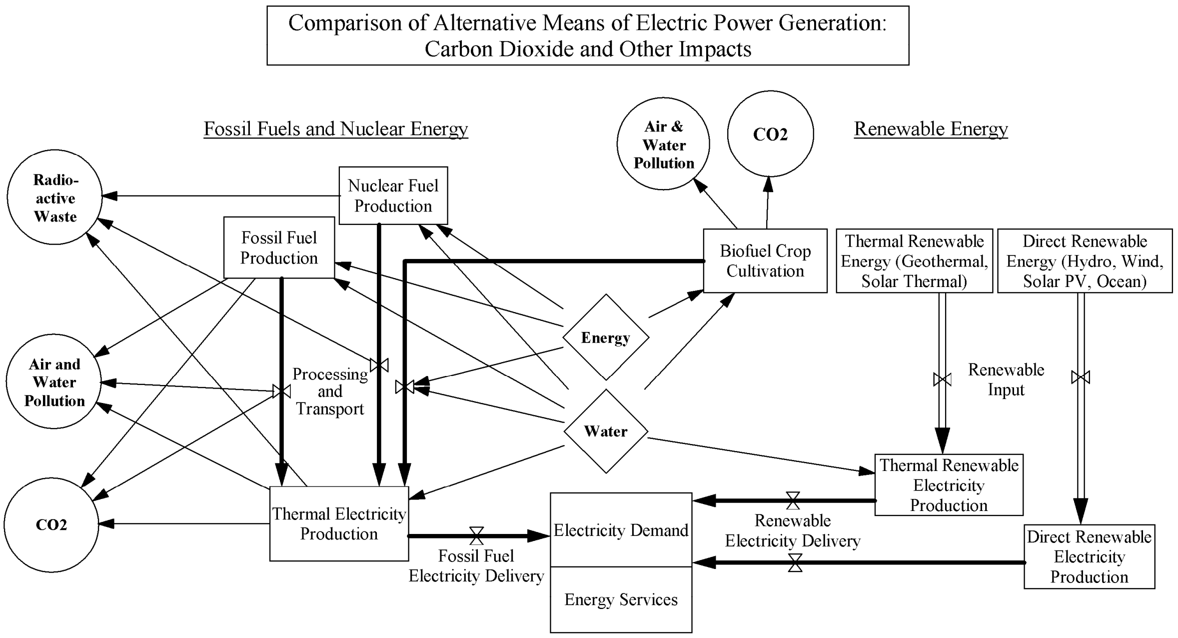

Figure SPM 3. Comparison of co-benefits, water use and CO_2 emissions associated with primary energy sources for electricity production. Not included are land impacts from surface mining of coal, land clearance for bioenergy and hydro reservoirs or methane leakage from coal natural gas and petroleum production and use or damage from oil spills and coal ash storage [1.1.6].

As for every type of energy technology, environmental and social impacts exist for each of the RE technologies, and will need to be carefully managed to ensure sustainable growth of supply. Because of the diversity of RE sources and technologies and their reliance on differing and sometimes-diffuse energy resources, the impacts and their potential mitigation will vary by technology. Such social and environmental impacts affect deployment opportunities for RE as well as conventional energy sources. Details of the most significant environmental social and impact topics, both positive and negative, are shown in Table SPM 3.

Table SPM 3. Environmental and Social Benefits (+) and Concerns (-) Associated with Renewable and Conventional Energy Sources [9]

From/ on		Bioenergy	Direct Solar	Geothermal	Hydropower	Ocean Energy	Wind Energy	Nuclear	Fossil Fuels
Land Use and Population	+	positively intensified land uses (e.g. degraded land)	decentralized energy allowing better land use (e.g. degraded or desert)	decentralized energy allowing better land use	stored water for irrigation and other uses (fisheries, domestic use, recreation)	decentralized energy allowing better land use	In many cases decentralized electricity co-existing with farming, forestry, etc.	low land use from power plants	some fuels (LPG, kerosene) allow decentralized energy avoiding deforestation
	-	competition with food supply; threats to small landowners	land use (mostly urban) for large installations	risks of land subsidence and/or soil contamination	population displacement / impacts on cultural heritage	competition for areas (e.g., fishing and navigation)	competition for areas, landscape alterations	accidents may affect large areas; mining; decommissioning sites	land occupation and degradation (e.g. mining),
Air and Water	+	decentralized electricity for water extraction and supply; lower GHG emissions	no direct atmospheric emissions; water pumping from PV electricity	no direct atmospheric emissions	low GHG emissions in most cases; impounded water can be used for irrigation, fisheries and domestic uses	no direct atmospheric emissions	no direct atmospheric emissions	no direct atmospheric emissions under normal operation	
	-	water usage for crops; fertilizers nitrate pollution; risk of fires; GHG emissions from land clearing	(limited) life cycle pollution; water for cooling CSP plants in arid areas	water usage by power plants in arid areas; risk of water contamination	risks of water quality degradation and associated health impacts; potential high methane emissions in some cases	swell/waves & tidal/ocean currents: possible effects on pollution		risks of leakages and accidents releasing toxic material	significant atmospheric emissions (GHG, other pollutants); risks of water spills, leakages, accidents, fires
Ecosystem and Biodiversity	+	possible integration between crops and with bio-corridors/ conservation units	no harm and some benefits (reflectors shade improving micro-climate)	-	-	increase of biodiversity for some constructions	-	no or little impact under normal operation	-
	-	Biodiversity loss; impacts from monoculture, burning practices and habitat land clearing and landscape diversity; invasive species; use of agrochemicals	risks from large scale projects (disruption of ecosystem structure); CSP may affect birds	water contamination effects	loss of biodiversity from inundation, new hydrological regimes; obstacle to fish migration and introduction of alien species	ecological modification from barrages	bird and bat fatalities, habitat and ecosystem modifications	short to long-term effects in case of contamination	loss of biodiversity from pollution and spills; change of vegetation and wildlife in mining and waste-fields
Human Health	+	lower and less toxic air pollutant emissions improving human health	virtually no pollution	cleaner air and improved public health; hot water for spa resorts	virtually no air pollution; water supply from reservoirs can contribute to improved health	virtually no pollution	virtually no pollution	virtually no pollution	-
	-	indoor pollution from traditional biomass burning; health effects from crop burning practices (e.g. sugarcane)	toxic waste from manufacturing and disposal of PV modules	some risks of contaminations	risk of spreading vector borne diseases in tropical areas; odor in isolated cases	-	nuisances from noise	very significant impacts from potential accidents	effects from pollution (occupational, local, regional, global); significant impacts from potential accidents
Built Environment	+	high level of socio-economic benefits from new infrastructure (e.g. jobs, local development.)	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure; wave power protects coast from erosion	socio-economic benefits from new infrastructure;	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure
	-	changes in landscape, negative visual aspects		induced local seismicity (EGS hydrofracturing); impact on scenic quality and use of natural areas	existing infrastructure damage due to inundation; risks from dam bursts; impacts from induced occupation	changing conditions at discharge sites (OTEC/osmotic power); irreversibility (tidal barrages)	impacts of wind turbines on radar systems; visibility of wind turbines	changes in landscape; necessary escape routes	large mining and processing structures; risks of accidents; impacts from induced occupation

There are options to mitigate the adverse impacts of RE technologies, making them sustainable [9]. The methods for mitigating environmental and social impacts of RE sources reflect the diversity of the technologies themselves. For example, synergies with better natural resource management practices (e.g. soil carbon enhancement and restoration, water retention functions), improvements in agricultural management and the introduction of strong sustainability frameworks help to mitigate the negative impacts of bioenergy. For solar energy, dry cooling technology can be used to limit water needs for CSP power plants, and aggressive recycling of PV modules can limit concerns about electronic waste; land usage concerns can be minimized by relying on otherwise-unused land, already-disturbed land, or by integrating solar energy with buildings. For hydropower, fish migration can be restored in many cases by constructing fish ladders or elevators, and hydropower projects can provide an opportunity for the protection and creation of high-value ecosystems. Close involvement of affected human populations in the project planning process can help reduce social concerns. Ocean energy developments may benefit to some degree from earlier experience with other forms of RE (e.g., being proactive in monitoring and early mitigation of potential effects), and integrated marine spatial planning is being introduced to address competition and environmental effects. Appropriate planning and siting of wind power plants can help minimize the impact of wind energy development on local communities and the environment, and engaging local residents in consultation during the planning stage is often an essential aspect of the development process. Nonetheless, some impacts will remain, and efforts to better understand the nature and magnitude of these remaining impacts, together with efforts to minimize and mitigate those impacts, will therefore need to be pursued in concert with increasing wind energy deployment. [2.2, 2.5, 2.8, 3.6, 4.5 5.6, 6.5, 7.6]

Assessing, minimizing, and mitigating these varied impacts for all RE sources are common elements of the planning, siting, and permitting processes that occur at the national and local levels.

The output of some RE technologies is variable (dependent, for example, on natural energy flows), whereas other technologies are able to offer controllable output.(See Box SPM 1) Some RE systems are variable, from seasonal to hours and minutes. Short term wind, solar and wave power variations can be managed by better forecasting, flexible grids and inter-connections. For autonomous systems such as mini-grids and individual buildings, energy storage is an option but usually costly [1.2.2, 8.2.1] Integrating several types of RE into a hybrid system can, with suitable controls, provide controllable electric power. [8.2.1]

RE can be deployed at the point of use (decentralized) in rural and urban environments, and can be employed within large (centralized) energy networks. RE electricity generation, produced from large hydropower plants, large wind farms, geothermal, concentrating solar power or PV systems has similar transmission and distribution requirements as any other large fossil fuel or nuclear power plant but may be more remote based on the RE resource availability.

Building integrated PV and other forms of distributed energy systems require construction of minimal transmission and distribution infrastructure, when integrated into the grid, and are highly suitable for urban settings. Distributed RE technologies are also suitable for remote rural locations and islands where conventional energy infrastructure is not viable because of low energy demands and high investment costs. Mass produced RE technologies can be readily scaled to meet changing demand as they are modular and installed soon after delivery to a construction site, thereby giving a relatively fast rate of project development. [1.2.1]

RE and energy efficiency work synergistically to lower the energy required to provide each end use energy service by lowering power density demands to match those of RE supply. A disadvantage of many forms of RE is their low power density. Following the idea of suitable “system solutions”, this can best be addressed by lowering the energy requirements needed for the energy services desired. Optimising the interaction amongst energy carriers and energy efficiency options expands the opportunities for the efficient integration of RE into the energy system.

4. Mitigation Potentials

The potential role of RE in addressing climate change depends on various aspects including the rate, magnitude and location of RE project deployment [10.2]. Deployment of low-carbon energy technologies are based on energy policy choices, mitigation goals, and the fundamental drivers of energy demand including population growth, economic growth, and evolution and emergence of end-use technologies that convert energy into useful services. Deployment of RE in different regions of the globe over time depends on how strongly mitigation targets are pursued in different countries and the particular manner in which each country takes action on climate mitigation and other energy-related issues such as energy security. RE deployment rates depend on competition with other low-carbon energy technologies such as nuclear and CCS.

Published scenarios, following significantly different core assumptions, indicate a broad range of future RE deployments *[10.2]*. Meeting long-term climate goals requires a reduction in energy-related GHG emissions and those from other anthropogenic sources including deforestation, agriculture, industrial processes and wastes. As the stringency of a long-term climate goal increases, CO_2 emissions tend to decrease, and low-carbon energy makes up part of the gap. Uncertainty in the magnitude of the energy system, reflected by the wide variation in projected primary energy consumption among scenarios, means there is a large variation in low-carbon energy required to meet any long-term goal. There is also variation in projected RE deployment being only one of several low-carbon options. The projected levels of RE deployment out to 2050 are dramatically higher than those of today in the vast majority of the scenarios reaching between 200 and 400 EJ/yr compared to about 62 EJ/yr in 2007 (Figure SPM 4).

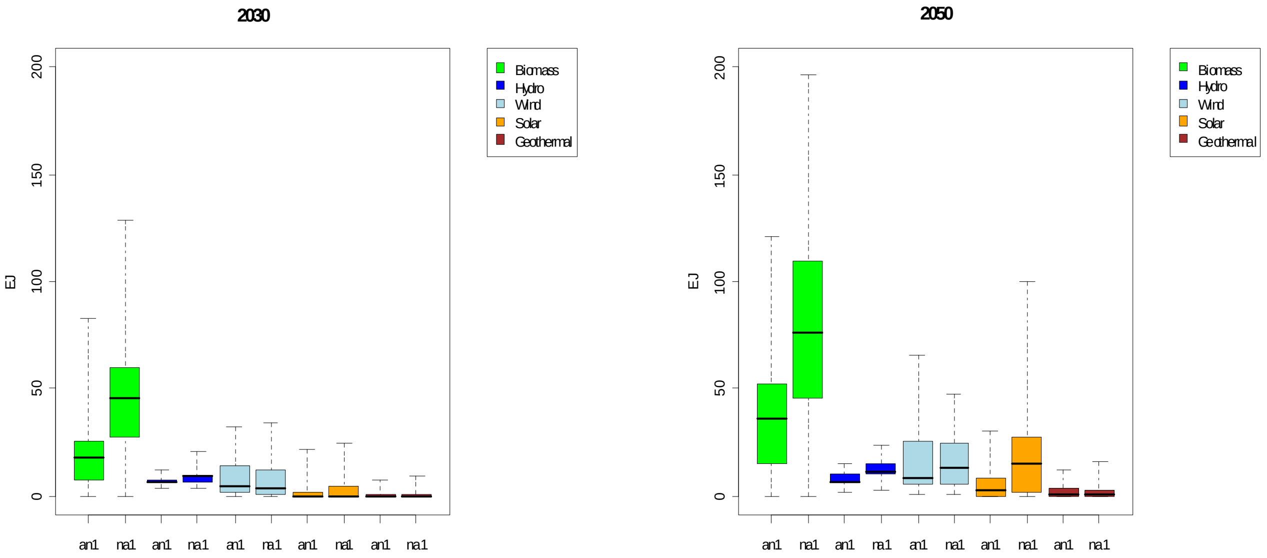

Figure SPM 4: Renewable primary energy consumption by source in Annex I and Non-Annex I countries in the mid- to long-term scenarios by 2030 and 2050. Thick black lines depict the median; coloured box the inter-quartile range (25th-75th percentile); dotted lines the total range across all reviewed scenarios.

Within the context of total RE deployment, there is great variation in the deployment characteristics of individual technologies [10.2]. Based on the scenarios in the available literature, bioenergy is shown to have a higher potential deployment over the coming 40 years than any other RE technology. By 2050, wind and solar are shown to increase more than hydro and geothermal power, while increases in ocean energy are uncertain due to unknown technology developments.

The time-scale for deployment varies across different RE technologies due to differing assumptions about technological maturity. Hydro, wind and biomass show a significant deployment being the most mature of the technologies with solar progressing after 2030 assuming continued successful technology innovations. In reality, deployment of RE technologies is the result of a complex mixture of driving forces (e.g. climate protection, security of energy supply), barrier and energy policies. In the various scenarios, because of the assumptions on technological maturity, some RE technologies (e.g. wind, hydro, direct use of bioenergy) are mostly shown to deploy independent of ambitious climate targets, whereas other RE technologies (e.g. solar, geothermal, commercial biomass) are shown to deploy mostly as the result of the underlying mitigation targets.

The distribution of RE deployment across world regions is highly dependent on the policy structure *[10.2]*. In scenarios that assume a globally efficient regime in which emissions reductions are undertaken where and when they will be most cost-effective, non-Annex 1 countries begin to take on a larger share of RE deployment toward mid-century. This is a direct result of these regions continuing to represent an increasingly large share of total global energy demand, assuming that RE supplies are large enough to support this growth. All other things being equal, and in consideration of environmental and climate related constraints, higher energy demands will require greater deployment of RE sources, highlighting that RE for climate mitigation is an issue for both Annex I and non-Annex I countries as discussed in the UNFCCC context.

Under real world conditions regional distribution of RE deployment depends on the country specific frame conditions [10.2]. In a real-world context, the distribution of RE deployments in the near-term would be skewed toward those countries taking the most proactive actions. Scenarios considering a delayed accession (no early action on climate) in specific countries show, that in those countries from a near to midterm perspective the relative deployments of RE are lower. The effect of delay on RE deployments is ambiguous in the period the countries have begun mitigation. In some cases, deployments are larger in the long-term and in some cases they are lower. This ambiguity is in part because the countries may need to quickly ramp up mitigation efforts by 2050 if action has been delayed but the same long-term climate target is to be met as the case with immediate action.

The competition with other options for reducing carbon emissions affects the deployment of RE technologies *[10.2]*. Nuclear energy, fossil energy with CCS, and RE produce GHG reductions as do more efficient end-use technologies or a reduction in end-use demand. All other things being equal, RE deployment will be lower if other options are more competitive. A review of individual models shows that higher deployment of competing low-carbon supply technologies leads to lower RE deployment (Figure SPM 5).

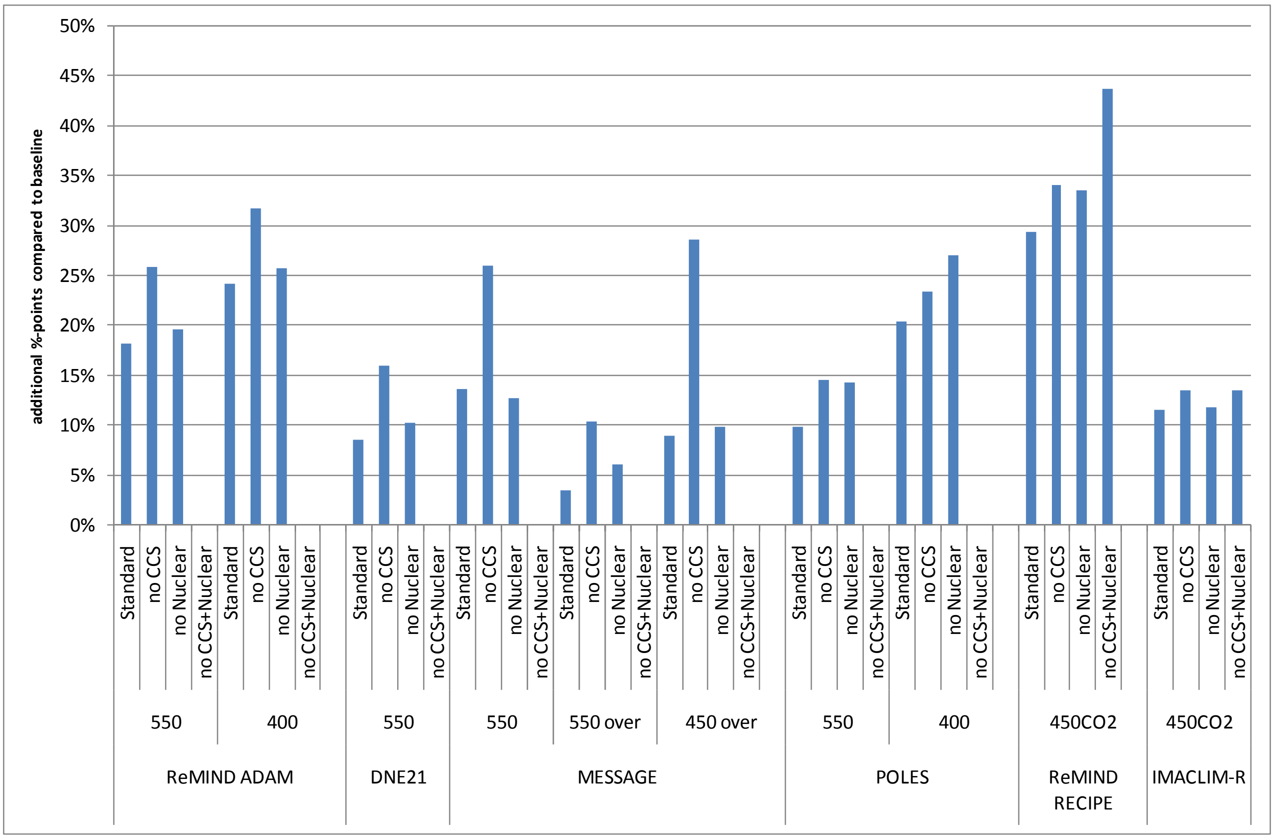

Figure SPM 5: Increase in the global share of RE by 2050 in 1st- and 2nd-best mitigation scenarios compared to the respective baseline scenarios. The exact definition of "no CCS", "no Nuclear" and "no CCS+Nuclear" varies across models; the magnitude of the increase shows a large spread, mostly because the deployment in the respective baselines differs significantly between the models.

Variations in assessments of RE deployment across scenarios can be attributed to the assumptions made of future competing options, characteristics of RE technologies, fundamental drivers of energy systems(economic growth, population growth, energy intensity, and energy end use improvements) [10.2]. Other aspects (e.g. system integration constraints) may also play a role in determining the future role of RE [8]. As a result, the presence or absence of large-scale deployment of CCS and/or nuclear power are not the only or most critical determinants of future RE deployment.

A regional breakdown for the scope of future RE deployment shows growing shares in every world region and deployment rates significantly lower than their technological limits *[10.3]*. The regional and global energy scenarios found in the literature show a wide range of RE shares in the future. Figure SPM 6 illustrates that aspect for two selected scenarios, one representing a more or less Business as Usual pathway (IEA WEO 2008) and another scenario which follows an optimistic application path for RE assuming that the current dynamic in the sector can be maintained. Even without having reached their full technological development limits, technical potentials are not the limiting factors for the expansion of RE.

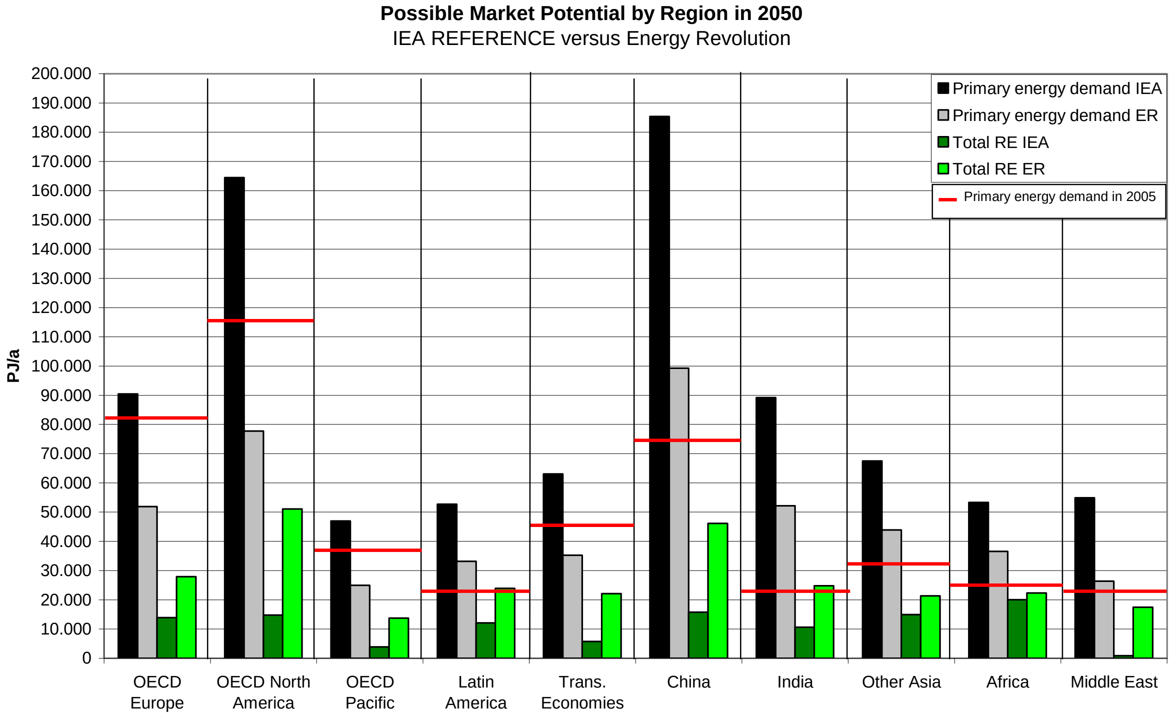

Figure SPM 6. Regional breakdown from possible RE market potential in 2050 for selected scenarios.

5. Renewable Energy Technologies

The technical and market development status of renewable energy varies by source and technology. Many of the RE technologies are technically mature and have already been or are being deployed at a significant scale, while others are in an earlier phase of technical maturity and commercial deployment (Table SPM 1).

Bioenergy: Bioenergy technologies have varying maturities, with some (e.g. domestic pellet based heating systems, small and large scale boilers) at later stage commercial development, others (e.g. gasification-based power plants) at early-stage commercial development, and still others (e.g. algue fuel production) at stages of R&D. Many bioenergy technologies have experienced decades if not centuries of practical application. Of the RE sources, biomass contributes most substantially toward global primary energy demand (10%, or 48 EJ/y, in 2007), representing 3% of primary energy in industrialised countries and 22% in developing countries. The majority of this biomass use (37 EJ/y) is non-commercial: charcoal, wood, and manure used for cooking and space heating, generally by the poorest part of the population in developing countries. Modern bioenergy uses (for industry, power generation, or transport fuels) are growing: in 2008, modern bioenergy contributed approximately 1 EJ (1.4%) of the world's total electricity generation and 2 EJ of heat (mainly via combustion of lignocellulosic materials, such as forest residues). In 2008, 2 GW of biomass electricity capacity was added for a cumulative total of 58 GW by the end of that year. Biofuels production has expanded rapidly since the end of the 1990s, mainly ethanol produced from sugar cane, corn, and cereals, and contributed about 1.5% (1.5 EJ) of transport fuel use worldwide in 2008. [2.1, 2.4, 2.8]

Direct solar energy: Solar technologies have varying maturities, ranging from early-stage R&D (e.g., solar fuels) to later-stage commercial (PV, low temperature solar thermal, and passive solar architecture). The use of solar thermal for hot water has been growing quickly, especially in China

(19 GW_{th} of additions worldwide in 2008, for a cumulative total of 145 GW_{th}, of which more than 70% was in China), while deployment of PV (more than 7 GW of additions in 2009, for a cumulative total of roughly 22 GW) has been strongly motivated by government policy in Europe, the United States, and Japan. Cumulative CSP installations by the end of 2009 were roughly 700 MW, with more than 1,500 MW of additional capacity under construction [3.4].

Geothermal energy: Hydrothermal power plants[3] and thermal applications of geothermal energy rely primarily on mature technologies, whereas EGS projects are in the demonstration and pilot phase; offshore submarine geothermal energy is in the research and development stage. Building on more than a century of commercial experience, by the end of 2009 geothermal power plants totalled almost 11 GW and were located in 24 countries, with six countries using geothermal energy to provide 10% or more of their electricity needs. Direct-use thermal applications of geothermal energy totalled 50 GW_{th} by the end of 2009, while the use of geothermal heat pumps in new and retrofit building applications accounted for 17 GW_{th} by the end of 2009. [4.3, 4.4]

Hydropower: Of the RE technologies used for electricity production, hydropower is the most mature, and leads in installed electricity capacity and production: hydropower additions in 2008 totalled roughly 35 GW, for a cumulative 945 GW by the end of that year and accounting for 16% of the world's total electricity generation. The market drivers for hydropower development include not only energy needs, but also the desire for flexibility in power systems as well as water management systems. In 2006, 43% of hydropower installations were in OECD countries (with most concentrated in Europe, the USA and Canada) and 57% in non-OECD countries (with most in China, Brazil and Russia). Recent growth in hydropower has centred on emerging markets such as China, India, and Brazil, where significant potential remains untapped; in South East Asia, trans-boundary projects have also been developed [5.2, 5.4]

Ocean energy: With the exception of tidal barrages, most ocean technologies are at the demonstration and pilot project (wave, tidal/ocean current, OTEC, and osmotic power) or research and development (marine biomass) stages. Tidal barrages have been in operation since 1966, though current worldwide capacity remains comparatively small with 264.4 MW installed. Several additional projects are under consideration in China, the Republic of Korea, Russia and the United Kingdom that, if implemented, would account for an added capacity of 21.9 GW. Most international R&D is currently focused on wave and tidal current technologies. In total, fewer than 300 MW of ocean energy facilities were operational by the end of 2009. [6.4, 6.6, 6.7]

Wind energy: Modern wind turbines have evolved from small, simple machines to large, highly sophisticated devices, driven in part by more than three decades of basic and applied R&D. As a result, on-shore wind energy technology is already being deployed at a rapid pace in Europe (e.g., Germany, Spain), North America (U.S.), and Asia (China, India), while off-shore wind energy is also beginning to expand but is at an earlier phase of technical and commercial development. From a cumulative capacity of 14 GW by the end of 1999, the global installed wind power capacity increased to almost 160 GW by the end of 2009 (38 GW was added in 2009) and was capable of meeting 1.8% of worldwide electricity demand. From 2000-2009, roughly 11% of global net electric capacity additions came from wind power plants. [7.3, 7.4]

The global technical potential of RE sources will not limit market growth. On a worldwide basis, studies have consistently found that the technical potential for RE is more than an order of magnitude larger than global energy demand (Table SPM 4). A wide range of estimates are provided in the literature, and those estimates are not entirely comparable. Nonetheless, these studies find that the technical potential for solar energy is the highest among the RE sources, but

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[3] Hydrothermal power plants are the most common form of geothermal power plants. They use the heat energy contained in water and steam flowed from geothermal wells to generate electricity.

that substantial technical potential exists for all forms of RE. Though the technical potential for individual RE sources is not evenly distributed across the globe, all regions have substantial technical potential. Even in regions with relatively lower levels of technical potential for any individual RE source there are typically significant opportunities for increased levels of deployment. The absolute size of the global technical potential is unlikely to constrain RE development. Regional resource limitations, sustainability concerns, system integration/infrastructure constraints, economic factors, and other issues are more likely to limit the future use of RE technologies. [2.2, 2.8, 3.2, 4.2 5.2, 6.2, 6.4, 7.2, 10.3]

Table SPM 4. Global Technical Potential of Renewable Energy Sources (compare to global primary energy supply in 2007 of 482 EJ) for 2020, 2030, and 2050 [10.3, 1.2.3].

		Technical Potential (EJ/y)					
		Krewitt et al. (2009)[1]			Range of Estimates		***Sources for Range of Estimates*** [2]
		2020	*2030*	*2050*	*Low*	*High*	
Electric Power (EJ/y)	Solar PV[3]	1126	1351	1689	1338	14766	Krewitt *et al.* (2009); Chapter 3 reports total range of solar electric potential (PV and CSP) of 1440 to 50,400 EJ/y
	Solar CSP[3]	5156	6187	8043	248	10603	Krewitt *et al.* (2009); Chapter 3 reports total range of solar electric potential (PV and CSP) of 1440 to 50,400 EJ/y
	Geothermal	4.5	18	45	1.4	144	Krewitt *et al.* (2009)
	Hydropower	48	49	50	45	52	Krewitt *et al.* (2009)
	Ocean	66	166	331	330	331	Krewitt *et al.* (2009)
	Wind On-shore	362	369	379	70	1000	Chapter 7: low estimate from WEC (1994), high estimate from WBGU (2004) and includes off-shore
	Wind Off-shore	26	36	57	15	130	Chapter 7: low estimate from Fellows (2000), high estimate from Leutz *et al*. (2001)
Heat (EJ/y)	Solar	113	117	123	na	na	Krewitt *et al.* (2009)
	Geothermal	104	312	1040	3.9	12590	Krewitt *et al.* (2009)
Primary Energy (EJ/y)[4]	Biomass Energy Crops[5]	43	61	96	49	260	Chapter 2 (higher quality lands): large number of studies and several recent assessments, e.g., Dornburg *et al*. (2010)
					10	70	Chapter 2 (marginal/degraded lands): large number of studies and several recent assessments, e.g., Dornburg *et al*. (2010)
	Biomass Residues	59	68	88	100	200	Chapter 2: large number of studies and several recent assessments, e.g., Dornburg *et al*. (2010)
IEA Forecast (EJ/y)[6]	BAU Primary Energy	605	703	868[7]			
	450ppm Scenario	586	601				

1. Technical potential estimates for 2020, 2030, and 2050 are based on a review of studies in Kewitt et al. (2009); data presented in Chapters 2-7 may disagree with these figures due to differing methodologies.
2. Range of estimates comes from studies reviewed by Krewitt et al. (2009), as revised based on data presented in Chapters 2-7.
3. Estimates for PV and CSP from Krewitt et al. (2009) for 2020, 2030, and 2050 are based on different data and methodologies, which tend to significantly understate the technical potential for PV relative to CSP.
4. Primary energy from biomass could be used to meet electricity, thermal, or transportation needs, all with a conversion loss from primary energy ranging from roughly 20% to 80%.
5. Even the high-end estimates presented here take into account key limitations with respect to food demand, water availability, biodiversity and land quality.
6. IEA (2009)
7. DLR (2008)

Climate change will have impacts on the size, geographic distribution, and variability of renewable energy technical potential. Because RE sources are, in some cases, dependent on the climate, it follows that global climate change will affect the RE resource base. Research into the possible effects of global climate change on the size, geographic distribution, and variability of RE technical potential is nascent, but the RE sources likely to be most impacted include bioenergy, hydropower, and wind energy. The technical potentials of biomass are influenced by and interact with climate change, but the mechanics and details of those impacts are still poorly understood. The overall impact of a modest temperature change is likely to be relatively small on a global basis, but strong regional differences can be expected [2.5, 2.8]. For hydropower, climate change is expected to increase overall average precipitation, but regional patterns will vary: precipitation is anticipated to increase at higher latitudes and in part of the tropics, and decrease in some sub-tropical and lower mid-latitude regions. The impact of these changes on river flows and hence on the technical potential of hydropower is subject to a high level of uncertainty: the impact is likely to be relatively small on a global basis, but significant regional changes in river flow volumes and timing are possible [5.2]. For wind energy, research to date suggests that global climate change will alter the geographic distribution of the wind energy resource, but that those effects are unlikely to be of a magnitude to greatly impact the *global* mitigation potential of wind energy [7.2]. For direct solar energy, though climate change is expected to influence the distribution and variability of cloud cover, the overall effect of these changes on the technical potential of direct solar energy is anticipated to be small [3.2]. Climate change is not expected to have significant impacts on the size or geographic distribution of geothermal and ocean energy resources [4.2, 6.1, 6.2]. However, for all of the RE technologies, climate-induced extreme weather and climate events we well as instable water regimes will need to be considered in project and technology design.

Currently, the levelized costs of energy*[4] *(LCOE) are higher for the majority of RE technologies than for fossil fuel-based energy services (See Figure SPM 7). More mature RE technologies are often competitive at current prices without financial government support. Less mature technologies can also provide competitive energy services in some cases, e.g. in regions with favourable conditions like high quality resources, a lack of energy infrastructure, and/or limited availability of alternatives. Table SPM 5 provides ranges of current LCOEs for commercially available RE technologies at varying discount rates.

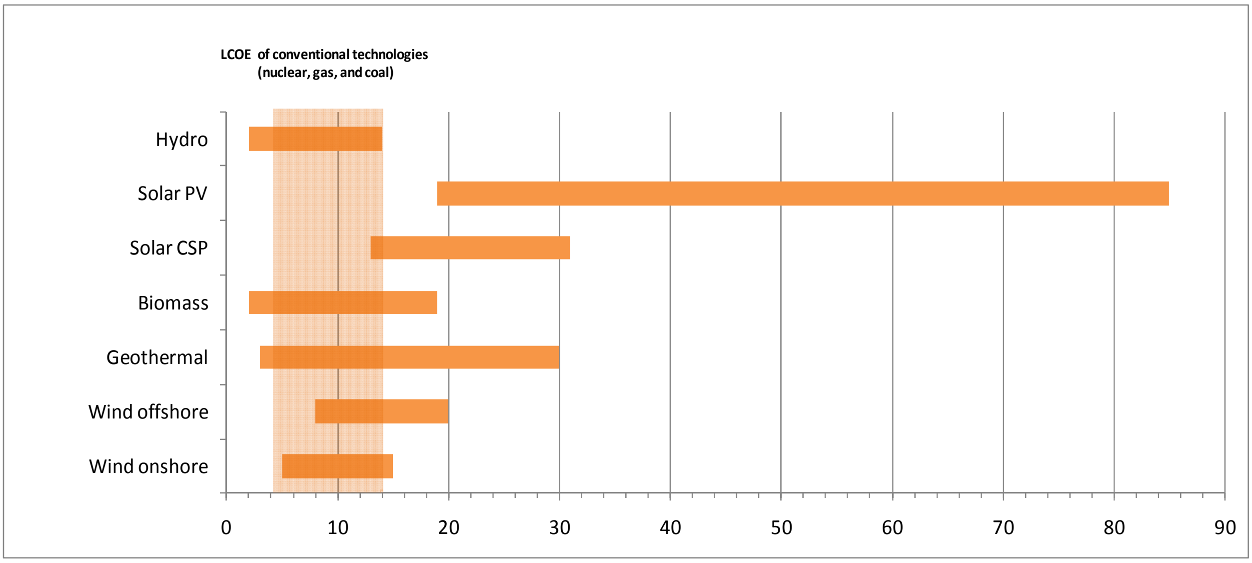

Figure SPM 7. Cost-competitiveness of selected renewable power technologies [10.5.1].

Notes: The figure is based on IEA data and updated by cost data collected for the IPCC SRREN (this report). The LCOE are given in US-cent/kWh, and have been calculated at a 10% discount rate. LCOE of conventional technologies depict the range valid for North America, Europe, and Asia Pacific. For OECD countries a future carbon price of US$ 30/t CO_2 is assumed. [Authors: This figure will be updated to clearly present which numbers originate from the IEA and which from the IPCC SRREN as are reflected in Table SPM5.]

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[4] The LCOEs of technologically identical devices can vary across the globe. They depend on the quality of the resource (which affects the capacity factor), regional investment costs including material and labour costs of construction, on the cost of financing (which affect the appropriate discount rate), and – to a lesser extent – the cost of operation and maintenance.

Table SPM 5. **Levelized Cost of Energy (2005 US$/kWh) for various RE sources[5].**

Source	**RE technology**	**LCOE at 3%**		**LCOE at 7%**		**LCOE at 10%**		**Learning Rate (%)**	
		lower bound	***higher bound***	***lower bound***	***higher bound***	***lower bound***	***higher bound***	***lower bound***	***higher bound***
Direct Solar Energy	**PV, res roof**	0.20	0.50	0.31	0.69	0.40	0.85	11	26
	PV, com roof	0.17	0.46	0.26	0.64	0.34	0.79	11	26
	PV, fixed tilt	0.11	0.25	0.17	0.34	0.22	0.42	11	26
	PV, 1-axis	0.10	0.28	0.15	0.38	0.19	0.47	11	26
	CSP	0.11	0.19	0.16	0.25	0.20	0.31	5	15
Geothermal Energy	**Condensing-flash**	0.03	0.08	0.04	0.11	0.04	0.13	n.a.	n.a.
	Binary-cycle	0.03	0.11	0.04	0.14	0.05	0.17	n.a.	n.a.
Hydro	**all**	0.01	0.06	0.02	0.08	0.02	0.11	0.5%	2%
Wind Energy	**On-shore, Large**	0.04	0.09	0.05	0.13	0.06	0.15	10	17
	Off-shore, Large	0.07	0.12	0.10	0.16	0.12	0.20	n.a.	n.a.

Note: The following default assumptions were made to define the LCOE if data were unavailable:
time of construction - one year, no production during that year
O&M costs - *constant over lifetime*
production - *start after commissioning at (nameplate capacity x capacity factor)*
lifetime - *excludes years of construction*
retrofit or other major costs during regular lifetime -*assumed to be included as annuity in O&M costs, i.e., constant costs after construction*
decommissioning - *costs not included in LCOE*
Lower bound = lower bound of capital and O&M cost, higher bound of capacity factor (CF) and lifetime
Higher bound = higher bound of capital and O&M cost, lower bound of CF and lifetime

The costs of energy generated by renewable energy technologies have declined over time and are expected to decline further*. *Continued technical improvements will increase the potential for GHG reductions from renewable energy over time as costs decline. Technical advancements over the last decades have been substantial, driven by public and private R&D as well as deployment-oriented learning. Learning rates are widely used as estimates for future cost reductions[6] (See Table SPM 5). Technical advancements are expected to lead to continued cost reductions in the years ahead, resulting in greater potential for GHG reductions.

<u>Bioenergy:</u> Technological learning and related cost reductions have been substantial for bioenergy cropping systems, supply systems and logistics, and conversion. As a result, there are several bioenergy systems, most notably sugar-cane based ethanol production and heat and power generation from biomass residue/waste that are already deployed at a competitive prices. Depending

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[5] Some bioenergy technologies are commercially available. However, these technologies have not been included in the table due to great variations based on local conditions, biomass supply and other factors. [Authors: Efforts will be made to include comparable bioenergy costs in this table in subsequent revisions.] For a discussion of bioenergy costs see Chapter 2.
For technologies that are not yet commercially available, there are no historical reference data that allow for a balanced selection of cost-performance parameters to calculate LCOEs. Therefore, LCOEs have not been derived for technologies that are still in the pre-commercial phase, such as enhanced geothermal systems and most ocean energy technologies. Estimates of cost-performance parameters expected for projects using current technologies and current costs of input factors (projected costs) are presented and discussed in the relevant technology chapters.

[6] Learning rates may be estimated for different periods in time, different regions and for different performance measures.

on market conditions, other smaller-scale bioenergy applications can cost-effectively contribute to rural poverty reduction. Further improvements in power generation technologies, biomass supply systems, and perennial cropping are anticipated, reducing the cost of biomass electricity and heat. With respect to second-generation biofuels, recent analyses have indicated that advancements by roughly 2020 may allow these technologies to compete with oil prices of 60-70 U$/barrel. [2.7]

Direct Solar Energy: Historically, every doubling of cumulative production of PV modules has led to a reduction in module costs of 13-26% and future technical advancements are expected through reduced material use, new semiconductor materials, and improved manufacturing techniques. Further cost reductions of solar technologies in line with the known learning curves for solar PV and CSP are anticipated as the technologies mature [3.7].

Geothermal Energy: EGS cost estimates range from 75 to 175 US$/MWh for resources at 4 to 5 km depth and 200-330°C. The cost of hydrothermal power plants is anticipated to decline by about 10-15% by 2050; EGS cost reductions are expected to be more significant, at perhaps 50% by 2050, assuming a reduction in drilling costs through learning effects and success in developing stimulation technology. The capital investment for direct-use applications ranged from 1200 to 2700 US$ per installed thermal kilowatt in 2008. [4.7]

Hydropower: As a mature technology, further cost advancements for hydropower are likely to be less significant than some of the less-technically-mature RE technologies. Nonetheless, there is substantial potential[7] for improving the performance and extending the life-time of existing hydropower plants through plant refurbishment. Research is also being conducted to make hydropower projects technically feasible in a wider range of natural conditions, reduce costs, and improve environmental performance. [5.3, 5.7, 5.8]

Ocean Energy: R&D on ocean energy did not really begin until the 1970s and developments remained halting until the turn of the 21st Century, at which point R&D investment accelerated. A diverse set of technologies is under consideration, and the most cost-effective technical solutions are not yet clear; as a result, the cost of ocean energy technologies is currently higher than many of the other RE sources. Based on the current technologies and related costs[8], wave energy is forecast to have an LCOE of US$214–788/MWh, whereas tidal current energy is forecast to have an LCOE range of US$161–321/MWh. Older forecasts for OTEC plants range from US$160–200/MWh for early commercial plants, and recent forecasts for early salinity gradient plants range from US$670–1,340/MWh. As niche markets develop for these technologies (e.g., remote communities and islands), and as public and private R&D continues, costs are forecast to decline. [6.6, 6.7]

Wind Energy: Continued incremental advancements in on-shore wind energy technology are expected to yield improved design procedures, increased reliability and energy capture, reduced O&M costs, and longer turbine component life. Even greater technical advancement possibilities exist for off-shore wind energy, and fundamental research to better understand the environment in which wind turbines operate is expected to yield benefits for both on- and off-shore wind energy technology. Available literature suggests the possibility of reductions in the LCOE of on-shore wind energy of 15-35% and off-shore energy of 20-45% by 2050. [7.7, 7.8]

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[7] Over the past decade, orders received for the refurbishment of hydropower plants have been in the order of 10,000 MW/yr, or roughly 1% of existing global capacity. Refurbishment yields an estimated efficiency increase of 5%, corresponding to an increased production of 1500 GWh/year worldwide with the same amount of water. A major refurbishment will typically extend the life time of a hydropower plant by several decades.

[8] LCOEs presented here for ocean energy are not based on historical data, but forecasts. Since the underlying assumptions, including but not limited to the applied discount rates, are not transparent, these estimates are not readily comparable to LCOEs listed in the table.

Technical and market barriers will need to be addressed to achieve high levels of renewable energy deployment. RE offers significant potential for near- and long-term GHG emissions reductions, but a variety of technology-specific barriers would need to be overcome to achieve that potential (see below). In general, potential deployment levels of RE technologies may be influenced by a number of factors. Regionally, economic development and technology maturity are primary determinants: for mature technologies (e.g. hydropower) much of the available potential in OECD countries has been exhausted and the largest future expansion is expected in Non-OECD countries. Other, less mature technologies will likely initially focus on expansion in affluent regions where financing conditions and infrastructure integration are favourable. The need for cost and technological advancements varies according to the maturity of a given technology. For large-scale deployment of some technologies, integration and supply chain considerations may also be relevant. [10.2.3]

Bioenergy: Though still uncertain, competitiveness of biomass use for fuels and feedstock materials is expected to strongly improve over time, providing a push for biomass into energy markets in the longer term. A key precondition for the increased use of bioenergy is the application of well functioning sustainability frameworks and strong policies that avoid conflicts with food production, biodiversity, water and socioeconomic developments. Land-use planning, the alignment of bioenergy production with efficiency increases in agriculture and livestock management, and the use of degraded lands are especially important in this regard. Well developed logistical capacity for bioenergy markets and the facilitation of international bioenergy trade would also be important, as would further technical advancements especially for next-generation biofuels and biorefineries; analyses indicate that if R&D and near-term market support are offered, technological progress could allow for competitive 2nd generation biofuel production around 2020. [2.2, 2.7, 2.8]

Direct Solar Energy: The main barrier to the widespread use of direct solar energy is the current higher cost of certain solar technologies (PV, CSP and in some countries solar heating and cooling): further cost reduction through R&D and learning-based experience are therefore especially important. Regulatory and institutional barriers can also impede deployment, particularly for smaller, decentralized solar energy systems; to widely implement decentralised solar electricity, a different paradigm for electric system infrastructure may be needed. The deployment of passive solar technologies depends heavily on spatial planning and building codes. [3.9]

Geothermal Energy: Technical improvements, if successful, have the potential during this century to enable a two orders of magnitude increase (up to more than 1,000 GWe in 2100 from 11 GWe in 2009) in the use of geothermal energy. Achieving that result, however, will require sustained support and investment from governments and the private sector. The most important R&D challenge for geothermal is to prove that EGS can be deployed economically, sustainably, and widely; social and environmental concerns will require careful attention, including concerns about induced local seismicity for early EGS plants. Improvements in the delivery infrastructure and additional technical improvements are also important for more widespread utilization of geothermal heat in direct use applications. [4.6, 4.8]

Hydropower: The potential exists to triple the contribution of hydropower in worldwide electricity supply. As hydropower is already a mature and cost-effective RE technology, the technical and economic challenges facing such developments are limited. New hydropower projects are sometimes controversial, however, and environmental and social concerns may limit growth; benefits therefore exist in further developing sustainability assessment tools for hydropower projects. Enhanced regional and multi-party collaboration can also help in meeting energy supply and water resources management needs.[5.6, 5.9, 5.10]

Ocean Energy: Deployment of ocean energy is likely to accelerate as R&D continues and commercial maturity is achieved. In the near term, growth in tidal barrage capacity is anticipated, with tidal current and wave/swell devices moving towards commercial maturity. In addition to continued R&D investments, the deployment of ocean energy will benefit from testing centres for demonstration and pilot projects and from dedicated policies that encourage the early deployment of the technologies. [6.4]

Wind Energy: Studies suggest that the rapid recent increase in global wind power capacity is likely to continue in the near- to medium-term. By 2050, global wind electricity supply could reach or even exceed 20% of total electricity supply if ambitious efforts are made to reduce GHG emissions. Achieving this level of wind energy supply would likely require not only economic support policies of adequate size and predictability, but also an expansion of wind energy utilization regionally, increased reliance on off-shore wind energy in some regions, technical and institutional solutions to transmission constraints and operational integration concerns, and proactive efforts to mitigate and manage the social and environmental concerns associated with wind energy deployment. [7.8]

6. Integration of RE into current and future energy supply systems

To achieve greenhouse gas stabilisation levels at around 450 ppm, high levels of RE penetration will need to be integrated into existing electricity, heating, cooling and transport energy supply systems to displace some future fossil fuel demand across all sectors (Figure SPM 8). To achieve this will require around double the present annual rate of deployment of all RE technologies.

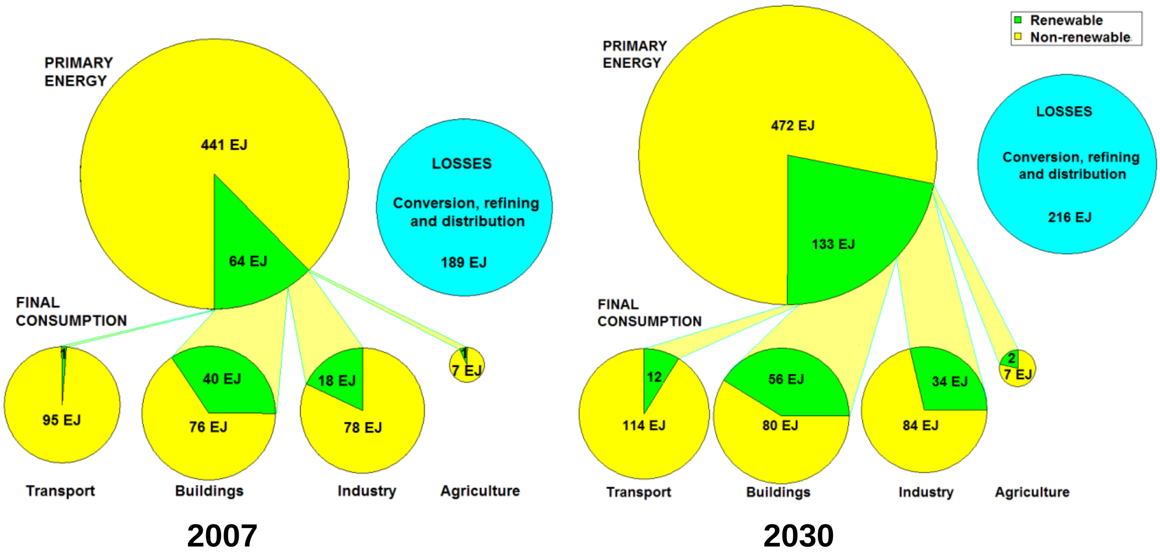

Figure SPM 8. RE shares (including traditional biomass) of primary energy and final consumption in the transport, buildings, industry and agriculture sectors in 2007 and an indication of the increasing shares needed by 2030 to meet a 450ppm scenario. [8.1]

[Authors: this figure will be updated to include WEO 2010 data and an attempt will be made to include other scenarios as reflected in SPM 3. Mitigation Potentials. It will also be amended to use the direct equivalent method for calculating primary energy. These changes are unlikely to change the RE shares as shown to any significant degree.]

Increased RE penetration through integration into existing energy systems is technically feasible in most regions, but reaching much higher levels than today could be constrained by cost, lack of infrastructure investment, societal acceptance, appropriate policy framing and lack of trained personnel as well as competition from other low-carbon technologies (including nuclear and carbon dioxide capture and storage) [8.1].

Over the long term, as related infrastructure and energy systems develop through system integration, there are few, if any, technical limits to developing a portfolio of RE technologies to meet a significant share of total energy demand in regions where suitable resources exist. A well-designed portfolio could enhance energy system reliability, security of supply, and provide improved access to energy services in both developed and developing countries. [8.1]

However, competition between RE systems to meet local and regional energy demands could reduce the future deployment potential for any single technology (for example, transport powered by either liquid biofuels, biomethane, hydrogen or electricity [8.3.1], or heating/cooling demands being met by bioenergy, solar thermal or ground source heat pumps installed in buildings competing with district heating schemes or electricity. [8.2.2]

Improved energy end-use efficiency, together with flexibility in the time of energy use in the transport, buildings, industry and agriculture sectors can facilitate greater shares of RE supply since local RE resources may then be sufficient to better meet local energy demands. [8.3]

Building-integrated RE technologies in urban or rural locations provide the potential for buildings to become net energy suppliers rather than net energy users. [8.3.2]

RE uptake can be increased in all final end-use sectors (Figure SPM 9) both directly (by utilising solar, bioenergy, and geothermal technologies integrated with new or existing buildings or into industrial processes) and indirectly (where, an increased share of RE sources can be integrated into grid-based energy carriers such as electricity, district heating, district cooling, liquid fuel blends, and biomethane and hydrogen in gas grids). [8.2.3, 8.2.4]

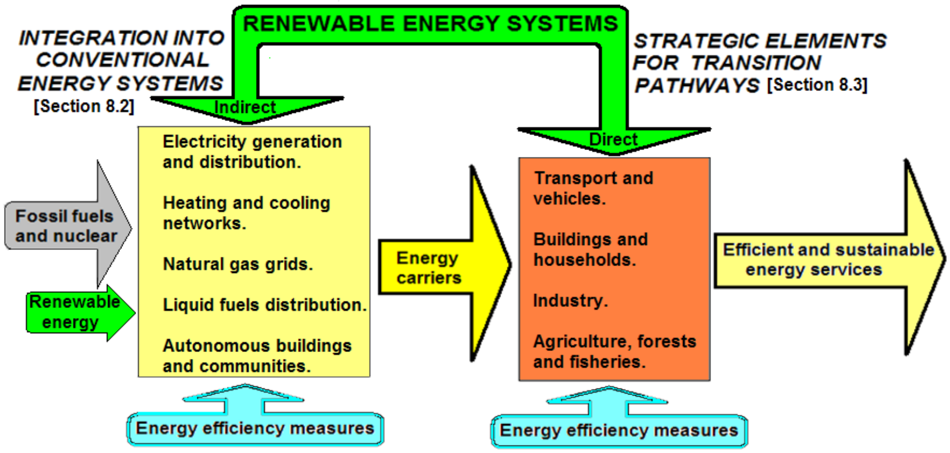

Figure SPM 9. RE sources, additional to those presently being utilised in conventional energy systems, can be utilised directly on site by end-use sectors or indirectly through enhanced integration into energy carriers.

The readily acceptable limit to the share of RE integrated into a specific energy system depends upon the existing system design (for power supply being either distributed, centralised, autonomous or inter-connected), its present operation, scale, local RE sources available, proportion of variable resources, cost-competitiveness of present technologies, social aspects, public perception and future developments. [8.2]

Electricity from RE sources are either variable (wind, ocean and solar PV) or dispatchable (reservoir hydro, bioenergy, CSP and geothermal). Experience from managing wind penetration in some countries confirms that integrating large shares (>20%) of variable sources in existing power supply systems requires designing a more flexible and intelligent grid together with a mix of generation technologies and corresponding dispatch methods (aided by short-term forecasts). The aim is to maintain a reliable system balance and secure operation at all times, therefore avoiding possible increased system operating costs.

Solutions to minimise integration costs can include investment in more transmission, stronger and inter-connected grids, improved market and system management, including the use of a wide range of existing and potential future demand response options, better RE resource forecasts that can help provide a smoothing effect, and making the system more flexible overall. Energy storage is more important to balance autonomous systems and isolated grids than it is for inter-connected grids. [8.2.1, 8.2.5]

District heating and cooling systems offer flexibility with regard to the primary energy source and can therefore use low grade RE inputs (such as geothermal heat), or heat with no or few competing uses (from industrial processes, bioenergy heat from cogeneration, or combustion of biomass derived from wastes and residues). [8.2.2]

Integrating biofuels with liquid transport fuels and injecting biomethane or hydrogen into gas distribution grids can be successfully achieved and used for a range of applications if appropriate standards can be met. [8.2.3, 8.2.4]

Additional costs of integration depend on the character of the existing system, the RE sources available, how a specific system evolves and the level of penetration. Due to the complexity of integrating RE into individual systems, it is difficult to obtain “typical” system costs and benefits in general terms from the literature. In addition, any changes in costs may not be easily attributed to a specific RE investment. [8.2]

7. Policies for advancing RE deployment

Various market failures, policy failures and barriers impede RE deployment [1.5; 11.4]. Market failures that impede RE deployment may include un-priced environmental impacts and risks, underinvestment in invention and innovation and the existence of monopoly powers in actual markets, limiting competition among suppliers or demanders, free entry and exit.

When directed to boost non-RE systems and technologies, existing policies and regulations can act as barriers to RE deployment. Government policies enacted to promote RE technologies can have negative impacts and slow the transition to a low-carbon energy economy if they are poorly formulated, inappropriate, inconsistent, or too short-term.

Barriers to RE deployment are unintentional or intentionally constructed impediments made by man. They may be categorized into the following: information and awareness barriers (e.g. a lack of consensus on the best way for a low-carbon energy transition to proceed, a lack or knowledge about best-practice for RE deployment, or a lack of knowledge about the risks of investment); socio-cultural barriers; technical and structural barriers; and economic and institutional barriers [1.4, 11.5.1]. Issues - distinct from barriers – are natural properties that impede the application of some RE sources at some place or time (e.g. flat land impeding hydropower, the inability to collect direct solar energy during dark hours) [1.4].

Comprehensive supporting policies for RE address specific barriers that hinder RE deployment; penalise negative externalities; reward positive externalities; stimulate RE innovations; and enhance international cooperation [11.5].

Targeted RE policies accelerate RE development and deployment. Public RD&D combined with deployment policies have been shown to drive down the cost of technology and sustain its deployment. Steadily increasing deployment allows for learning, drives down costs of RE technologies through economies of scale, and attracts further private investment in R&D, thereby creating virtuous cycles of technology development and market deployment.

Policy design can vary greatly and depends on the specific target or goal of the policymaker. Some policies support the deployment of one particular RE technology in a specific area. Others address all RE options in a country, region, or regional sub-grouping[9]. Policies can be weighted toward GHG emission reduction, diversification of energy sources (e.g. developed countries), or toward giving populations access to modern and clean energy sources (developing and underdeveloped countries).

The way countries design their RE policies depends on their specific circumstances. Some countries (e.g. Brazil, Germany, China, Vietnam and South Africa) have intertwined RE policies with industrial development initiatives to create niche markets and pull new RE technologies through the innovation cycle; and other countries (e.g. Nepal, Vietnam) have linked RE policies with decentralization and rural development initiatives.

Though links exist between climate and RE policy, supporting policies for RE are still necessary [11.2; 11.5] At least two broad policy approaches are required to address the major market failures of climate change: 1) carbon pricing (by carbon trading, carbon taxes, or implicitly through regulation) and 2) support for research and development and diffusion of a low-carbon technology.

Carbon pricing at levels that encourage behavioural change is necessary, but not a sufficient tool to give a low-cost transition to a low-carbon economy. There are three reasons to support RE alongside climate-change policy. First, governments have not yet implemented ‘ideal’ carbon pricing or ‘ideal’ low-carbon technology support. Second, even if governments were to implement ‘ideal’ carbon pricing and ‘ideal’ development support, there are a range of other relevant market failures (e.g. financial market failures, oligopoly and imperfect competition, etc.) that might justify additional intervention. Finally, RE yields a range of other non-market benefits (e.g. reduction in local air pollution, health benefits) relative to fossil-fuel based energy production. Without public policy to account for these benefits, RE deployment may remain low.

Successful policies are well-designed and – implemented, conveying clear and consistent signals. Successful policies take into account available RE resources, the state and changes of the technology, as well as financing needs and availability. They respond to local, political, economic, social, financial, ecological and cultural needs and conditions.

For these policies to be successful requires:

- a fair rate of return to attract investment, create strong industries, drive down costs and sustain a steadily growing market;
- the removal of economic and non-economic barriers to RE;
- a viable, predictable, clear and long-term government commitment and policy framework;
- appropriate incentives that guarantee a specific level of support varying with technology and its level of maturity;
- a combination of different types of instruments (regulatory, fiscal, etc.) to address range of barriers;
- flexibility to learn from experience, including mistakes, and to adapt policies as circumstances (technologies, market conditions, etc.) change;
- acceptance of RE on all levels as the density of RE projects increases.

Policy performance needs to be evaluated for ‘learning’ to be captured and incorporated into the designing and implementation of RE policies. Criteria of effectiveness and efficiency can establish whether policies accord with political realities, local values, administrative and other capacities for implementing the policies. Follow-up and understanding of progress and performance, successes

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[9] The Pacific Islands for example.

and failures enable learning to take place and feed iterative improvements in design and implementation.

There is more than 30 years of experience with policies targeted to overcome RE uptake and investment constraints on capacity, R&D, and infrastructure necessary for integrating RE in existing energy systems. Some have proven efficient and effective, others have not. There is substantial literature to facilitate understanding of the effectiveness, efficiency and equity aspects of policies supporting RE power generation but less so for transport, heating and cooling.

***Well-designed RE policies are more likely to emerge and to function most effectively in an enabling environment*[10]. ** [11.6]**.** Increasing the deployment of RE technologies depends on the coordination of policies and the components of an enabling environment (See Figure SPM 10). Governments, the private sector, research and NGO organizations help to make an environment enabling for RE by creating the education, institutional and investment capacity and mechanisms necessary to overcome barriers and stimulate technology diffusion.

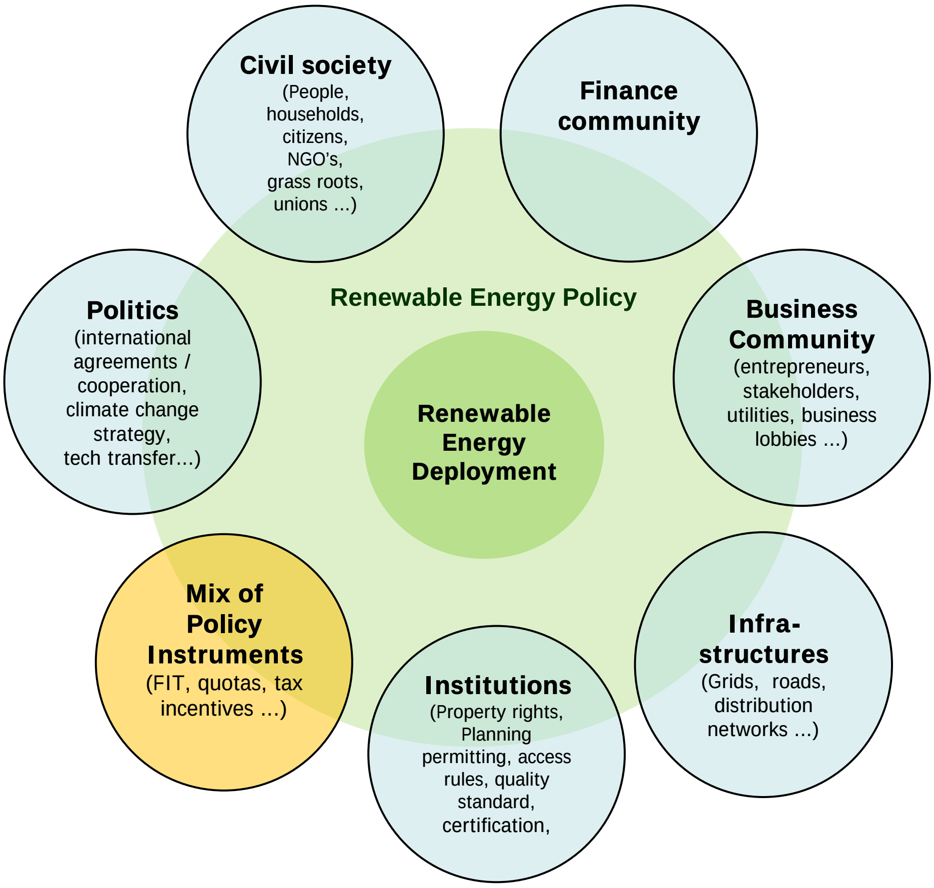

Figure SPM 10. RE technology is embedded in an enabling environment, in which RE policy instruments is one decisive dimension of many.

Accelerated deployment of RE may be facilitated by new international public and private partnerships and cooperative arrangements of multiple stakeholders. [11.2, 11.1, 11.6]. Bringing energy, environment, land planning, NGOs, experts, pressure groups and other stakeholders such as members of civil society, into a common policy network makes it easier for institutions to generate

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[10] An enabling environment is a network of institutions, social norms, infrastructure, education, technical capacities, financial and market conditions, laws, regulations and development practices that in concert provide the necessary conditions to create a rapid and sustainable increase in the role of RE sources in local, national and global systems [11.6].

institutional learning[11] thereby enabling policy making to become more comprehensive and reflexive, and enabling policy adaptation to better respond to local needs and conditions.

New suitable finance mechanisms on national and international levels, involving cooperation between the public and private sectors, work to stimulate technology transfer[12] and worldwide RE investment as well as advancing the necessary infrastructure for RE integration. The role of governments in providing not only a supportive policy environment, but also funding, fiscal policies, and the establishment of standards and regulation, is a critical element [11.6.6].

Strong political support and predictable and sustained regulatory commitment to RE deployment reduces risk for investors and often results in greater RE deployment. [11.6.2; 11.6.4; 11.2.3]. Policies that are well-designed and predictable, providing clear and long-term market signals, encourage greater levels of private investment, thereby reducing the amount of public funds required to achieve the same level of RE development and deployment.

In developed countries, governments can play a role in reducing the cost of capital and improving access to capital by mitigating the key risks, particularly non-commercial risks that cannot be directly controlled by the private sector. Given the budgetary constraints facing most developing country governments, additional funding may be necessary in those countries to underwrite the costs of low-carbon policy frameworks [11.7].

Spatial/land use planning and permitting play an important role in the sustainable deployment of most RE technologies. They provide rules and procedures to address differences in perspectives and interests that often become manifest in the process of developing a specific RE project. [11.6.5] Planning and permitting frameworks reflect historically evolved 'ways of doing', with huge differences between countries, such as traditions of administrative coordination between different levels of government [11.6.5.2; 11.6.5.3].

Many existing planning and permitting systems have not been tailored to RE technologies. [11.6.5.1]. Existing evidence points at the need for planning and permitting systems to become pro-active - anticipating rather than reacting to the emergence of new RE technologies – as well as place- and scale-sensitive. In order to support the deployment of RE, they should account for timely local participation, collaborative networking, co-construction of plans and should identify multiple benefits and benefit-sharing mechanisms in relation to local needs, concerns and expectations [11.6.5.4].

Social innovation[13] may be a key factor for supporting the emergence and the deployment of RE and adapting it to local contexts [11.6.1]. Technical options alone cannot successfully drive the transition from energy-intensive, mainly carbon-based societies to low energy-intensive, non-carbon-based societies. Preferences for consumption patterns depend on values, culture, lifestyles, incomes, and more non-technical attributes. Drastic reductions in carbon and energy intensities paired with adapting activities imply the active involvement of citizens. The transitions to low-carbon energy systems are systemic and evolutionary social processes. This implies important changes in societal activities, practices, and institutions with public policies driving the transformations.

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[11] Institutional learning comes about through developing knowledge or an understanding of how to undertake a successful process as a result of actively constructing and re-constructing processes of social interaction. It is a process that develops over time and incorporates learning from past mistakes.

[12] Technology transfer is the flow of technologies and know-how within and between countries resulting from a variety of arrangements and exchanges, including international trade, overseas development assistance, foreign direct investment, international exchanges and cooperation in scientific and technical training.

[13] Social innovation is the ability of people and/or institutions to change the way in which they do things.

Changes in energy using behaviours have mostly been targeted through education and information policies. Their effectiveness often depends on contextual factors, emphasizing the role of social networks as well as the consistency of RE policy frameworks in sustaining changes in individual habits [11.6].

8. Knowledge Gaps

Due to the site and technology specific nature of RE, and the complexity of energy system transitions, knowledge gaps exist primarily with regard to regional potentials of RE sources, particularly in developing countries, costs of and enabling frameworks for integration of large shares of (variable) RE into existing and future energy systems, the impacts of climate change on RE resources, the social and environmental impacts of RE (relative to other energy technologies), and policies and financial mechanisms to enhance RE development and deployment particularly in developing countries.

Specific knowledge gaps identified by this report include:

- Regional assessments of RE potentials, particularly in developing countries, including efficient tools for the identification of suitable locations and forecasting tools for optimal integration and operation [1, 7, 11]
- Potential future impacts of climate change on regional RE resources [2.2, 3.2, 4.2, 5.2, 6.2 7.2].
- Coherent sets of actual primary and secondary energy data and technical potentials [1]
- Assessment of the energy demand side in developing countries [11]
- Information on the physical characteristics of the environment in which RE technologies operate. For individual RE technologies this could help 1) reduce the cost of RE by facilitating innovative installation strategies and the introduction of less costly and more reliable technology; and 2) assess RE resource potential, as for some technologies the improvement of weather models and validation with measurements are necessary to provide accurate assessment of locations where RE generation could be attractive; this is particularly important for developing countries where measurements are sparse and computer models may provide the primary assessment of potential RE production [7].
- Improved measurement and forecasting of energy output variability of variable RE resources over time horizons ranging from milliseconds to years [7].
- Tools and information to determine RE mitigation potential and support decision making over short time horizons that explicitly address all existing policies and regulations, such as market outlooks or shorter-term national analyses (global integrated assessment models cannot provide sufficient information for short time frames, better suited to medium-long term assessments) [10].
- Information to accurately determine, in any time frame, the real mitigation potentials of RE [10].
- Adequate representation of RE potentials and contributions outside the power sector, and of distributed RE structures [1].
- Coherent sets of cost data for RE integration options [1], including comparative assessments. [8.2]
- Consistent low-carbon portfolios to determine options that create synergy, and options that are conflicting [11].

- Better understanding of the social and environmental impacts of RE technologies, relative to other energy technologies, and approaches to assess, minimize, and mitigate those impacts [7, 11].
- Reliable estimates of net GHG emissions of RE technologies, in particular of some biomass based energy technologies and large hydropower dams in the tropics [2.5, 5.6].
- A good taxonomy of (positive and negative) attributes, in particular externalities, of RE supplies [11]
- A good nomenclature of RE supplies (= sources X technologies) [11]
- Qualification of RE supplies based on the above two taxonomies on one or more sustainability indicators [11]
- Systemized information and coherent evaluations of policies and instruments to enhance access to energy services based on RE for the poor [11]
- Systematized information on financial mechanisms to develop RE in developing countries [11.2.3]
- Assignment of responsibilities for RE technology transfer and development in/to developing countries (under the UNFCCC) [9]
- Better understanding of social and institutional processes behind the development and deployment of RE technologies, including the comparison of national and local experiences with the various RE sources [11]
- Better understanding of the role of planning and permitting processes and of their articulation between the international, national and local levels [11]

Technical Summary

Chapter:	Technical Summary					
Title:						
(Sub)Section:	All					
Author(s):	CLAs:	tbd				
	LAs:	Dan Arvizu, Ottmar Edenhofer, Andre Faaij, Manfred Fischedick, Gerardo Hiriart, Olav Hohmeyer, Terry Hollands, John Huckerby, Susanne Kadner, Anund Killingtveit, Arun Kumar, Tony Lewis, Oswaldo Lucon, Patrick Matschoss, Lourdes Maurice, Monirul Mirza, Catherine Mitchell, William Moomaw, Jose Moreira, Lars Nilsson, Ramon Pichs, Jayant Sathaye, Roberto Schaeffer, Tormod Schei, Steffen Schloemer, Kristin Seyboth, Ralph Sims, Graham Sinden, Youba Sokona, Aviel Verbruggen, Christoph von Stechow, Francis Yamba, Timm Zwickel				
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COMMENTS BY TSU TO EXPERT REVIEWERS

Turquoise highlighted – inserted comment text from Authors or TSU i.e. [AUTHORS/TSU: ….]

The Technical Summary has been allocated a total of 102 pages in the SRREN. The actual length is 134 pages (excluding cover page), a total of 32 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened in terms of text and/or figures and tables.

All monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to US$ for the base year 2005.

Please note that the Technical Summary should not contain any references in the text; only figures and tables are referenced. In addition, section numbers should be provided in brackets, indicating where the original text can be found in the chapters.

SRREN – TECHNICAL SUMMARY

CONTENTS

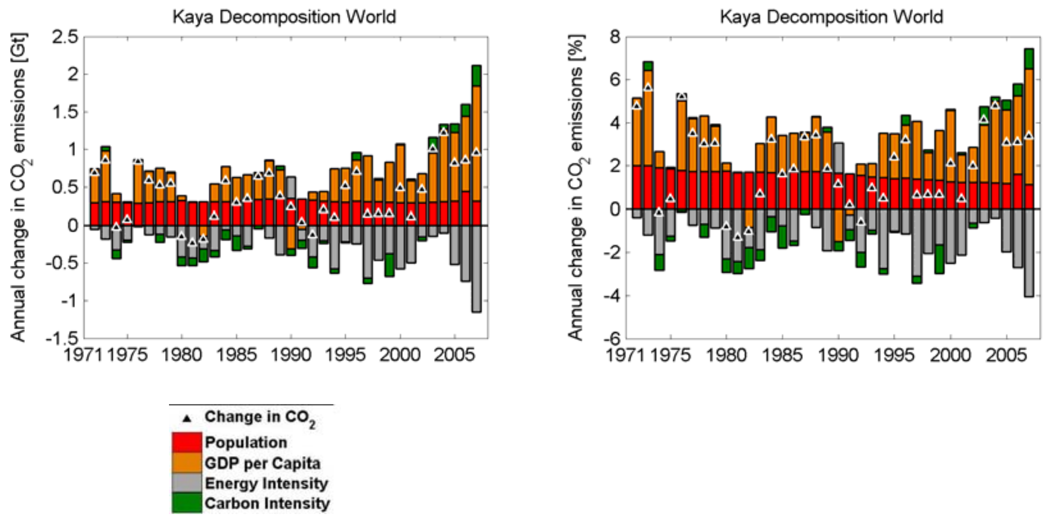
Renewable Energy and Climate Change

Climate Change

A primary driver of the industrial era has been the burning of fossil fuels to provide energy for industry, transportation, heat and electric power. The trapping of radiant heat by carbon dioxide (CO_2) released during combustion of these fuels is now understood to be a major contributor to global warming and climate change. In 2007, the IPCC's Fourth Assessment Report (AR4) expressed very high confidence (>90%) that the global average net effect of human activities since 1750 has been one of warming. The AR4 projected that global annual average temperature will rise over this century by between 1.1 and 6.4°C depending on which of the socio-economic scenarios best fits actual future GHG emissions.

To develop strategies for reducing CO_2 emissions, we can use the Kaya identity (Figure TS 1.1) which decomposes energy related CO_2 emissions into four factors: 1) Population, 2) GDP per capita, 3) energy intensity (i.e., total primary energy supply (TPES) per GDP) and 4) carbon intensity (i.e., CO_2 emissions per TPES).

$$CO_2 = \text{Population} \times (\text{GDP/population}) \times (\text{TPES/GDP}) \times (CO_2/\text{TPES})$$



a) Absolute growth **b) Relative growth**

Figure TS 0.1. Kaya decomposition of global energy related CO_2 emissions by population (red), GDP per capita (orange), energy intensity (grey) and carbon intensity (green) from 1971 to 2007. Total annual changes are indicated by a black triangle. Part (a) Absolute changes; Part (b) percentage changes. Data source: IEA, 2009b.

While GDP per capita and population growth had the largest effect on emissions growth in earlier decades, decreasing energy intensity significantly slowed emissions growth in the period from 1971 to 2007. In recent years (2000 – 2007), increases in carbon intensity have mainly been driven by the expansion of coal use in both developed and developing countries, demonstrating the need of shifting from carbon intensive fossil fuels to alternative low carbon sources for energy services. Renewable energy technologies have an important role to play in reducing emissions of CO_2.

The Role of renewable energy in addressing Climate Change

The challenge is to find a way to continue providing energy and other services in a sustainable manner that does not impact climate. There are multiple means for lowering the heat trapping emissions from energy sources, while still providing energy services. The AR4 identified renewable energy (RE) along with efficiency improvements as major contributors toward reducing anthropogenic emissions that impact climate.

The following mitigation options related to energy supply are relevant:

- Shift to zero carbon primary RE sources such as solar, geothermal, hydropower, oceans and wind.
- Shift from coal, petroleum or natural gas to solid, liquid or gaseous biomass energy that is produced in a low-carbon emitting manner.
- Utilize combined heat and power technologies for thermal production of electric power from both fossil fuels and renewable energy sources.
- Switch from fossil fuels with high specific CO_2 emissions (especially coal) to fossil fuels with lower specific CO_2 emissions (especially natural gas) or to nuclear power.
- Utilize carbon capture and storage (CCS) technology to prevent fossil fuel combustion products from entering the atmosphere. CCS has the potential to remove carbon dioxide from the atmosphere when biofuels are burned.
- Reduce the release of black carbon particulates from diesel engines and other combustion sources and from the burning of biomass fuels.

RE is any type of energy produced from natural geophysical or biological sources. Renewable energy (RE) is any form of energy from geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. As long as the rate of extraction of this energy does not exceed the natural energy flow rate, then the resource can be utilized for the indefinite future, and may be considered as “inexhaustible.” Not all energy classified as ‘renewable’ is necessarily inexhaustible; e.g. it is possible to utilize biomass at a greater rate than it can grow, or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. By contrast, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the earth.

While the low density and disbursed distribution of many forms of RE may not be suitable to some applications (such as energy intense industry), the use of RE and its decentralised nature incurs a number of co-benefits. Apart from climate change mitigation, RE can play a significant role in meeting sustainable development goals, enhancing energy security, employment creation and meeting Millennium Development Goals (MDGs). Production and utilisation of RE can also spur rural and economic development, providing opportunities for farmers and entrepreneurs to produce feedstocks for RE production and participate as owners of production facilities across all types of RE.

This Special Report on RE explores the potential for low carbon renewable energy sources in combination with energy efficiency to meet GHG reduction goals. It provides information for policy makers, the private sector and civil society on:

I. Renewable resources by region and impacts of climate change on these resources;
II. Mitigation potential of RE sources;
III. Linkages between RE growth and co-benefits in achieving sustainable development by region;
IV. Impacts on global, regional and national energy security;
V. Technology and market status, future developments and projected rates of deployment;
VI. Options and constraints for integration into the energy supply system and other markets, including energy storage options;
VII. Economic and environmental costs, benefits, risks and impacts of deployment;

VIII. Capacity building, technology transfer and financing in different regions;
IX. Policy options, outcomes and conditions for effectiveness; and
X. How accelerated deployment might be achieved in a sustainable manner.

Summary of Renewable Energy Resources and Potential

The theoretical potential for renewable energy exceeds current and projected global energy demand by far, but the challenge is to capture and utilize it to provide the desired energy services in a cost effective manner. Since 1990, global energy consumption almost doubled, rising to around 441 EJ in 2007. Various forms of RE are universally available, and can readily be introduced in both developed and developing countries. The technical potential for RE exceeds the estimated 'business as usual' demand by a factor of 50 by 2050.

Renewable resources are far more widely distributed among all nations than are fossil fuels and uranium. Thus, from an energy security perspective, they are more reliable than other energy resources for fossil-fuel poor countries. In most cases, the costs of RE technology are known and, while there will be local variation, there is considerable certainty over future energy prices, which for many renewables is zero. Reducing price volatility is important for all economies, but especially for poorer nations.

There may be potential resource disadvantages but these can be addressed. Variability may be overcome by using multiple RE technologies with differing variability timing and frequency, matching demand to supply (solar energy and space cooling), decoupling demand and supply as in water pumping or desalination, and through demand side management and energy storage systems. These approaches increase complexity and information management requirements and raise the cost of RE systems. Higher initial capital investment can be addressed by financing systems similar to meeting capital costs of other capital-intensive investments.

The theoretical potential for renewable energy significantly exceeds the global demand but the challenge is to capture and utilize RE to provide the desired energy services in a cost effective manner. Still, Table TS **1**1.1 shows that even the technical potential exceeds the estimated business as usual demand by at least a factor of 10 by 2050. The table provides a perspective for the reader to understand the relative sizes of the RE resources in the context of demand for energy in the future. Both the technical potentials and future demand are highly uncertain; any further refinement of the values adds little to the discussion.

Table TS 1.1 Technical potential for renewable energy (EJ/y)

	Energy	Technical Resource Potential (EJ/y)					*Sources for Range of Estimates*[2]
		Krewitt et al. (2009)[1]			Range of Estimates		
		2020	*2030*	*2050*	*Low*	*High*	
Electric Power (EJ/y)	Solar PV[3]	1,126	1,351	1,689	1,338	14,766	(Krewitt, et al., 2009); Chapter 3 reports total range of solar electric potential (PV and CSP) of 1440 to 50,400 EJ/y
	Solar CSP[3]	5,156	6,187	8,043	248	10,603	(Krewitt, et al., 2009); Chapter 3 reports total range of solar electric potential (PV and CSP) of 1440 to 50,400 EJ/y
	Geothermal	5	18	45	1	144	(Krewitt, et al., 2009)
	Hydropower	48	49	50	45	52	(Krewitt, et al., 2009)
	Ocean	66	166	331	330	331	(Krewitt, et al., 2009)
	Wind On-shore	362	369	379	70	1,000	Chapter 7: low estimate from (WEC, 1994), high estimate from (WBGU, 2004) and includes off-shore
	Wind Off-shore	26	36	57	15	130	Chapter 7: low estimate from (Fellows, 2000), high estimate from (Leutz, Ackermann, Suziki, Akisawa, & Kashiwagi, 2001)
Heat (EJ/y)	Solar	113	117	123	na	na	(Krewitt, et al., 2009)
	Geothermal	104	312	1,040	4	12,590	(Krewitt, et al., 2009)
Primary Energy (EJ/y)[4]	Biomass Energy Crops[5]	43	61	96	49	260	Chapter 2 (higher quality lands): large number of studies and several recent assessments, e.g., (Dornburg, van Vuuren, van de Ven, Leangeveld, & al., 2010)
					10	70	Chapter 2 (marginal/degraded lands): large number of studies and several recent assessments, e.g., (Dornburg, et al., 2010)
	Biomass Residues	59	68	88	100	200	Chapter 2: large number of studies and several recent assessments, e.g., (Dornburg, et al., 2010)
IEA Forecast (EJ/y)[6]	BAU Primary Energy	605	703	868[7]			
	450ppm Scenario	586	601				

1. Technical potential estimates for 2020, 2030, and 2050 are based on a review of studies in (Krewitt, et al., 2009); data presented in Chapters 2-7 may disagree with these figures due to differing methodologies.

2. Range of estimates comes from studies reviewed by (Krewitt, et al., 2009)as revised based on data presented in Chapters 2-7.

3. Estimates for PV and CSP from (Krewitt, et al., 2009) for 2020, 2030, and 2050 are based on different data and methodologies, which tend to significantly understate the technical potential for PV relative to CSP.

4. Primary energy from biomass could be used to meet electricity, thermal, or transportation needs, all with a conversion loss from primary energy ranging from roughly 20% to 80%.

5. Even the high-end estimates presented here take into account key limitations with respect to food demand, water availability, biodiversity and land quality.

6. IEA (2009)

7. DLR (2008)

Meeting Energy Service Needs and Current Status

Renewable energy can supply the same energy services to users as conventional primary energy sources, and in some cases without the thermal losses to which combustible fuels are subject. The same energy services can also be provided with differing amounts of end-use energy. Economies are driven by energy, and over 80% of primary energy comes from the combustion of fossil fuels, which is the source of 60% of GHGs. Hydropower, nuclear energy and a portfolio of renewable sources provide the remainder of non carbon dioxide emitting energy.

There is a multi-step process whereby primary energy is converted into an energy carrier, and then into end use energy (total final consumption) to provide energy services for the various economic sectors. Since it is the ultimate energy services of electronics, lighting, heating, cooling, transportation or industrial and mechanical processes, careful design can minimize the amount of energy required to accomplish those services, and extract the required energy from renewable and other low GHG emitting sources. This is illustrated in Figure TS 1.2.

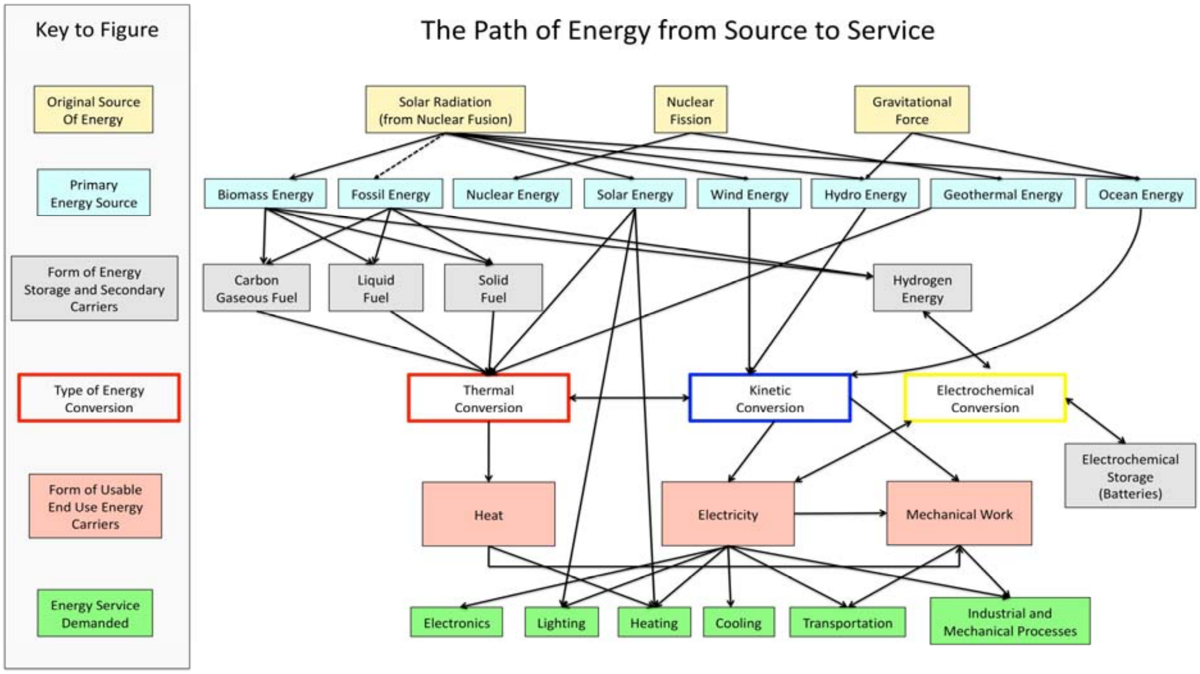


Figure TS 1.2 The Path from Source to Service. The energy services delivered to the users can be provided with differing amounts of end use energy. This in turn can be provided with more or less primary energy and with differing emissions of carbon dioxide and other environmental impacts. [TSU: reference missing]

Thermal conversion processes to produce electricity (including from biomass and geothermal) suffer losses of approximately 50-90% and losses of around 80% to supply the mechanical energy needed for transport. Direct energy conversions from solar, hydro, ocean and wind energy to electricity do not suffer these thermal losses. Direct heating from geothermal, biomass and solar thermal systems can also be highly efficient processes. By comparison, CCS requires substantial energy inputs, which would increase the demand for primary energy to supply the same amount of end use energy for energy services [1.3.1.1].

Global energy flows and investment in primary RE

UNEP data indicates that global investment in RE rose 5% and exceeded that for coal and natural gas $140 billion to $110 billion in 2008, despite a decline in overall energy investments (UNEP, 2009; REN 21, 2009b). UNEP estimates that an additional $15 billion was invested in energy efficiency during the year. Approximate technology shares of 2008 investment were wind power at 42%, solar PV 32 %, biofuels 13%, biomass and geothermal power and heat 6%, solar hot water 6% and small hydropower at 5%). An additional $40–45 billion was invested in large hydropower ((REN21, 2009a)).

In recent years, RE has contributed 23% of added capacity. Traditional biomass accounted for the majority of global primary energy consumption due to its wide spread traditional use particularly for cooking and lighting in developing countries.

Between 2003 and 2008, solar installations grew at an average annual rate of 56%, biofuels and wind at 25% and hydro by 4%. Germany in 2008 produced 15% of its electricity and 10% of its total energy from renewable sources. The developing world is particularly ripe to adopt evolving RE technologies as it can often leapfrog adaptation in developed economies. Evolving scenarios suggest that a significant portion of future energy needs on the electricity supply on-site heat production and transport fuels could be met by RE.

Figure TS 1.3 reflects primary RE only, utilizing the data for 2007. ‘RE’ here includes combustible biomass, forest and crop residues and municipal solid waste as well as the other types of RE considered in this report: solar energy, hydropower, oceans, geothermal and wind.

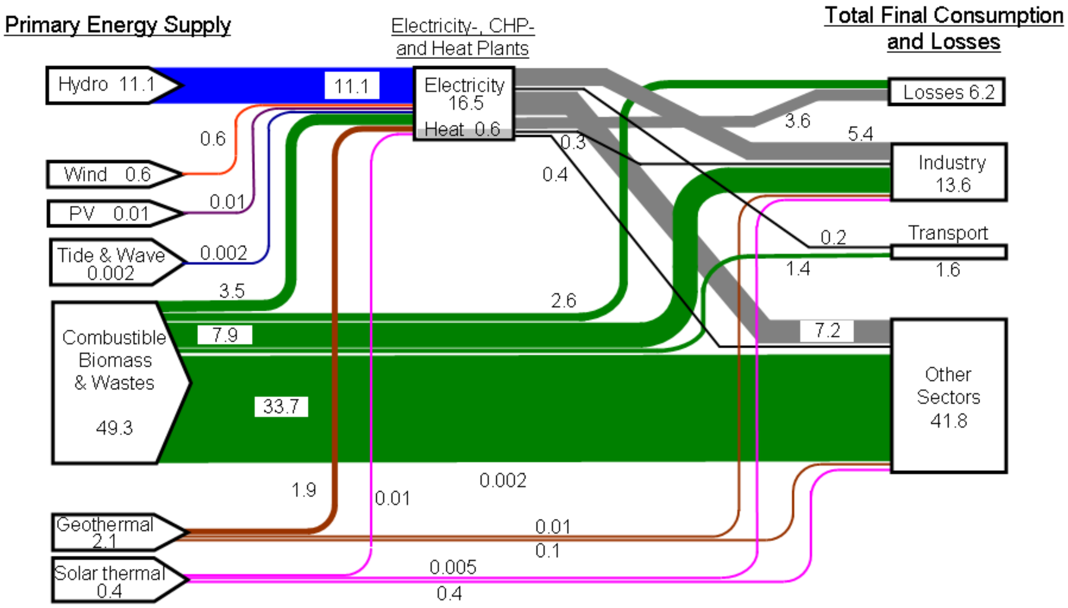


Figure TS 1.3 Global energy flows (EJ in 2007) from primary RE through carriers to end-uses and losses (based on IEA data). ‘Other sectors’ include agriculture, commercial and residential buildings, public services and non-specified other sectors. ‘Transport sector’ includes international aviation and international marine bunkers.

In 2007, renewable sources generated 18% of global electricity (19,756 TWh), which consisted of 13% of primary energy (including traditional sources) and 18% of end use energy. The flow of biomass, which includes traditional uses, dominates this figure, but there is significant investment in modern RE technologies as noted above and accompanying rapid growth.

To integrate large fractions of RE into electric power systems requires improved transmission, distribution and storage technology and greater use of information technology in what is referred to as a smart grid as described in Chapter 8. Fully integrated energy planning for power production, heating, cooling and transportation will require both management of supply and demand, improved end use efficiency and utilizing RE in ways that match its availability and appropriateness to specific tasks.

Economic, social, and ecological benefits are further motivating governments and individuals to adopt RE because they offer the potential to simultaneously realise multiple goals in relation to sustainable development [11.3] The key drivers of RE policy are: climate change mitigation; enhanced access to energy services, in particular for the poor as a basic aspect of poverty reduction and achievement of the MDGs; improved health, education and environmental living conditions; higher security of energy supply at stable prices; diversity of energy sources; and economic development and domestic job creation. The relative importance of the drivers, opportunities and benefits of RE varies from country to country and over time as changing circumstances affect economies, attitudes and public perceptions [10.6, 11.3].

RE generation replaces conventional energy generation reducing local pollutants. See Figure TS 1.4. For energy production technologies based on combustion, impacts and external costs arise largely from emissions of particulates and gases to air [10.6.2]. RE technologies have significant benefits for reducing air and water pollution, and damage to land from mining, subsidence and oil spills [1.1.6].

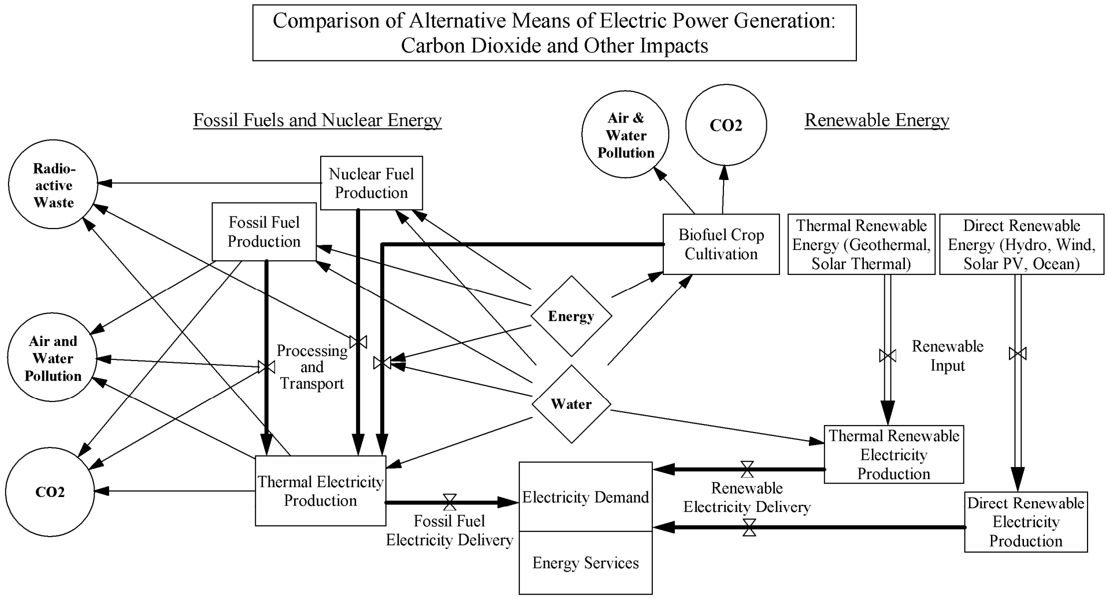


Figure TS 1.4. Comparison of co-benefits, water use and CO_2 emissions associated with primary energy sources for electricity production. Not included are land impacts from surface mining of coal, land clearance for bioenergy and hydro reservoirs or methane leakage from coal natural gas and petroleum production and use or damage from oil spills and coal ash storage [1.1.6]. [TSU: reference missing]

Climbing the Energy Ladder in Developing Countries

RE plays an important role in the movement from more traditional to more modern forms of energy supplied to consumers simply because it is typically available locally and can, with the right technologies, advance consumers up the energy ladder. RE based on off-grid energy systems can contribute to poverty alleviation and assist in achieving MDGs by providing unmet energy services, as indicated in section 1.1.5.

Regions and communities without electricity and other modern sources of energy suffer from extreme poverty, limited freedom of opportunities, insufficient health care, etc. Although the energy system may be different from that of developed countries, to raise the electrification rate is indispensible for developing countries.

Biomass is the dominant energy source in many developing countries and is increasingly being harvested in an environmentally unsustainable way. To avoid the inefficient traditional biomass utilization for cooking and heating, solar thermal energy utilization is practically useful as well as modern biofuel production. For example, as discussed in chapter 2, improved biomass stoves save 10% to 50% of biomass consumption for the same cooking services and can dramatically improve indoor air quality, as well as reduce black carbon and GHG emissions. Solar water heating is an established technology that can be manufactured in developing countries (China is already the world's largest producer). Many developing countries in desert regions may be suitable locations for solar concentrating power technology (chapter 3).

With development, there is generally a transition up the 'energy-ladder' to fuels that are progressively more efficient, cleaner, convenient and expensive, such as natural gas, LPG and electricity. Electricity allows tasks previously performed by hand or animal power to be done much more quickly with electric powered machines. Of interest in the energy ladder transition is the opportunity to use RE rather than diesel generators for either off or on-grid applications. Commercial energy sources also permit the use of modern technologies that transform the entire production process at the factory level, in agriculture and within the home.

Barriers and Issues

Almost everywhere in the world, one can find a RE resource of one kind or other. Then, why then is RE not in universal use?

Firstly, there are *barriers*, defined in the IPCC Fourth Assessment Report as 'any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy programme or measure'. The various barriers can be categorised as informational, socio-cultural, technical and structural, economic, or institutional. More importantly, however, they are interrelated and need to be dealt with in a comprehensive manner. Some of these barriers relate directly to energy prices and not accounting for the 'externalities' they do or do not address. Others (e.g., the institutional or informational barriers) would remain barriers to RE even in the presence of 'perfect markets'. A summary of barriers and potential policy instruments to overcome these barriers is shown in Table TS1.2.

Table TS 1.2. A categorisation of barriers to RE deployment

Type of barrier	**Some relevant policy instruments (see chapter 11)**
Market failures	Carbon taxes, emission trading schemes, public support for R&D on RE)
Information and awareness barriers	Energy standards, information campaigns
Socio-cultural issues	Improved processes for land use planning
Technical and structural barriers	Enabling environment for innovation, revised technical regulations, international support for technology transfer (e.g., under UNFCCC or UNIDO)
Economic barriers	economic climate that supports investment, carbon taxes, emission trading schemes
Institutional barriers	Microfinance, technical training, liberalisation of energy industries

Secondly, other *issues*, not so amenable to policies and programs, can also impede the uptake of RE. An obvious example is that the resource may be too small to be useful at a particular place.

As for every type of energy technology, environmental and social impacts exist for each of the RE technologies, and will need to be carefully managed to ensure sustainable growth of supply. Because of the diversity of RE sources and technologies and their reliance on differing and sometimes-diffuse energy resources, the impacts and their potential mitigation will vary by technology. Such social and environmental impacts affect deployment opportunities for RE as well as conventional energy sources.

Role of Policy, R&D, Deployment, Scaling Up and Implementation Strategies

The growth of RE systems in industrialised countries in the last decade or two has been greatest where it has been supported by policies such as feed-in tariffs, mandatory RE targets, or tax concessions for RE investment. In particular, the long-term certainty inherent in European feed-in-tariffs has proven successful in creating a manufacturing industry for renewable energy technologies. Currently, one sees the private sector leading R&D of technologies that are close to market deployment, while public funding is essential for the longer term and basic research. Sufficient investment will be required to ensure that the best technologies are brought to market in a timely manner. However, market barriers exist that prevent the development and penetration of novel renewable energy technologies into the energy system. Therefore, the role of the policy maker is important, whether to invest in R&D or to ameliorate the risks faced by R&D products in the market.

There are a variety of approaches to facilitate the introduction of RE to the market. Some of these, such as price, which modify relative consumers' preference, provide a demand-pull and enhance utilization for a particular technology. Other such as government supported research and development attempt to create new products through market push.

The major focus for renewable energy is the electric power sector where there is a need to introduce new technologies and to rebuild the transmission and distribution grid. For the transport sector, there are major questions of developing the infrastructure for either biofuels, renewably generated hydrogen or battery and hybrid electric vehicles that are "fuelled" by the electric grid or from off-grid renewable electrical production. The agriculture sector presents unique opportunities for capturing methane from livestock production and using manure and other crop wastes to provide on-farm fuels.

It is necessary to incorporate externalities of a switch to renewable energy supply (land use, option values, aesthetic concerns, etc.) as well as review co-benefits associated with the development of that particular form of renewable energy. It is also critical to consider the potential of RE to reduce emissions from a life cycle perspective.

Most countries have found that there are significant barriers to introducing renewable energy to the grid because of the structure of existing regulations that do not recognize the benefits of these technologies and favour traditional power sources. Where these issues have been addressed, the penetration of renewable energy has been greatest.

Bioenergy

Introduction Current Pattern of Bioenergy Use and Trends

Chapter 2 discusses biomass, a primary source of fibre, food, fodder and energy. Estimating the future mitigation potential of bioenergy presents unique analytical challenges compared to other renewable energy sources, given the many existing and rapidly evolving bioenergy sources; complexities of physical, chemical, and biological conversion processes; variability in site specific environmental and socio-economic conditions; the many interlinkages between bioenergy and other land-based activities, such as food and fibre production, forest protection, and more, and political interests triggered by the rapid evolution in production and use of liquid biofuels. Methodological and practical challenges are overcome by undertaking an integrated and comprehensive global review of the mitigation potential of bioenergy up to the year 2030.

Since society began biomass is the most important renewable energy source, providing about 10% (46 EJ) of the annual global primary energy demand. A major part of this biomass use (37 EJ) is related to charcoal, wood and manure used for cooking and space heating, generally by the poorer part of the population in developing countries called traditional bioenergy. Modern bioenergy use (for industry, power generation, or transport fuels) is already making a significant contribution of 9 EJ, and this share is growing.

Currently, modern bioenergy chains involve a range of feedstock, conversion processes and end-uses. Feedstock types include dedicated crops or trees, residues from agriculture and forestry and related transformation industries, and various organic waste streams. Their economics and yields vary across world regions and feedstock type/conversion processes, with costs ranging from 5 to 80 US$/GJ biofuels, from 5 to 20 US$/GJ for electricity, and from 1 to 5 US$/GJ for heat from solid fuels or waste. There are several important competitive bioenergy systems today, most notably sugar cane based ethanol production and heat and power generation from residual and waste biomass. Depending on energy prices and specific market conditions, smaller scale applications (for power heat and biofuels) can compete, such as Jatropha oil production in rural settings.

Resource Potential

The assessment of the biomass potential renders a range of estimates from different sources as well as the opportunities and limitations from the potential competition for land, water and other resources. Narrowing the biomass resource potential to distinct numbers is not possible. But it is clear that several hundred EJ per year can be provided for energy in the future, given favourable developments. It can also be concluded that:

- Biomass use for energy can already today be strongly increased over current levels based on increased use of forestry and agricultural residues [2.2.5]
- The medium and longer term energy crop potential depends strongly on productivity increases that can be achieved in food production and environmental constraints that will restrict energy crop cultivation on different land types. [2.2.5]
- The cultivation of suitable lignocellulosic crops can allow for higher potentials by making it possible to produce bioenergy on lands where conventional food crops are less suited and would lead to larger soil carbon emissions. [2.2.5]
- Water constraints may limit production in regions experiencing water scarcity. The use of suitable drought tolerant energy crops can help adaptation in water scarce situations. Assessments of biomass resource potentials need to more carefully consider constrains and opportunities in relation to water availability and competing use. [2.2.5]

While recent assessments employing improved data and modelling capacity have not succeeded in providing narrow distinct estimates of the biomass resource potential, they have advanced the understanding influential parameters. Some of the most important parameters are inherently uncertain and will continue to obscure long term biomass supply potentials. However, insights from resource assessments can improve the prospects for bioenergy by pointing out crucial development areas. [2.2.5]

The expected deployment of biomass for energy on medium to longer term differs considerably between various studies. Large scale biomass deployment is largely conditional: deployment will strongly depend on sustainable development of the resource base and governance of land-use, development of infrastructure and on cost reduction of key technologies. Based on the current state-of-the-art analyses, the upper bound of the biomass resource potential halfway this century can amount over 400 EJ. This could be roughly in line with the conditions sketched in the IPCC SRES A1 and B1 storylines, assuming sustainability and policy frameworks to secure good governance of land-use and improvements in agricultural and livestock management are secured. [2.8.3]

If the right policy frameworks are not introduced the expansion of biomass use can lead to significant conflicts in different regions with respect to food supplies, water resources and biodiversity. Supply potential may then be constrained to a share of biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands and some regions where biomass is evidently a cheaper energy supply option compared to the main reference options (which is the case for sugarcane based ethanol production). Biomass supplies may then remain limited to an estimated 100 EJ in 2050. [ES]

Technology

Feedstock production or recovery. Feedstock types may be classified as dedicated crops or trees (i.e., plants grown specifically for energy purposes), primary residues from agriculture and forestry, secondary residues from agro and forest industries, and organic waste from livestock farming, urban, or industry origin. Biomass may be harvested several times a year (for forage-type feedstock such as hay or alfalfa), once a year (for annual species such as wheat or perennial grasses), or every 2 to 50 years or more (for short-rotation coppice and conventional forestry, respectively). Problems arise if fuelwood extraction and wood extraction for commercial purposes exceeds forest regeneration capacity, which occurs in many parts of the world. [2.3.1.1]

The intensity in the use of production factors (inputs, machinery, labour or land) may vary across world regions for a similar species. Within a given region, similar yield levels may be reached through a variety of cropping systems and production intensities. [2.3.1.1]

Recoverability of **primary residues** is 25 and 50 % for logging residues and 33 and 80% of processing residues (plant materials that remain on the farm after removal of the main crop produce). **Secondary residues** are by-products of post-harvest processing of crops, namely, cleaning, threshing, sawing, sieving, crushing, etc. Although modes and volumes of agricultural residue production may differ by production area, the rates of production of residues relative to crop marketable yield are reported as 140% for rice, 130% for wheat, 100% for corn, and 40% for rhizomic crops. There are several alternative uses of agricultural residues (e.g., animal feed, soil erosion control, animal bedding, and fertilizers). Residue availability is difficult to predict and varies seasonally. [2.3.1.1]

Residues and waste streams are a coveted resource since their apparent costs only include collection, pre-conditioning and transport. Their export has to be carefully managed to avoid jeopardizing soil organic matter content and fertility in the long-run, which typically brings down their theoretical availability by 70% to 80%. Nutrient exports should also be compensated for, possibly by recycling residual ash, stillage or digestate from the bioenergy conversion process. [2.3.1.1]

Bioenergy feedstock interactions with the agriculture, food & forest sectors. Energy feedstock production may compete with the food, feed, fibre and forest sectors directly for land or for a stream of biomass (e.g., cereal straw for cattle bedding material vs. energy production). The outcome of these competition effects hinges on the economics of supply and demand for the various sectors and markets involved, at regional to global scales. At a local scale, synergistic effects may also emerge between competing usages. For instance, integrated agroforestry enables land use for both food and energy purposes with mutual benefits for the associated species, integrated agriculture for food, feed, and various types of energy products is already taking place including grazing reductions requirements in several cases. Double cropping and mixed cropping are strategies to maximize the output of land. [2.3.1.2]

Perennial species create positive externalities such as erosion control, improved fertilizer use efficiency, reduction in nitrate losses and water stress, and provision of habitat for biodiversity and biological control of pests. According to Practical Action Consulting (2009) bioenergy feedstock does not affect local staple food security provided feedstock benefits are distributed to local communities. [2.3.1.2]

Logistics and supply chains. Most non-woody biomass is available in loose form with low bulk densities, causing handling, transportation and storage problems. Shredded biomass residues may be densified by briquetting or pelletizing. Briquettes and pellets can be renewable substitutes for coal, lignite and fuelwoodthat have consistent quality, size, better thermal efficiency, and higher density than loose biomass. Chips, a by-product of conventional forestry, require less processing and are cheaper than pellets. Charcoal has double the calorific value of the original feedstock, burns without smoke, and is used widely. In Africa, illegal charcoal production is seen as a primary threat to remaining wildlife habitats. [2.3.2.1] Charcoal making is an enterprise for rural populations to supply urban markets. Crop residues and dung are normally used by the owners as a seasonal supplement to fuelwood. [2.3.2.2]

Conversion technologies. Biomass feedstocks can be converted through a variety of existing and evolving conversion processes to products for a variety of end-use summarized in Table TS 2.1. Many types of integrated biomass refineries are entering markets worldwide in various scales. [2.3.3]

One thermochemical process is biomass combustion, used by about 2.4 billion people in developing countries, who use firewood in inefficient traditional open fire cook stoves in poorly ventilated kitchens leading to major health problems. Major efforts launched to improve efficiency and reliability of cook stoves have reached 800 million people so far over the past ten years (WHO, 2009). Simultaneously, large-scale combustion and cogenerationof more than one form of energy from one source are reaching combined efficiencies of 90% in Nordic and other countries and used in district heating. [2.3.3.1]

Bioenergy Systems and Chains: Description of existing state of the art systems. Liquid biofuels are mainly used in the transport sector and ethanol costs are usually lower than biodiesel for commercial systems (based on rapeseed, soya and oil palm). Conversion efficiency (from feedstock to end-use product) is modest, from a little over 50% to around 10% for co-products of food production. Solid biomass, mostly used for heat, power and heat & power usually has lower production costs than liquid biofuels. Unprocessed solid biomass is less costly than pre-processed (via densification), but for the final consumer the transportation and other logistic costs have to be added, which justify the existence of a market for both types of solid biomass. [2.3.4]

Table TS 2.1. Main routes for converting biomass to a range of possible end-uses

Process	Type of Feedstock	Example of Conversion Technology	End use from conversion technologies
Thermo-chemical conversion	Lignocellulosic crops, wood , primary and secondary residues, aquatic biomass	Combustion Cogeneration Pyrolysis Gasification Liquefaction	Cooking/heating/electricity/ cogeneration Last three also provide liquid fuels such as ethanol, other alcohols, ethers, hydrogen, methane, hydrocarbon fuels. Also monomers for polymers and chemicals
Chemical	Oil crops or aquatic biomass, waste	Hydrolysis/ Transesterification Catalytic processing	Electricity /liquid biofuels (biodiesel)/ chemicals Renewable hydrocarbon fuels
Biochemical	Starch, sugar, lignocellulosic crops, wood, residues, organic waste, aquatic biomass	Anaerobic digestion Pretreatment/Hydro-lysis followed by Fermentation or Biological synthesis or Catalytic upgrading	Cooking/heating/ power /liquid biofuels for vehicles Ethanol, butanol, direct diesel and jet fuel replacements. Monomers for plastics or biobased products

Source: E4tech, 2009, Cherubini et al.,2009, IEA Bioenergy: ExCo: 2007:02

Global and Regional Status of Market and Industry Development

We provide the global and regional status of market and industry development in bioenergy. For local markets the use of bioenergy technologies provides a simple, local and renewable solution for energy related to cooking, heating and lighting mainly in rural areas. Widespread dissemination of these technologies may be limited by purchasing power, availability, and access to the biomass resource. Lack of education, awareness and motivation are among the prime factors that hinder regional penetration.

The amount of traditional biomass used is very uncertain because fuels are often not purchased commercially and therefore must be estimated indirectly in most cases. Modern bioenergy use (for industry, power generation, or transport fuels) is making already a significant contribution of 10 EJ and this share is growing. Today, biomass (mainly wood) contributes some 10% to the world primary energy mix, and is still by far the most widely used renewable energy source (Figure TS 2.1).

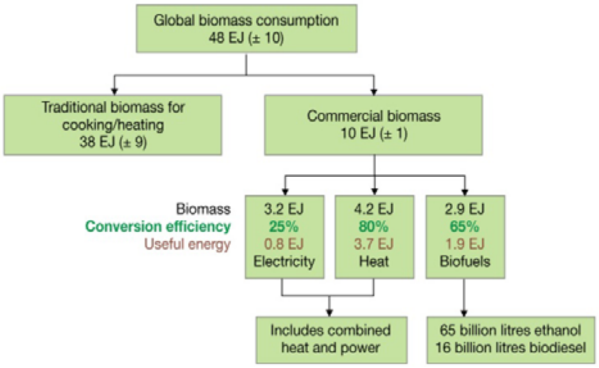


Figure TS 2.1 Global biomass consumption for bioenergy and biofuels in 2008. Source: based on IEA 2009 update of 2007

One of the fastest-growing applications of biomass is the production of biofuels based on agricultural crops –global biofuels preliminary supply estimates are at 1.9 EJ (2008), a significant growth from1.43 EJ in 2007, when it accounted for 1.5% of total road-transport fuel. Most of the increase in the use of biofuels in 2007 and 2008 occurred in the OECD, mainly in North America and Europe.

Review of developments in biomass use, markets and policy shows acceleration of efforts over the past years. Bionergy use is growing, in particular, in biofuels with an increase of 37% from 2006-2009.Significant overcapacity was built because the global economic situation deteriorated, but is projected to recover. Projections from IEA, but also many national targets, count on biomass to deliver a substantial share of projected renewable energy increases. According to the 2009 World Energy Outlook scenarios, biofuels may contribute 5.7 to 11.6 EJ to the global transport fuel demand, meeting about 5% to 11% of total world road-transport energy demand, up from about 2% today (IEA, 2009). In the 450 Scenario, biomass consumption also increases and in 2030 is 14.7 EJ higher than in the Reference Scenario.

International trade of biomass and biofuels has also become much more important over time, with roughly 10% of biofuels and a third of all pellet production for energy producing trade internationally (Junginger et al., 2010). The latter has proven to be an important facilitating factor in both increased utilisation of biomass in regions where supplies are constrained as well as mobilising resources from areas with reduced demand, creating economic development opportunities for both. Many barriers remain in developing well working commodity trading of biomass and biofuels that meet sustainability criteria.

The policy context for bioenergy in many countries changed rapidly and dramatically with rapid increases in food prices in 2007 reaching a peak in 2008 and then falling rapidly again to now down 13% for the year while non-food agricultural commodities are up 20%. The debate on food vs. fuel competition and the growing concerns about other conflicts have resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefineries and second generation biofuel options does to drive bioenergy to more sustainable directions.

Leading modern biomass use nations like Brazil, Sweden, Finland and the US, have shown that persistent policy and stable policy support is a key factor in building biomass production capacity and working markets, the required infrastructure and conversion capacity that gets more competitive over time, and generates considerable economic activity.

Countries differ in their priorities, approaches, technology choices and support schemes bioenergy development. On one hand policies are complex, but this is a reflection of the many aspects that affect bioenergy deployment; agriculture and land-use, energy policy & security, rural development and environmental policies. Priorities, stage of development and physical potential and resource availability differ widely from country to country and for different settings.

Environmental and Social Issues

The effects of bioenergy on social and environmental issues – ranging from health and poverty to biodiversity and water quality – may be positive or negative depending upon local conditions, the specific feedstock production system and technology paths chosen, how criteria and the alternative scenario are defined, and how actual projects are designed and implemented, among other variables. Perhaps most important is the overall management and governance of land-use when additional biomass is produced for energy purposes on top of meeting food and other demands from agricultural production (as well as livestock).

In case biomass production is in balance with improvements in agricultural management undesirable (i)LUC effects can be avoided, while unmanaged, conflicts may emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land-use. Such processes are shown in Figure TS 2.2, along with benefits and risks, and how biomass production can be influenced by interactions and feedbacks among land use, energy and climate in scales that range from field level up to global market effects. Tradeoffs between environmental, social, and economic dimensions exist and need to be resolved by appropriate strategies. Such strategies are currently emerging due to many efforts targeting the deployment of sustainability frameworks and certification for bioenergy production, setting standards for GHG performance, addressing land use change (LUC) effects, environmental issues, social aspects, etc., but these are by no means finalized and fully implemented. The main challenge is to interlink land use management and the agricultural sector at large with (gradual) development of the potential biomass resource potential.

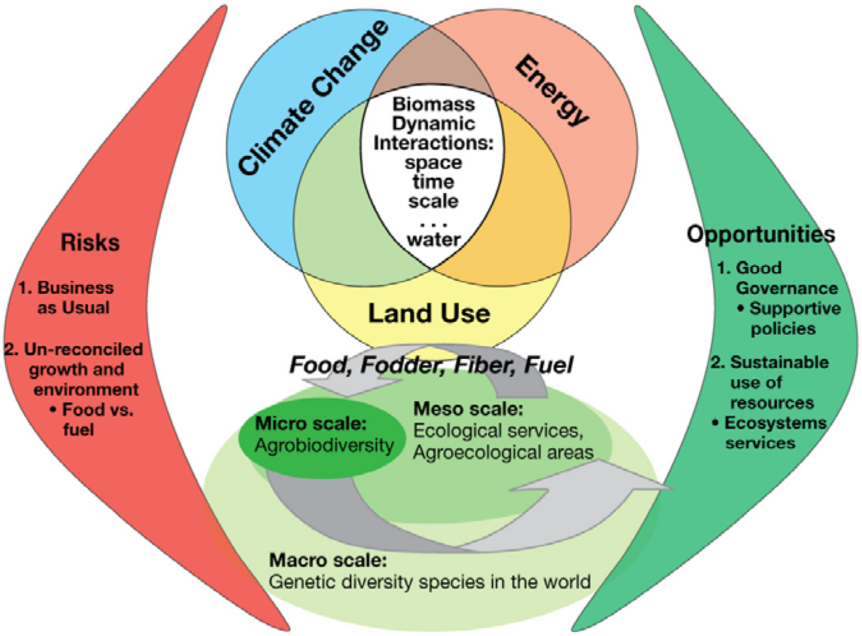


Figure TS 2.2 Climate Change-Land Use-Energy Nexus. Adapted from Dale et al., submitted and van Dam et al., 2009.

GHG impacts of bioenergy systems are well quantified in state-of-the-art literature. Recent assessment of GHG performance of key biofuel production systems deployed today and possible 2nd generation biofuels using different calculation methods (see, Hoefnagels et al., 2010) conclude that well managed bioenergy production and utilization chains can deliver high GHG mitigation percentages (80-90%) compared to their fossil counterparts,especially lignocellulosic biomass used for power generation, and when commercially available 2nd generation biofuels. Generally residues and organic wastes used for energy result in good performance. Most current biofuel production systems have positive GHG balances, without iLUC effects incorporated. Sugar cane based ethanol typically already shows good GHG performance (with reductions over 80%) and most biofuel production from corn and rapeseed, when managed properly, shows reductions in the 35%- 50% range. (i)LUC can strongly affect those scores and when conversion of land with large carbon stocks takes place directly or indirectly, emission benefits can shift to negative levels. Extreme carbon emissions are obtained if peatlands are drained and converted to oil palm rather than established on marginal grasslands with lower carbon stocks than the plantation itself, then overall negative GHG emissions can be achieved (Wicke et al., 2008). The GHG mitigation effect of biomass use for energy (and materials) strongly depends on feedstock choice, location (in particular avoidance of converting carbon rich lands to carbon poor cropping systems) and avoiding iLUC (see below). In contrast, perennial cropping systems can store large amounts of carbon and enhance sequestration on marginal and degraded soils in addition to replacing fossil fuels. Governance of land-use and proper zoning and choice of biomass production systems is key to achieve good performance.

Other key environmental impacts cover water use, biodiversity and other emissions. Just as for GHG impact, proper management determines emission levels to water, air and soil. Development of standards and criteria pushes bioenergy production to low emission management. Description of specific biofuel production (and use) with many functionalities enables an appropriate assessment of trade-offs for the use of land and water, and the type(s) of bioenergy products suited for specific projects. An illustrative case study is a prospective impact analysis of alternate Argentinean land-use strategies and cropping systems guiding future development of food, feed, and biofuel (van Dam et al., 2009a,b). Location is the key driver. Environmental impact assessments more broadly quantify environmental, ecological, health impacts, landscape habitat and response, and generate an economic analysis of benefits and impacts.

Water is a critical issue that needs better analysis on a regional level to understand the full impact of vegetation and land-use management changes. Recent studies indicate (Dornburg et al., 2008; Berndes, 2003; Rost et al, 2010) that considerable improvements can be made in water use efficiency in conventional agriculture and biomass crops. Depending on location and climate, perennial cropping systems in particular can achieve benefits in terms of improved water retention and lowering direct evaporation from soils. Without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable.

Similar remarks can be made with respect to biodiversity, although more scientific uncertainty exists due to ongoing debate on quantification methodologies. Large scale monocultures clearly occur at the expense of nature area biodiversity (for example highlighted in CBD, 2007). In contrast, establishing mixed cropping systems (e.g. agroforestry) as monocultures replacements could increase biodiversity. This is highly location specific and dependent on land-use planning, zoning and depending on biomass production systems. This is also an area that deserves considerably more research, as well as proper monitoring.

As bioenergy production grew rapidly in the past ten years in concert with rising oil and food prices, the consequences of bioenergy development in terms or land use and impacts on the global economic system were questioned. Initial LCA tools were coupled to a variety of macroeconomic/econometric models and to biophysical models or data to assess the consequences of fuel levels proposed by legislation in several countries to agriculture, forestry, and related sectors economic systems. Assessment of the available literature showed that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation than necessary because of the lack of lands such as pastures in Brazil. The early paper of Searchinger claimed an iLUC factor of 1 (losing one hectare of forest land for each hectare of land used for bioenergy), later macro-economic model based studies tuned that down to 0.3 – 0.15 and more detailed evaluations of e.g. (Lapola et al., 2010 and IFRI (Al-Fiffai et al, 2010) acknowledge that iLUC effects strongly or even fully depends on the rate of improvement in agricultural and livestock management and the rate of bioenergy production deployment. This balance in development is the basis for the recent European biomass resource potential analysis, for which expected gradual productivity increments in agriculture are the basis for possible land availability as reported in (Fischer et al, 2010 and Wit & Faaij, 2010) and take avoidance of competition with food (or nature) as a starting point. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel producing countries is now producing results that are converging to lower overall land use change impacts and acknowledgement that land use management at large is key [2.5.3.1].

Estimates of (i)LUC effects require value judgments on the temporal scale of analysis, land use under the assumed “no action” scenario which has been the basis for most studies , expected uses in the longer term, and allocation of impacts among different uses over time. A system that ensures consistent and accurate inventory and reporting on carbon stocks is considered an important first step toward LUC carbon accounting. Key is that (i)LUC can be avoided and this can be used as starting point for developing bioenergy resources with interlinked integral governance of land use, land use planning and zoning, development of agriculture and livestock [2.5.3.1].

Social impacts from large expansions of bioenergy are complex and difficult to quantify. Generally bioenergy options have a larger positive impact on job creation in rural areas than other energy sources. Rationalized conventional agriculture ‘frees up land’’ for bioenergy providing for increased employmentt and value added in rural regions (see e.g.. Wicke et al., 2009). For many developing countries, the potential bioenergy has for generating employment and economic activity in rural areas is a key driver. Expenditures on fossil fuel (imports) can also be (strongly) reduced. Whether such benefits end up with rural farmers depends largely on production chain organization and land-use governance. Rapid bioenergy deployment could compete with food production. Increases in food prices can be significant especially for poor people as shown by many recent studies that focused on implications of rapid expansion of first generation biofuels produced from food crops. It is acknowledged in many analyses that when such competition is avoided, and value chains are properly organized (e.g, with cooperatives with proper ownership structures and using agroforestry systems), farmers and local economies can be major beneficiaries of additional biomass production for energy (see, e.g., Wiskerke et al., 2010) [2.5.5].

Bioenergy is a component of much larger agriculture and forestry systems of the world, and land and water resources need to be properly managed in concert with the type of bioenergy most suited to the specific region and its natural resources and economic development situation. Bioenergy has the opportunity to contribute to climate mitigation, energy security, diversity goals, and economic development in developed and developing countries. The effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, how actual projects are designed and implemented, among many other factors.

Prospects for Technology Improvement, Innovation and Integration

Increasing land productivity is a crucial prerequisite for realizing large scale bioenergy potentials. Most increases in agricultural productivity over the past 50 years came through plant breeding and improved agricultural management including irrigation, fertilizer and pesticide use. The adoption of these techniques in the developing world is most advanced in Asia, where it entailed a strong productivity growth during the past 50 years. Considerable potential exists for extending the same gains to other regions, like Sub-Saharan Africa, Latin America, Eastern Europe and Central Asia where adoption has been slow. Recent long-term foresight by the FAO expects global agricultural production to rise by 1.5 percent a year for the next three decades, significantly faster than projected population growth. Major food staple crop’s maximum yields may increase by more than 30% by switching from rain-fed to irrigated and optimal rainwater use production. Moving from intermediate to high input technology may result in 50% increases in tropical regions and 40% in subtropical and temperate regions. One should note that environmental tradeoffs may be involved under strong agricultural intensification. [2.6.1]

Conversion technologies & bioenergy systems. Advanced cultivation techniques could be taken up to increase the production of biomass for energy purposes all over the world. Various developments in technologies are also being explored to improve the conversion efficiencies and for the development of multiple products for various end use applications. In particular, with advances in science and technology of the past ten years, the portfolio of biofuels that now can be produced from biomass has expanded to include a variety of higher energy density fuels that have properties similar to those of diesel and jet fuels, in addition to traditional biofuels (see Table TS 2.1).This progress rests, in part, in the development of key intermediaries from lignocellulosic biomass – mixture sugars, synthesis gas, and pyrolysis oils – that have the potential to reach cost competitiveness with fossil fuels. Processing to fuels is taking advantage on one hand of engineering microbes and enzymes, using biological synthesis to design specific products and on the other hand of advances in catalysis and engineering, and molecular understanding of bio and chemical processes. Similarly, biobased materials are emerging as full replacements or partial replacements of fossil fuel-derived plastics and materials. [2.6.3]

Cost Trends

Cost trends and technological learning in bioenergy systems have long been less well described compared to other solar and wind energy technologies. Recent literature gives more detailed insights on the experience curves and progress ratios of various bioenergy systems. Table TS 2.2 summarizes analyses that have quantified learning (e.g., expressed by progress ratios) and experience curves for the systems (i) sugarcane based ethanol production (Van den Wall Bake et al.; 2009), (ii) corn based ethanol production (Hettinga et al., 2009), (iii) wood fuel chips and CHP in Scandinavia (Junginger et al., 2005 and a number of other sources). PR denotes the progress ratio, expressing the rate of unit cost decline with each doubling of cumulative production. For example, a PR of 0.8 implies that after one doubling of cumulative production, unit costs are reduced to 80% of the original costs, i.e. a 20% cost decrease. The definition of the 'unit' may vary. The absolute performance of the two major commercial ethanol systems is illustrated in terms of a variety of functional units related to climate impact and fossil energy, as a function of time [2.5, and Table 2.5.1].

There is clear evidence that further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring down the costs of power (and heat) generation to attractive cost levels in many regions, especially when competing with natural gas. If 20-30 U$/tonne carbon taxes were deployed (or CCS), biomass can be competitive with coal based power generation. There is evidence that technological learning and related cost reductions occur with comparable progress ratios as other renewable energy technologies. This is true for cropping systems (following progress in agricultural management when annual crops are concerned), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (ethanol production, power generation, biogas and biodiesel).

With respect to second generation biofuels, recent analyses have indicated that the improvement potential is large enough to make them compete with oil prices of 60-70 U$/barrel. Currently available scenario analyses indicate that if R&D and market support on shorter term is strong, technological progress could allow for this around 2020. Several short term options can deliver and provide important synergy with longer term options, such as co-firing, CHP and heat production and sugar cane based ethanol production. Development of working bioenergy markets and facilitation of international bioenergy trade is another important facilitating factor to achieve such synergies.

Table TS 2.2 Overview of experience curves for biomass energy technologies / energy carriers. Cost/price data collected from various sources (books, journals, press releases, interviews) PR = Progress Ratio, R2 is the correlation coefficient of the statistical data

Learning system	PR (%)	Time frame	Region	n	R^2
Feedstock production					
Sugarcane (tonnes sugarcane) Van den Wall Bake et al.; 2009	68±3	1975-2003	Brazil	2.9	0.81
Corn (tonnes corn) Hettinga et al, 2009	55±0.02	1975-2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden) Junginger et al., 2005	85-88	1975-2003	Sweden / Finland	9	0.87-0.93
Investment & O&M costs					
CHP plants (€/kW$_e$) Junginger et al., 2005	75-91	1983-2002	Sweden	2.3	0.17-0.18
Biogas plants (€/m^3 biogas/day) Junginger et al., 2006a	88	1984-1998		6	0.69
Ethanol production from sugarcane Van den Wall Bake et al.; 2009	81±2	1975-2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs) Hettinga et al, 2009	87±1	1983-2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane Goldemberg et al., 2004	93 / 71	1980-1985	Brazil	~6.1	n.a.
Ethanol from sugarcane Van den Wall Bake et al., 2009	80±2	1975-2003	Brazil	4.6	0.84
Ethanol from corn Hettinga et al., 2009	82±1	1983-2005	USA	6.4	0.96
Electricity from biomass CHP Junginger et al., 2006a	91-92	1990-2002	Sweden	~9	0.85-0.88
Electricity from biomass IEA, 2000	85	Unknown	EU (?)	n.a.	n.a.
Biogas, Junginger et al., 2006a	85- 100	1984-2001	Denmark	~10	0.97

Data availability is limited for production of biomaterials and biochemicals, bio-CCS concepts and algae. Recent scenario analyses indicate that advanced biomaterials (and cascaded use of biomass) and bio-CCS may become attractive mitigation options on medium term. Algae may have potential to produce liquid or gaseous fuels with minimal land-use, but deployment is uncertain and may not be significant before 2030.

Potential Deployment

Bioenergy at large has a significant GHG mitigation potential, provided resources are developed sustainably and provided the right bioenergy systems are applied. Perennial cropping systems and biomass residues and wastes are in particular able to deliver good GHG performance in the range of 80-90% GHG reduction compared to the fossil energy baseline. For estimates of the potential future deployment of bioenergy see Figure TS 2.3.

Biomass potentials are influenced by and interact with climate change impacts but the detailed impacts are still poorly understood; there will be strong regional differences in this respect. Climate change impacts on bioenergy feedstocks production are real but do not pose serious constraints if temperature raise is limited to 2°C. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g. soil protection, water retention and modernization of agriculture) with production of biomass resources.

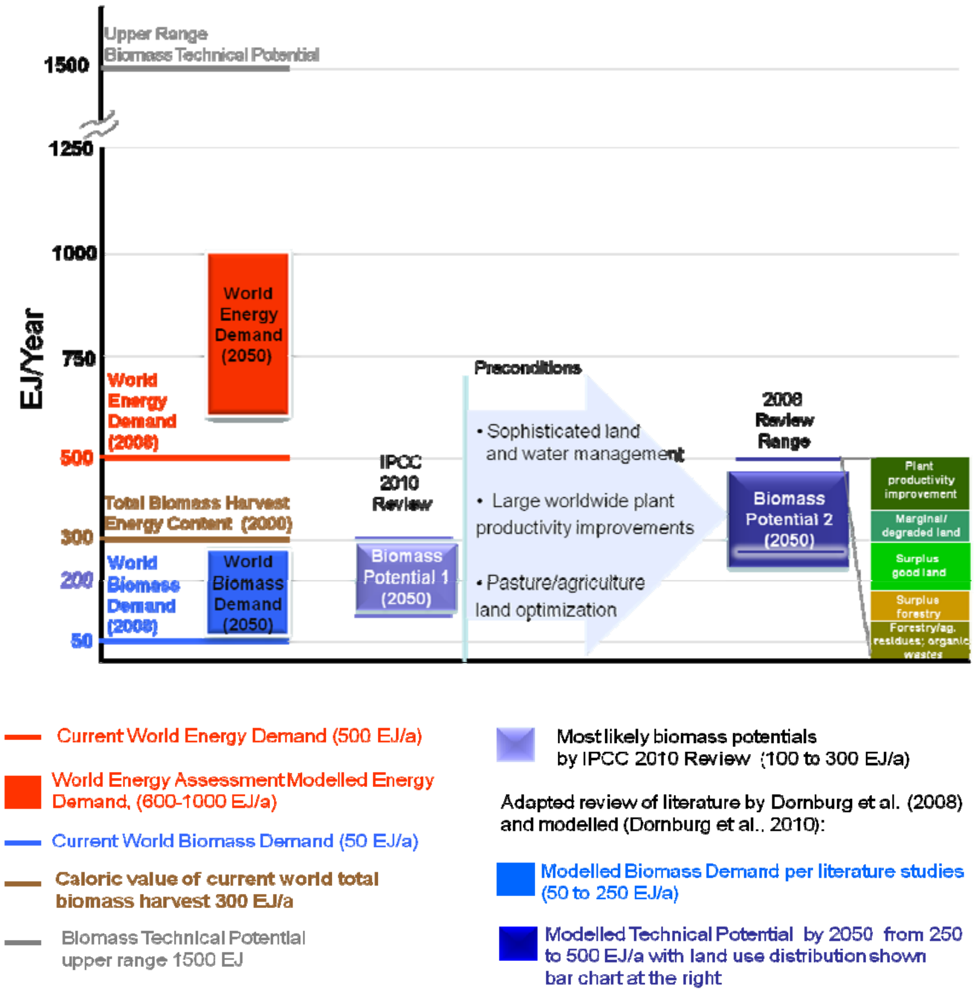


Figure TS 2.3 Upper technical biomass supply potentials, most likely biomass potential (IPCC review, this Chapter), modelled biomass potential (Dornburg et al., 2010), expected demand for biomass (primary energy) based on global energy models and expected total world primary energy demand in 2050. The Biomass Potential 2 scenario incorporates some key limitations and criteria with respect to biodiversity protection, water limitations, soil degradation, and considers developments in agricultural management between A2 versus A1/B1 scenario conditions. The breakdown consist of: (i) Residues: Agricultural and forestry residues; (ii) Forestry: surplus forest material (net annual increment minus current harvest); (iii) Exclusion of areas: potential from energy crops, leaving out areas with moderately degraded soils and/or moderate water scarcity; (iv) No exclusion: additional potential from energy crops in areas with moderately degraded soils and/or moderate water scarcity; (v) Learning in agricultural technology: additional potential when agricultural productivity increases faster than historic trend. Adapted from Dornburg et al. (2008) and Dornburg et al. (2010) based on several review studies.

The recently and rapidly changed policy context in many countries, in particular the development of sustainability criteria and frameworks and the support for advanced biorefinery and second generation biofuel options does drive bioenergy to more sustainable directions. There is consensus on the critical importance of biomass management in global carbon cycles, and on the need for reliable and detailed data and scientific approaches to facilitate more sustainable land use in all sectors. Table TS 2.3 describes key preconditions and impacts for two possible extreme biomass scenarios.

Table TS 2.3 Two opposing storylines and impacts for bioenergy on long term Adapted from Dornburg et al. (2008) and Dornburg et al. (2010).

Storyline	Key precyonditions	Key impacts
- High biomass scenario		
Largely follows A1/B1 SRES scenario conditions,	Assumes: - well working sustainability frameworks and strong policies - well developed bioenergy markets - progressive technology development (biorefineries, new generation biofuels, - successful deployment of degraded lands.	- Energy price (notably oil) development is moderated due to strong increase supply of biomass and biofuels. - Some 300 EJ of bioenergy delivered before 2050; 35% residues and wastes, 25% from marginal/degraded lands (500 Mha), 40% from arable and pasture lands 300 Mha). - Conflicts between food and fuel largely avoided due to strong land-use planning and aligning of bioenergy production capacity with efficiency increases in agriculture and livestock management. - Positive impacts with respect to soil quality and soil carbon, negative biodiversity impacts minimised due to diverse and mixed cropping systems.
Low biomass scenario		
Largely follows A2 SRES scenario conditions, assuming limited policies, slow technological progress in both the energy sector and agriculture, profound differences in development remain between OECD and DC's.	- High fossil fuel prices expected due to high demand and limited innovation, which pushes demand for biofuels for energy security perspective - Increased biomass demand directly affects food markets	- Increased biomass demand partly covered by residues and wastes, partly by annual crops. - Total contribution of bioenergy about 100 EJ before 2050. - Additional crop demand leads to significant iLUC effects and impacts on biodiversity. - Overall increased food prices linked to high oil prices. - Limited net GHG benefits. - Socio-economic benefits sub-optimal.

Key messages and policy recommendations from chapter 2

- Biomass resource potential, even when key sustainability concerns are incorporated, is significant (up to 30% of the world's primary energy demand in 2050) but conditional. A large part of the potential biomass resource base is interlinked with improvements in agricultural and forestry management, investment in infrastructure, good governance of land, smart land use and introduction of effective sustainability frameworks and land-use monitoring.
- If the right policy frameworks are *not* introduced, expansion of biomass use can lead to significant conflicts with respect to food supplies, water resources and biodiversity. Conflicts can also be avoided and synergize with better management of land and other natural resources, (e.g. soil carbon enhancement and restoration, water retention functions) especially agriculture and livestock management to contributing to rural development. Logically, such synergies should explicitly be targeted in comprehensive policy frameworks.
- Bioenergy largely has a significant GHG mitigation potential, provided resources are developed sustainably and provided the right bioenergy systems are applied. Perennial cropping systems

and biomass residues and wastes are able to deliver good GHG performance of 80-90% GHG reduction compared to the fossil energy baseline.

- Optimal use and performance of biomass production and use is regionally specific. Policies need to take regional conditions into account and incorporate the agricultural and livestock sector into good land-use governance and rural development.
- The recent and rapidly changing policy context in many countries drives bioenergy to more sustainable directions. Particularly the development of sustainability criteria and frameworks that support advanced biorefinery and second generation biofuel.
- Lignocellulose based biofuel technology and other advanced bioelectricity options (e.g. carbon capture and storage and advanced biorefieries) are expected to offer fully competitive technologies in the future. Several short term options can provide important synergy with longer term options, such as co-firing, CHP and heat production and sugarcane based ethanol production. Development of working bioenergy markets and facilitation of international bioenergy trade is an important synergy facilitating factor.
- Biomass potentials are influenced by and interact with climate change impacts but the detailed impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g. soil protection, water retention and modernization of agriculture) with production of biomass resources.

DIRECT SOLAR ENERGY

Introduction

Solar energy is an abundant energy resource. Indeed, in just one hour, the solar energy intercepted by the Earth exceeds the world's energy consumption for the entire year. Drawing its energy from a nuclear fusion reaction in the sun's core and constituting the heat radiation emitted by the sun's surface at 5800 K, solar energy consists of a flow of photons or electromagnetic waves that range in wavelengths to cover the ultraviolet, visible, and infrared spectra. Just outside Earth's atmosphere, the magnitude of solar energy is about 1368 watts (W) per square meter of surface facing the sun. But at ground level, this energy is attenuated by the atmosphere to about 1000 W/m^2 on a clear occasion within a few hours of noon (a condition called "full sun")—and to about 500 W/m^2 at a similar time on a day of average atmospheric makeup, and to about 100 W/m^2 on a completely overcast occasion. The use of solar energy embraces a family of technologies classified here under four categories: solar thermal, which includes both active and passive heating of buildings, domestic and commercial solar water heating, swimming pool heating, and process heat for industry; electricity generation via direct conversion by photovoltaic (PV) cells; electricity generation by concentrating solar energy to obtain high temperature and then using that energy to drive heat engines and electrical generators; and finally, solar fuels production methods, which use solar energy to produce useful fuels.

Resource Potential

The *theoretical* potential of solar energy is estimated at 10.8×10^8 TWh per year, but producing this energy would require the full use of all available land area, at 100% conversion efficiency. Determining the *technical* potential requires assessing the fraction of land that can practically be used as well as a realistic conversion efficiency. Estimates for this quantity range from 0.44×10^6 TWh (1580 EJ) per year to 1.4×10^6 TWh (5122 EJ) per year—that is, from 3.1 to 10.2 times the world's primary energy consumption rate in 2007 [3.2.1]. The available energy is spread over the world, so every country and region has a sizeable solar resource that can contribute substantially to its energy base. Part of solar radiation consists of rays arriving directly from the sun without being scattered in the atmosphere: this is the so-called beam or direct solar radiation that is used by concentrators and is most available in desert-like areas. A wide network of solar radiation measurement stations spans the globe [3.2.2], and has yielded (typically hourly) data of solar radiation on a horizontal surface at ground level over the last 40 years or more for many locales. Supplementary data are obtained from measurements from an array of Earth-orbiting satellites. The results are available for solar designers who can use the data to project what energy will be delivered on average by their solar conversion devices in the future. Figure TS 3.1 shows two maps of global solar flux at the Earth's surface.

In the following, we review each of the four solar technologies under various headings.

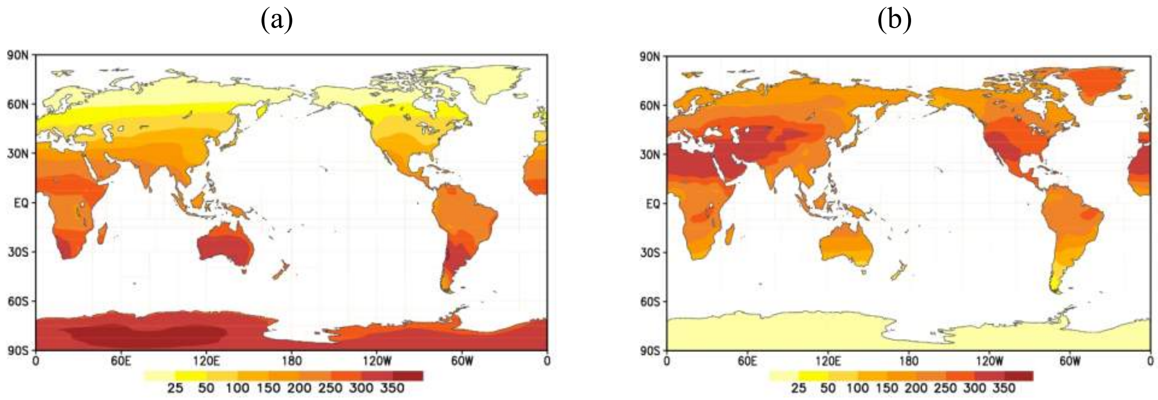
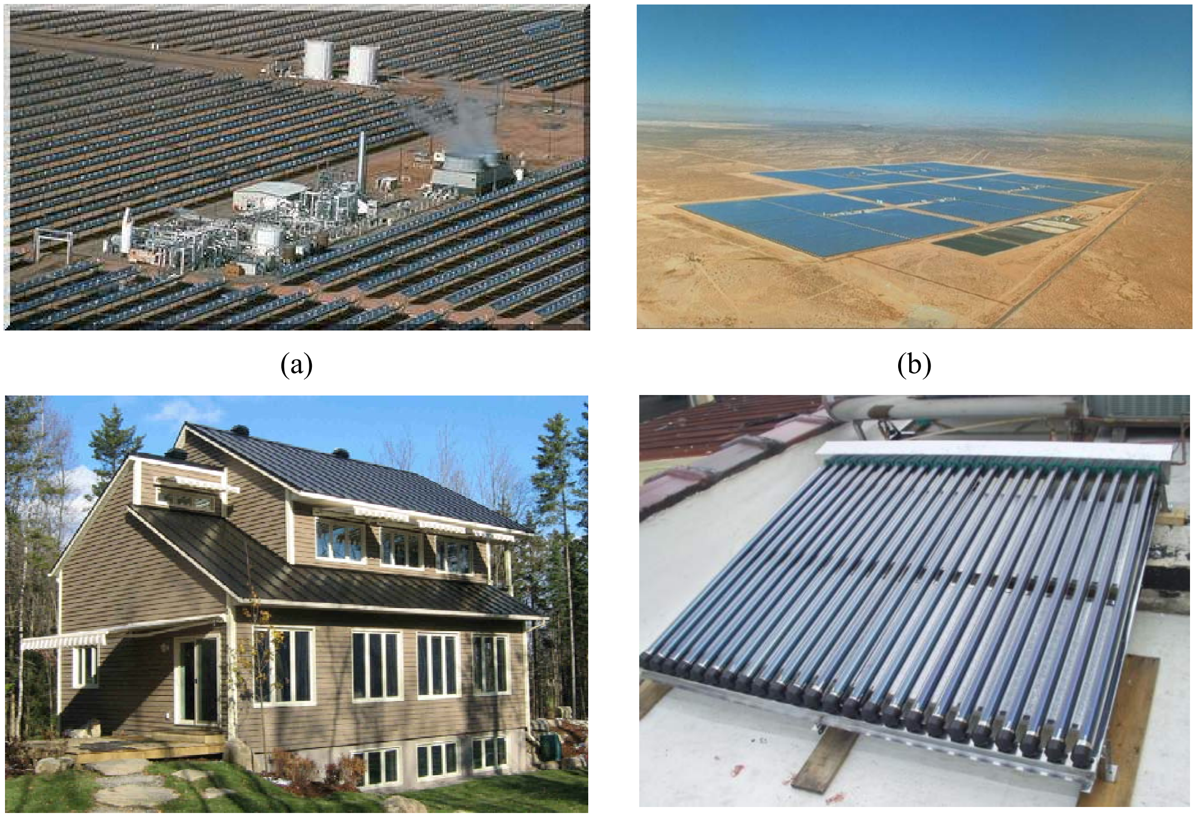


Figure TS 3.3 The global solar flux (in W m^{-2}) at the Earth's surface—derived from the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)—averaged over two 3-month periods: (a) December-January-February and (b) June-July-August.

Technology and Applications

1. Solar Thermal: The key component in "active" thermal solar systems is the solar collector. The flat-plate solar collector consists of a blackened plate exposed to the sun, with conduits—either integral to it or attached to it—through which the fluid to be heated passes into and out of the collector. The fluid then passes to other components, such as a domestic hot-water tank, releasing its heat before being returned to the collector. The flat-plate collector may be classified as 1) unglazed, which is suitable for delivering heat at temperatures a few degrees above ambient temperature, 2) glazed, which has a sheet of glass or other transparent material placed parallel to the plate and spaced a few cm above the plate, making it suitable for delivering heat at temperatures of about 30°C to 60°C, or 3) evacuated, which is like the glazed, but the space between the plate and the glass cover is evacuated, making it suitable for delivering heat at temperatures of about 50°C to 120°C. (To withstand the vacuum, the plates of an evacuated collector are put inside glass tubes, which now constitute both the collector's glazing and container; thus, evacuated collectors are often referred to as tubular collectors.) The typical efficiency of a solar collector when used in its proper temperature range extends from about 40% to 70% at full sun. To obtain heat at higher temperatures, the solar rays are concentrated by mirrors. A common application for the flat-plate collector (and sometimes for the evacuated collector) is heating water for domestic and commercial use (e.g., for washing). They can also be used in active solar heating to provide comfort heat for buildings. Solar cooling uses solar collectors to provide heat in a particular refrigeration cycle called the absorption refrigeration cycle. Other applications for solar-derived heat are industrial process heat, agricultural applications such as drying of crops, and for cooking. Much effort has gone into developing special methods for storing solar-derived heat over longer periods than that provided by the water tanks commonly used to store heat over the day/night period or short periods of cloudy weather. Systems have been proven in the field that can store from summer to winter and ultimately can permit solar-heating systems to provide essentially 100% of the heat demand, compared to the 40% to 60% normally provided by systems with short-term storage [3.3.2]. Passive solar thermal, another way of providing comfort heating for buildings, has proven to be very popular. In passive solar heating, the building itself—particularly its windows—acts as the solar collector and natural methods are used to distribute and store the heat. The basic elements of passive heating architecture are high-efficiency equatorial-facing windows, thermal mass, protection elements, and occasionally, reflectors. The building should be well insulated before passive solar strategies are undertaken.



(a) (b)

(c) (d)

Figure TS 3.2 (a) one of the original SEGS plants in California built by LUZ, operating for 20 years, showing the parabolic trough collectors and steam turbine plant; (b) aerial view of the five SEGS III-VII plants at Kramer Junction, California; (c) Equatorial-facing triple-glazed window area the EcoTerra^{TM} demonstration solar house is 9.1% of heated floor area; (d) evacuated-tube thermal solar collector. [TSU: reference to figure in text is missing]

Studies have shown that using these strategies in new buildings in northern Europe or North America can reduce the building heating demands by up to 40%. For existing, rather than new, buildings retrofitted with passive heating concepts, reductions in the order of up to 20% are achievable [3.3.1].

2. Photovoltaic Electricity Generation: In photovoltaic generation, a plate of a semi-conductor material, such as silicon, is placed in the sun. Semiconductors contain valence electrons, which are bounded tightly to the positive nuclei of the atoms, and conduction electrons, which are more energetic and free to move throughout the material. The relative amount of each type of electron can be altered by introducing certain impurities into the semiconductor, in a process called "doping." N-type doping produces a relative excess of conduction electrons, whereas p-type doing produces a relative deficit. The semiconductor plate exposed to the sun actually consists of two layers: an n-type layer and a p-type layer. External electrical leads are attached to the plate, now called a cell, one to the n-type layer, the other to the p-type layer, and an electrical load (e.g., an electric motor) is connected to these leads. The contacting of the two layers produces a natural voltage or junction potential across the interface, but in the absence of solar rays, the junction potential cannot deliver electrical power at the leads. However, when the solar photons strike the cell, valence electrons can be promoted to conduction electrons. After crossing the junction, the newly formed conduction electrons can move toward the external electrical leads. This creates a flow of external electrons, or an electrical current, and electrical power is thereby delivered to the load (motor). A first distinction in the various forms of the silicon type of PV cells is based on the type of silicon: monocrystalline, multicrystalline, or amorphous. The best efficiency achieved by the cells is 25% for monocrystalline, 20.4% for multicrystalline, and 10.1% for amorphous silicon; amorphous silicon cells compensate for their lower efficiency by their ease of manufacturing. A hybrid of multicrystalline and amorphous layers has achieved an efficiency of 23%. Mono- and multicrystalline silicon cells are the dominant technologies on the PV market, with a 2009 market share of about 80%. Research on improving solar cells has concentrated on raising the efficiency and lowering the cost. An upper bound for the efficiency of the single-junction silicon cell is 31%, so efforts for higher efficiency have focused on using different semiconductor materials with higher junction potentials and introducing additional junctions, the latter strategy permitting a greater fraction of solar photons to generate conduction electrons. Solar cells, usually of the high-efficiency and expensive variety, can be placed at the focus of an optical concentrator; these concentrating photovoltaic (CPV) systems are being given high priority. As with concentrating solar power systems, the CPV systems work best in clear-sky locales. There has also been an effort to minimize the amount of silicon used; silicon is still the preferred material because of its abundance and low price, but because of the purity required, its cost still represents a significant portion of the cost of the cells. The thickness of crystalline layers (or wafers) were roughly halved from 1990 to 2009, to less than 200 micrometers. The wafer area has doubled over the same period, to over 100 cm^2. A group of cells are mounted side by side under a transparent sheet (usually glass) and connected in series to form a “module,” typically with dimensions of up to about 1 m by 1 m. In considering efficiencies, it is important to distinguish between cell efficiencies (quoted above) and module efficiencies; the latter are typically 50% to 80% of the former. Modules have expected lifetimes of 20 to 30 years. The application of PV for useful power involves more than just the cells; the PV system, for example, may include an inverter (to convert the DC power from the cells to AC power to be compatible with common networks and devices) and, for off-grid applications, the system may include storage devices such as batteries. Work is ongoing to make these devices more reliable and to extend their lifetime to be comparable with that of the modules. The applications of the PV-derived electricity can be categorized as either “stand-alone” or “grid-connected.” In the latter, the cells are connected to be another energy source on a conventional electrical grid of mains electricity, supplementing the other sources and reducing the power required to deliver to the load. In the former, the cells constitute the single source on a grid, and batteries are generally required to cover periods when the sun is not shining [3.3.3].

3. CSP Electricity Generation: Concentrating solar power (CSP) technologies produce electricity by concentrating the sun’s rays to heat a liquid or gas that is then used in a heat engine process (steam or gas turbine) to drive an electrical generator. CSP uses only the direct-beam component of solar radiation, and so its use tends to be restricted to a limited geographical range. The concentrator brings the solar rays to a point (point focus) as in central-receiver or dish systems or to a line (line focus) as in trough or linear Fresnel systems. In trough concentrators, long rows of parabolic reflectors that track the movement of the sun concentrate the sun on the order of 70 to 100 times, onto a heat-collection element (HCE) mounted along the reflector’s focal line. The HCE comprises a blackened inner pipe and a glass outer tube, with an evacuated space between the two. In current designs, a heat-transfer oil is circulated through the steel pipe and is heated to about 400°C. Linear Fresnel reflectors work in much the same way. The central-receiver (also called the “power tower”) system uses an array of mirrors (heliostats) on the ground, each tracking the sun along two axes to redirect the sun’s rays onto a point focus on top of a tall tower. At the focus is the receiver, a fixed inverted cavity in which the heat-transfer fluid circulates. It can reach a higher temperature (up to 1000°C) than achieved in the line-focus types, meaning that the heat engine can convert more of the collected heat to power. Temperatures of ~900°C are achieved in the other point-focus system, the dish system, in which just one paraboloid-shaped reflector (as opposed to an array of reflectors) is used for each heat engine. The dish redirects the solar rays onto a receiver that is not fixed but moves with and is connected to the dish, being only about one dish diameter away. In one popular realization of this concept, a Stirling engine driving an electrical generator is housed within the receiver housing. Each of the dish units just described is relatively small, producing 10 to 25 kW_e, but many units can be combined in a field to realize very large power output. All four CSP systems have been built and demonstrated, some delivering energy to the grid. The earliest commercial CSP plants were the Solar Electric Generating Stations (SEGS) in California, producing 354 MW of power; installed between 1985 and 1991, they are still in operation today. Time will tell which of the four systems will be most widely adopted. Introducing energy storage into these systems has a shorter history, and methods are still being developed. In contrast to PV electricity production, CSP does not need to store the electrical energy itself. Rather, the plan for CSP technologies (except for dishes) is to store thermal energy (or heat) after it has been collected at the receiver and before going to the heat engine—an approach generally considered more straightforward than storing electricity. Storage media considered include molten salt, steam accumulators (for short-term storage only), solid ceramic particles, high-temperature phase-change materials, graphite, and high-temperature concrete. Sizes of storage range from 1 hour (achievable now) to 7.5 hours and are either in operation or in the planning stage [3.3.4].

4. Solar Fuel Production: Solar fuel technologies convert solar energy into chemical fuels, such as hydrogen. The fuels derived can then replace fossil fuels, with a corresponding saving in greenhouse gas (GHG) production. The fuels can then be used in the myriad of applications common to most fuels: they can be directly burned to generate heat, which may then be converted into electrical or mechanical work via heat engines, say for transportation. They can also be used to generate electricity directly in fuel cells and for upgrading fossil fuels. Thus, they can give solar energy the transportability and flexibility that make fossil fuels particularly valuable. There are four basic routes to solar fuels, which can work alone or in combination: the electrochemical, photochemical/photo-biological, thermochemical, and solar fuel synthesis from solar hydrogen and CO_2. In the first, hydrogen is produced by an electrolysis process driven by solar-derived electrical power that has been generated by PV or CSP systems. Electrolysis of water is an old and well-understood technology, typically achieving 70% conversion efficiency from electricity to hydrogen. In the photochemical/photo-biological route, solar photons are used to drive photochemical or photo-biological reactions whose products are fuels: that is, they mimic what plants and organisms do. In the third route, the thermo-chemical route, high-temperature solar-derived heat (like that obtained at the receiver of a central-receiver CSP plant) is used to drive an endothermic chemical reaction whose output is a fuel. Here, the reactants can include combinations of water, carbon dioxide, coal, biomass, and natural gas, and the products, which constitute the solar fuels, can be any (or combinations) of the following: H_2, syngas, methanol, dimethyl ether (DME), and synthesis oil. Of course, in the case of a fossil fuel being used as a reactant, overall calorific values of the products will exceed those of the reactants, so that less fossil fuel needs to be burned for the same energy release. Solar fuel can also be synthesized from solar hydrogen and CO_2 by producing hydrocarbons compatible with existing energy infrastructures such as the natural gas network or conventional fuel supply structures.

Installed Capacity and Generated Energy

1. Solar Thermal: Service hot-water heating for domestic and commercial buildings is now a mature technology growing at a rate of about 16% per year and employed to various extents in most countries of the world. The world installed capacity of thermal power from these devices is estimated to be 200 GW_{th}, with a capacity factor of about 10%. The global market for solar thermal totaled an estimated 19 GW_{th} per year in 2008, of which 92.5% was for glazed flat-plate and evacuated-tube collectors; unglazed collectors, used principally for swimming pool heating, accounted for most of the rest. China accounted for about 80% of the new installations in 2008; the European Union accounted for about 10%. Other leading countries were Turkey (3.5%), Brazil

(1.5%), India (1%), and the United States, Australia, and Japan at 0.5%. The rate of rise in the solar thermal installations varies among the different countries. In Europe, the market size more than tripled between 2002 and 2008. The biggest push came from the German market, which more than doubled its capacity. China's growth rate in 2007 was 16%. Despite the above-noted gains in Europe, solar thermal still only accounts for a relatively small portion of the demand for hot water. For example, in Germany, with the largest market, only about 5% of one- and two-family homes are using solar thermal energy. One measure of the market penetration is the per capita annual usage of solar energy. The lead country in this regard is Cyprus, where the figure is 61 kW_{th} per 1 000 people. In Austria, which has one of the highest figures in Europe, it is 29 kW_{th} per 1 000 people [3.4.1].

2. Photovoltaic Electricity Generation: PV production is growing at a rate of about 40% per year, making it one of the fastest-growing energy technologies. Currently, it claims an installed capacity power production of about 22 GW, with a capacity factor estimated at about 11%. The rate of installation in 2009 is estimated to be between 6.6 and 7.9 GW per year. More than 90% of this capacity is installed in three leading markets: the EU with 73% of the total, Japan with 12%, and the USA with 8%. Roughly 95% of the PV installed capacity in the OECD countries is grid connected, the remainder being off-grid. The high rate of growth can no doubt be attributed primarily to the various government incentives, including the feed-in tariffs implemented in Germany and Spain, and the buy-down incentives coupled with investment tax credits implemented in the United States. The top seven PV markets through 2009 included Germany (9800 MW installed), Spain (3500 MW), Japan (2630), USA (1650 MW), Italy (1140 MW), Korea (460 MW), France (370 MW), and PR China (300 MW). Spain and Germany have seen, by far, the largest amounts of solar installed in recent years, with Spain seeing a huge surge in 2008 and Germany having experienced steady growth over the last five years [3.4.1].

3. Concentrating Solar Power (CSP): CSP has now reached a cumulative installed capacity of about 0.65 GW, with another 1.8 GW under construction. The capacity factors for CSP are expected to be quite high, in the range of 35% to 40%. Following the 354 MW of solar trough technology finished in 1991, there had been a slow period for CSP. But since about 2004, there has been a strong growth in planned capacity. The bulk of the current operating capacity consists of trough technology, but central-receiver technology comprises a growing share. By 2010, only about 60% of planned capacity was in the U.S., the remaining capacities being in Spain (30%), Abu Dhabi (6%), Algeria, Egypt, Australia, and Morocco [3.4.1].

4. Solar Fuel Production: Currently, solar fuel production is in the pilot-plant phase. Pilot plants in the power range of 300–500 kW have been built for the carbo-thermic reduction of ZnO, steam methane reforming of methane, and steam gasification of pet-coke. A 250-kW steam-reforming reactor is operating in Australia [3.4.1].

Industry Capacity and Supply Chain

1. Solar Thermal: Currently, flat-plate collector manufactures are producing about 27 million m^2 per year of solar collectors, a scale large enough to adapt to mass production, even though production is spread among a large number of companies around the world. Indeed, large-scale industrial production levels have been attained in most parts of the industry. In the manufacturing process, a number of readily available materials—including copper, aluminium, stainless steel, and thermal insulation—are being applied and combined through different joining technologies to produce the absorber plate and container box, and this is topped by the cover glass, which is almost always low-iron glass, now readily available. Most production is in China and is aimed at internal consumption; for that country, evacuated collectors are starting to dominate the market. Once a small part of the market, evacuated tubular collectors are now gaining in market share. Much of the export market occurs in total solar hot-water heating systems, rather than solar collectors *per se.* The largest exporters of solar water heaters are Australia, Greece, the USA, and France. Australian exports constitute about 50% of its production. In passive solar heating, part of the industry capacity and the supply chain lies in people: namely, the engineers and architects, who must systematically collaborate to produce a passively heated building. Close collaboration between the two disciplines has often been missing in the past, but the dissemination of systematic design methodologies issued by different countries has improved the design capabilities. Windows and glazing are an important part of passively heated buildings and the availability of a new generation of highly efficiency (low-emissivity, argon-filled) windows is having a major effect on solar energy's contribution to buildings heating requirements. These windows now constitute the bulk of the new windows being installed in most northern countries, although their part in the whole building stock is still relatively small. There does not appear to be any industrial capacity or supply-chain issues relating to the adoption of better windows. Another feature of passive design is adding mass to the building's structure. Concrete and bricks, the most commonly used storage materials, are readily available; phase-change materials (e.g., paraffin), considered the storage materials of the future, are not expected to have supply-chain issues [3.4.2].

2. Photovoltaic Electricity Generation: The compounded annual growth rate in manufacturing production from 2003 to 2009 was more than 50%. The current production rate of about 11 GW_{peak} per year is split between several countries and regions: China has about 37% of world's production; Europe has about 17%; Japan and Taiwan have about 14% each; and the U.S. has about 5%. Worldwide, some 200 factories produce silicon wafer-based solar cells and more than 300 produce solar modules. In 2009, silicon-based solar cells and modules represented about 80% of the worldwide market (Figure 3.21). The total market share of wafer-based silicon is expected to decrease over the next few years, whereas thin-film module production is expected to gain market share. Manufacturers are moving to original design manufacturing units and are moving parts of the module production closer to the final market. Between 2004 and early 2008, the demand for crystalline silicon (or polysilicon) outstripped supply. This led to a price hike, and with the new price, ample supplies have become available, the PV market now driving its own supply of polysilicon [3.4.2].

3. Concentrating Solar Power (CSP): Within just a few years, the CSP industry has gone from negligible activity to over 1,400 MW being either commissioned or under construction. More than ten different companies are now active in building or preparing for commercial-scale plants. They range from start-up companies to large organizations with international construction management expertise, and include utilities, such as Florida Power & Light. None of the supply chains for construction of plants is limited by the availability of raw material. Expanded capacity can be introduced with a lead time of about 18 months [3.4.2].

4. Solar Fuel Production: Solar fuel technology is still at an emerging stage, and there is no supply chain in place at present for commercial applications. Solar fuels will comprise much of the same solar-field technology as being deployed for other high-temperature CSP systems, in addition to downstream technologies similar to those in the petrochemical industry [3.4.2].

Impact of Policies

Direct solar energy technologies face a range of potential barriers to achieve wide-scale deployment, and policies to advance markets generally target three issues: 1) accelerating technology improvements by using incentives in the near-term, 2) streamlining planning and permitting processes, and 3) harmonizing global codes and standards. Solar water heating is supported by tax credits, grants and soft loans, and a few renewable electricity standards. For electricity-producing technologies, longer-term support for enabling technologies (e.g., storage and smart grids) is being pursued. Direct financial support for PV is driving the growth in PV markets. Feed-in-tariffs (FITs) set a legal framework for utilities in more than 40 countries to purchase PV-generated electricity at premium rates. Tax credits and soft loans are another set of direct financial tools that are frequently used, as are policies (most common in the United States) that obligate power suppliers to provide a specified fraction of electricity from renewable energy technologies [3.4.3].

Environmental and Social Impacts

Environmental Impacts: Land use is one form of environmental impact. For roof-mounted solar thermal and PV systems, this is not an issue, but it can be an issue for central-station PV. On the other hand, a recent study has shown that the central-station PV life cycle actually involves less land disturbance (in the southwest U.S.) than both fossil fuel and nuclear energy life cycles. The emission of CO_2 and pollutants emitted during the production and decommissioning of the PV modules is another environmental impact. Life-cycle GHG emissions for silicon-based PV modules have been determined to be about 32 g of CO_2-eq/kWh, very much less than that for burning fossil fuels, and this figure is expected to be reduced in the future. (This corresponds to an energy payback period of 2.0 to 2.5 years.) Although the PV industry uses some toxic materials, any release of these materials can be reduced to acceptable levels by strict controls. Moreover, the recycling of PV modules is already economically viable. The land use for CSP is expected to be less than that for PV because the CSP plants are generally more efficient, provided they are set up in clear-sky areas, which generally will be the case. One difference with CSP vis-à-vis PV is that it needs a method to cool the working fluid. Although such cooling often involves the use of scarce water, local air as the coolant is a totally viable option, even though it could involve a slight drop (2%–10%) in plant efficiency. Life-cycle GHG emissions for CSP modules have recently been estimated to be to be about 14 g of CO_2-eq/kWh. With regard to thermal solar, one of the few available studies found that the environmental impact of large-scale solar water-heating adoption in the UK would be very small, showing up mainly in the appearance of the solar collectors on the roofs [3.6.1].

Social Impacts: Apart from its benefits in GHG reduction, the use of solar energy over fossil fuels reduces by a large margin the release of pollutants—particulates and noxious gases—that lead to illnesses and deaths: an estimated 0.8 million deaths yearly are caused by exposure to urban air pollution. Not only would many lives be saved, but public health expenditures would also be drastically reduced if there were wide-scale adoption of direct solar energy. Job creation can be another benefit; it has been shown that at 0.87 job-years per GWh, solar PV had the greatest job-generating potential of any energy technology. Close behind is CSP with 0.23 jobs per GWh, both being well ahead of fossil technologies. When properly put forward, these arguments plus careful planning have been shown to accelerate social acceptance and increase public willingness to tolerate any disadvantages of solar energy, such as visual impacts. It is expected that next-generation PV panels will be so well integrated into the building structure that onlookers will hardly be aware of their presence. The positive benefit in the developing world provides arguments for their use. About 1.6 billion people do not have access to electricity. Solar home systems and local PV-powered community grids can provide economically favourable electricity to many areas for which connection to a main grid is too costly by other means. The impact of electricity on the local population is shown through a long list of important benefits: the replacement of kerosene lamps and similar indoor-polluting light sources, increased reading light levels and qualities leading to increased reading with all the benefits that go with that, street lighting for security and greater community involvement, and communications devices (e.g., televisions, radios) that provide a myriad of benefits in improving the lives of people [3.6.2].

Prospects for Technology Improvements and Innovation

1. Solar Thermal: In buildings of the future, solar panels—including PV panels thermal collector panels, and combined PV-thermal panels—will make up the viewed components of the roof and façades. They will be integrated at the earliest stages of building planning. These buildings will be put in place not just through the whims of individual builders/owners, but will be mandated, at least in some areas. For example, the vision of the European Solar Thermal Technology Platform is to establish the "Active Solar Building" as a standard for new buildings by 2030, where an Active Solar Building covers 100% of its demand for heating (and cooling, if any) with solar energy. Also expected in the future is that solar heating for industrial processes (SHIP), which is currently at a very early stage of development, will become cost-competitive. This will allow solar to move into an area that represents a sizeable fraction of the energy demands of developed countries, about 28% for the EU27 countries. It will be accomplished through a number of technological improvements, principally by developing solar collectors that can function efficiently at higher temperatures [3.7.2]. In highlighting the foreseen advances in passive solar, we can distinguish between two climates: those that are dominated by the demand for heating and those dominated by the demand for cooling. For the former, one can see a wider-scale adoption of the following items: evacuated glazing, dynamic exterior night-time insulation, and translucent glazing systems that can automatically change solar/visible transmittance and that also offer improved insulation values. For the latter, there is the expectation of 1) cool-roof technologies, 2) heat-dissipation techniques such as use of the ground and water as a heat sink, 3) methods that improve the microclimate around the buildings, and 4) solar control devices that allow penetration of the lighting, but not the thermal, component of solar energy. For both climates, there is the expectation of improved thermal storage to be embedded in building materials and also improved methods for distributing the absorbed solar heat around the building and/or to the outside air, perhaps even using active methods such as fans. Finally, improved design tools are expected to facilitate these various improved methods [3.7.2].

2. Photovoltaic Electricity Generation: Although currently a relatively mature technology, PV is still hampered by low efficiency and high cost; but following the trends of other semiconductor industries, steady improvements are expected in the future. Further technological efforts are being taken up in a large framework of intergovernmental cooperation, complete with roadmaps. At the cell level, four broad technological categories that require specific R&D approaches have been identified: 1) cell efficiency, stability, and lifetime, 2) high productivity and manufacturing, 3) environmental sustainability, and 4) applicability, which includes standardization and harmonization. Recognized as part of the first approach are the differences among three major classes of cells: the current class of cells; emerging cells considered to be medium risk and having a mid-term (10–20-year) timeline; and high-risk cells aimed at 2030 and beyond, which are considered to have extraordinary potential but involve new technologies. Examples of the emerging cells are multiple-junction polycrystalline thin films and crystalline silicon in the sub-100-micrometer-thickness range. Examples for the high-risk cells are biomimetic devices and quantum dots that have the potential to increase the maximum efficiency by up to 66%. Finally, there is the important work on the balance of systems (BOS), which looks at inverters, storage, charge controllers, system structures, and the energy network [3.7.3].

3. CSP Electricity Generation: Although CSP is now a proven technology at the utility scale, it is yet to be optimized, and further cost reductions can be expected. There is much scope for improving the heat-engine efficiency, which, for example, in trough plants is estimated to be 37%. To increase efficiency, alternatives to the use of oil as the heat-transfer fluid—such as water (boiling in the receiver) or molten salts—are being developed, permitting higher operating temperatures. For central-receiver systems, the overall efficiencies (including all component systems) are higher because the operating temperatures are higher, and further improvements are expected to achieve peak efficiencies of 35%. Trough technology will benefit from continuing advances in solar-selective surfaces, and central receivers and dishes will benefit from improved receiver/absorber designs that allow collection of very high solar fluxes. Capital cost reduction is expected to come from the benefits of mass production, economies of scale, and learning from previous experience [3.7.4].

4. Solar Fuel Production: Solar electrolysis using PV or CSP is available for niche applications, with estimated production costs at 1.5 to 2 times oil at US$100/bbl. Many paths are being pursued to develop the technology that will reduce the cost of solar fuels: the photoelectrochemical (PEC) cell (which combines all the steps in solar electrolysis to a single unit), producing biofuels from modified photosynthetic microorganisms (which has the potential to have solar energy conversion efficiencies much better than those based on field crops), and the so-called “SOLAR-H2” process (which integrates two frontline research topics: artificial photosynthesis in man-made biomimetic systems, and photo-biological H_2 production in living organisms) [3.7.5].

Cost Trends

1. Solar Thermal: Most solar thermal processes require an auxiliary—generally, a conventional—energy source, so the demand for energy is met by a combination of the two. Typically, between 20% to 80% of the demand is covered by the solar component. Solar equipment generally represents a high first cost to the user which must be amortized over the years of service and then added to the operating cost to determine the unit cost of energy. A European study established the current cost of solar thermal energy (mainly for hot water heating) as ranging from 5 to 17 €-cent per kWh for the regions of central and southern Europe. The same study projected the corresponding cost for 2030 to be 2 to 6 €-cent per kWh. At the latter prices, which are much less than energy from conventional sources, it is expected that solar thermal will extend into active heating of buildings, cooling, and process heat, creating a mass market. Over the last decade, for each 50% increase in installed capacity of solar water heaters, investment costs have fallen 20%. Of the high first cost mentioned above, the solar collectors themselves represent the main cost, with their installed costs ranging from 200 to 500 €/m^2 for flat-plate collectors to 450 to 1,200 €/m^2 for evacuated-tube collectors. The financial payback time required for a solar water heating system in southern Australia has been estimated to be 2 to 2.5 years [3.8.1,2].

2. PV Electricity Generation: The price for PV is often expressed as $ per W, which is the price of a PV module divided by the number of watts that the module will deliver in full sun. Obtaining the unit price of energy (cents per kWh) from a PV system will require first adding the BOS and installation costs, then using a method for amortizing the first cost over the energy delivered over the life of the panel, which will require knowledge of the capacity factor. Despite its simplicity, the $ per W figure gives a useful basis for comparison for both PV and CSP. The current average global price for PV modules with greater than a 75-W rating is just under 2 US$/W, which can be compared to the corresponding 1990 price of 9.30 US$/W. The PV module learning curve (price vs. cumulative production) shows a tight correlation, with the price being reduced by 20% for every doubling of cumulative sales. Prices are projected to continue to drop and are expected to be at or below 1.50 USD/W for all major PV technologies by 2015. This is the price of the modules. After adding in the price of the BOS and installation, a figure of 7.6 US$/W was found to apply in the U.S. in 2007; slightly lower costs have been experienced in Japan and Germany. By 2015, the U.S. Department of Energy projects the price of PV-generated electricity to range from 5 to 10 ¢ US per kWh, depending on the end-user [3.8.3].

3. CSP Electricity Generation: Currently, the average cost for installing a CSP plant is roughly 4 US$/W. The current cost of the energy delivered is estimated to be 12 to 14 ¢ US per kWh, and research projects in the U.S. and Europe are expected to reduce this to 7 to 10 ¢ US per kWh by 2015 and to less than 7 ¢ US per kWh, with 12 to 17 hours of storage by 2020 [3.8.4].

Potential Deployment

Given the capabilities of direct solar energy summarized above, it is appropriate to ask: What role can direct solar energy play on the world energy stage in the not too distant future? No doubt the role will depend on the amount of funding that the technologies will receive to drive the necessary R&D and establish the plants. It is not our goal to lay out new scenarios here. Rather, we summarize findings from previous studies, as taken from the literature, covering the years out to 2050. Only summary figures of those studies are presented in this Technical Summary. Table TS 3.1 below gives the summary data. Each entry in the second to fifth columns contains a single value and a range. The former are averages of values reported by differing literature sources for different funding levels; the latter are the standard deviations of these various values. Sources for the tabulated data are the following: Greenpeace (Revolution scenario); International Energy Agency (IEA), including both the ACT and Blue Maps; and Shell, including both the Scramble and Blueprints scenarios. The Shell data are limited to solar thermal technologies. The column on the right gives the necessary investment costs in RD&D needed between 2005 and 2030 to meet the given GW values, according to the IEA scenarios. The costs after 2030 were considered by the IEA as commercial investment costs.

Table TS 3.1 Evolution of the Cumulative Direct Solar Installations until 2050, by Technology

Technology	2010	2020	2030	2050	Investment
	Cumulative Installations in GW or GW_{th}				Cost, $\$\times10^9$
Solar Thermal (GW_{th})	192 ± 107	988 ± 640	4500 ± 850	9130 ± 5730	255 to 280
PV (GW)	18.5 ± 6.3	160 ± 100	700 ± 550	2100 ± 1300	180 to 222
CSP (GW)	5	91 ± 8	253 ± 41	980 ± 660	260 to 315

With regard to the solar thermal entries, note that passive solar contributions are not included in these data; although this technology certainly reduces the demand for energy, it is not part of the supply chain considered by the usual energy statistics [3.9].

Potential deployment scenarios range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of energy supply. Although it is true that direct solar energy provides only a very small fraction of the world energy supply, it is undisputed that this energy source has the largest potential and a promising future.

Reducing cost is a key issue in making direct solar energy more cost competitive. This can only be achieved if the solar technologies reduce their costs along their learning curves, which depend primarily on market volumes. In addition, continuous R&D efforts are required to ensure that the slope of the learning curves (see Fig. TS 3.3 for an example) do not flatten too early.

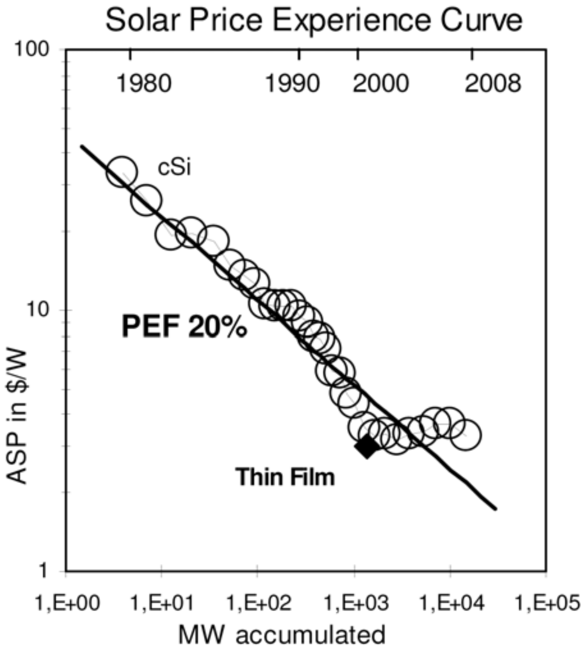


Figure TS 3.3 Solar price experience or learning curve for PV modules (Hoffmann *et al.*, 2009).

The true costs of implementing solar energy are still unknown because the main implementation scenarios that exist today consider only a single technology. These scenarios do not take into account the co-benefits of a renewable/sustainable energy supply via a range of different renewable energy sources and energy-efficiency measures.

Potential deployment depends on the actual resources and availability of the respective technology. However, to a large extent, the regulatory and legal framework in place can foster or hinder the uptake of direct solar energy applications. Minimum building standards with respect to building orientation and insulation can reduce the energy demand of buildings significantly and can increase the share of renewable energy supply without increasing the overall demand. Transparent, streamlined administrative procedures to install and connect solar power source to existing grid infrastructures can further lower the cost related to direct solar energy.

Geothermal Energy

Resource Potential

Geothermal resources consist of thermal energy stored at depth within the Earth in both rock and trapped steam or liquid water, and are used to generate electric energy in a thermal power plant or in other domestic and agro-industrial applications requiring heat [ES, 4.2.1]. It originates within the Earth and differs from "ground source heat" that is stored solar energy in soils and ground water [SRREN Glossary]. The theoretical potential for geothermal energy is estimated to be 105-400 x 10^6 EJ within 10 km depth, 65-140 x 10^6 EJ within 5 km depth, and 35-43 x 10^6 EJ within 3 km depth [4.2.1].

The geothermal technical potentials for electric generation and direct uses are presented in Figure TS 4.1. All of these estimates are lower than the AR4 estimate (5000 EJ/y) and are within the estimates from Krewitt et al. (2009).

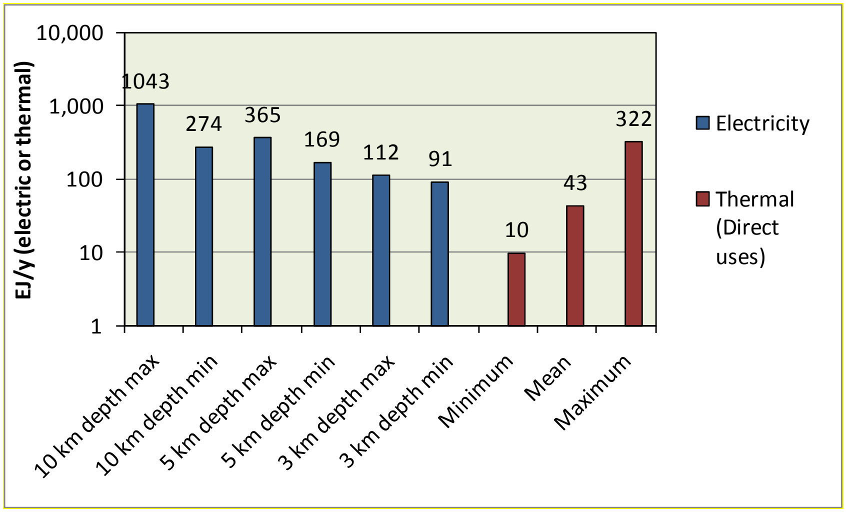


Figure TS 4.1 Geothermal technical potentials for electricity and direct uses (heat) [4.2.1] [TSU: reference is missing]

The technical potentials are presented on a regional basis in Table TS 4.1. The original regional assessment of theoretical potential was conducted by the Electric Power Research Institute in 1978 (EPRI, 1978), based on a detailed estimation of the thermal energy stored inside the first 3 km under the continents accounting for regional variations in the average geothermal gradient and the presence of either a diffuse geothermal anomaly or a high enthalpy region, associated with volcanism or plate boundaries. The values in Table TS 4.1 follow the EPRI approach for each region and applied to the minimum and maximum technical potentials mentioned before at 3, 5 and 10 km depth. The separation into electric and thermal (direct uses) potentials is somewhat arbitrary in that most higher temperature resources could be used for either or both in combined heat and power applications depending on local market conditions [4.2.2].

Table TS 4.1 Geothermal technical potentials for the IEA regions (prepared with data from EPRI, 1978, and the global technical potentials described) [4.2.2]

IEA REGION	Technical potential in EJ/y (electric) at depths to:						Technical potential in EJ/y (heat for direct uses)		
	3 km		5 km		10 km				
	Min	Max	Min	Max	Min	Max	Min	Mean	Max
1. OECD North America	18.7	23.1	37.0	79.7	58.1	221.7	2.1	9.3	69.5
2. Latin America	10.4	12.8	21.3	45.9	32.9	125.5	1.2	5.5	40.9
3. OECD Europe	4.7	5.8	8.4	18.1	13.8	52.7	0.8	3.6	26.8
4. Africa	14.5	17.9	25.5	55.0	42.4	161.7	1.4	6.1	45.8
5. Transition Economies	17.2	21.2	29.5	63.6	49.6	189.1	1.5	6.8	51.1
6. Middle East	3.2	4.0	5.7	12.2	9.4	36.0	0.3	1.4	10.2
7. Developing Asia	7.3	9.1	14.6	31.5	22.9	87.2	0.8	3.7	27.6
8. India	2.4	3.0	4.0	8.7	6.9	26.1	0.2	1.0	7.2
9. China	6.4	7.9	12.9	27.7	20.1	76.6	0.7	3.3	24.5
10. OECD Pacific	5.9	7.3	10.4	22.4	17.3	65.9	0.6	2.5	19.0
Total	**90.8**	**112.1**	**169.3**	**364.9**	**273.5**	**1042.6**	**9.8**	**43.0**	**322.6**

Technology and Applications (electricity, heating, cooling)

Geothermal heat is extracted using wells that produce hot fluids contained in hydrothermal reservoirs with naturally high permeability and porosity or by artificial fluids pathways in Enhanced Geothermal Systems (EGS). The principle of EGS is as follows: in the subsurface where temperatures are high enough for effective utilisation, a fracture network is created or enlarged to act as fluid pathways. Water is passed through this deep reservoir using injection and production wells, and heat is extracted from the circulating water at the surface. The extracted heat can be used for power generation and for district heating [4.3.5]. Once at surface, fluids can be indirectly used to generate electric energy in a power unit, and/or in a direct way in several applications requiring heat.

Geothermal energy is independent of climatic conditions [4.2.3]; it can be dispatched and used to meet peak demand. Hence, geothermal electric power can complement intermittent electricity generation [4.1].

Electric power from geothermal energy is especially suitable for supplying base-load power in an economical way due to the high average capacity factor of currently 71%, with newer installations above 90% [ES].

Since geothermal resources are underground, exploration methods (including geological, geochemical and geophysical surveys) have been developed to locate and assess them. The objectives of geothermal exploration are to identify and rank prospective geothermal reservoirs prior to drilling, and to provide methods of characterising reservoirs that enable estimations of geothermal reservoir performance and lifetime, focusing in the underground temperature distribution, the Earth's stress field and potential fluid bearing structures [4.3.2].

For drilling of geothermal wells over a range of depths up to 5 km, conventional rotary drilling methods are used similar to those for accessing oil and gas reservoirs. Advanced drilling technologies allow for high temperature operation and provide directional capability [4.3.2]. Monitoring, analyzing and modelling of the chemistry and thermodynamics of geothermal fluids, along with mapping their flow and movement in geothermal reservoirs allows for better sizing of power plant and pro-active management of the reservoir's development [4.3.3].

Geothermal power plants either make direct use of the steam from geothermal reservoirs or they deploy heat exchangers (binary cycle plants) that transfer the heat to another working fluid. Binary cycle plants allow for use of lower temperature reservoirs and are often constructed as linked modular units of a few MWe in capacity. Combined or hybrid plants comprise two or more of the above basic types to improve versatility, increase overall thermal efficiency, improve load-following capability, and efficiently cover a wide resource temperature range (200-260°C) [4.3.4].

Under appropriate conditions, high, intermediate and low temperature geothermal fields can be utilised for both power generation and the direct use of heat [4.3.1]. Direct use provides heating and cooling for buildings including district heating, fish ponds, greenhouses and swimming pools, water purification/desalination and industrial and process heat for agricultural products and mineral drying [4.3.7]. Geothermal heat pumps (GHP) are a subset of direct use that can be utilized anywhere in the world for heating and cooling [4.1] and are based on the relatively constant ground or groundwater temperature in the range of 4°C to 30°C. GHP can be of the closed loop or of the open loop type [4.3.8].

Prospects for Technology Improvement, Innovation, and Integration

Successful development and deployment of geothermal technologies will mean significantly higher energy recovery, longer field lifetimes and much more widespread availability of geothermal energy. Achieving that success will require sustained support and investment into technology development from governments and private sectors for the next 10 to 20 years. With time, better technical solutions are expected to improve power plant performance and reduce maintenance down-time. More advanced approaches for resource development, including advanced geophysical surveys, reinjection optimization, scaling/corrosion inhibition, and better reservoir simulation modelling, will help reduce the resource risks by better matching installed capacity to sustainable generation capacity [4.6.1].

In exploration, R&D is required for hidden geothermal systems and EGS prospects. Rapid reconnaissance geothermal tools will be essential to identify new prospects, especially those with no surface hot springs. Satellite-based hyper-spectral, thermal infra-red, high-resolution panchromatic and radar sensors are most valuable at this stage, since they can provide data inexpensively over large areas [4.6.2].

In order to improve access to reservoirs special research is needed in large diameter drilling through plastic, creeping or swelling formations such as salt or shale. The objectives of new-generation geothermal drilling and well construction technologies are to reduce the cost and increase the useful life of geothermal production facilities through an integrated effort. Ultimately a larger portion the geothermal resource would be economically accessible if drilling costs could be substantially reduced by developing improved technology, e.g. thermal, particle-assisted abrasives, and chemically-assisted drilling techniques [4.6.3].

Reservoir engineering, particularly in the case of EGS, need to be refined to significantly enhance the hydraulic productivity, while reducing the risk of seismic hazard. Imaging fluid pathways induced by hydraulic stimulation treatments through innovative technology would facilitate this. New visualisation and measurement methodologies (imaging of borehole, permeability tomography, tracer technology, coiled tubing technology) should become available for the characterisation of the reservoir [4.6.3].

The efficiency of the surface system components can still be improved, especially for low-enthalpy power plant cycles, cooling systems, heat exchangers and production pumps for the brine. New and cost-efficient materials are also required for pipes, casing liners, pumps, heat exchangers and for other components [4.6.4].

Enhanced Geothermal Systems (EGS)

While conventional, high-temperature, naturally-permeable geothermal reservoirs are profitably deployed today for power production and direct uses, the success of the EGS-concept would lead to widespread utilization of lower grade resources. EGS projects are currently at a demonstration and experimental stage. The key technical and economic challenges for EGS over the next two decades will be to achieve efficient and reliable stimulation of multiple reservoirs with sufficient volumes to sustain long term production, with low flow impedance, limited short-circuiting fractures, and manageable water loss (Tester et al., 2006) [4.6.1]. This requires, for instance, better understanding of how cracks form and propagate in different stress regimes and rock types and the ability to create multiple fracture zones from a single borehole [4.6.2].

Submarine geothermal power

Submarine geothermal power is still at the conceptual stage. In theory, submarine devices could make use of existing hydrothermal vents (without drilling) at mid-ocean ridges to generate electricity. Among others, critical challenges for these resources include the distance from shore and off-to-onshore grid-connection costs and the potential impact on unique marine life around hydrothermal vents [4.3.6].

Global and Regional Status of Market and Industry Development

Geothermal technologies from conventional geothermal resources are mature with established markets around the world. Geothermal-electric generation accounts for one century of commercial experience with 10.7 GW of installed capacity in 24 countries (Fig. TS 4.2) providing 10% to 30% of their electricity demand in six of them. There are also 50 GW thermal of geothermal direct applications operating in 78 countries, including space heating and cooling with GHP.

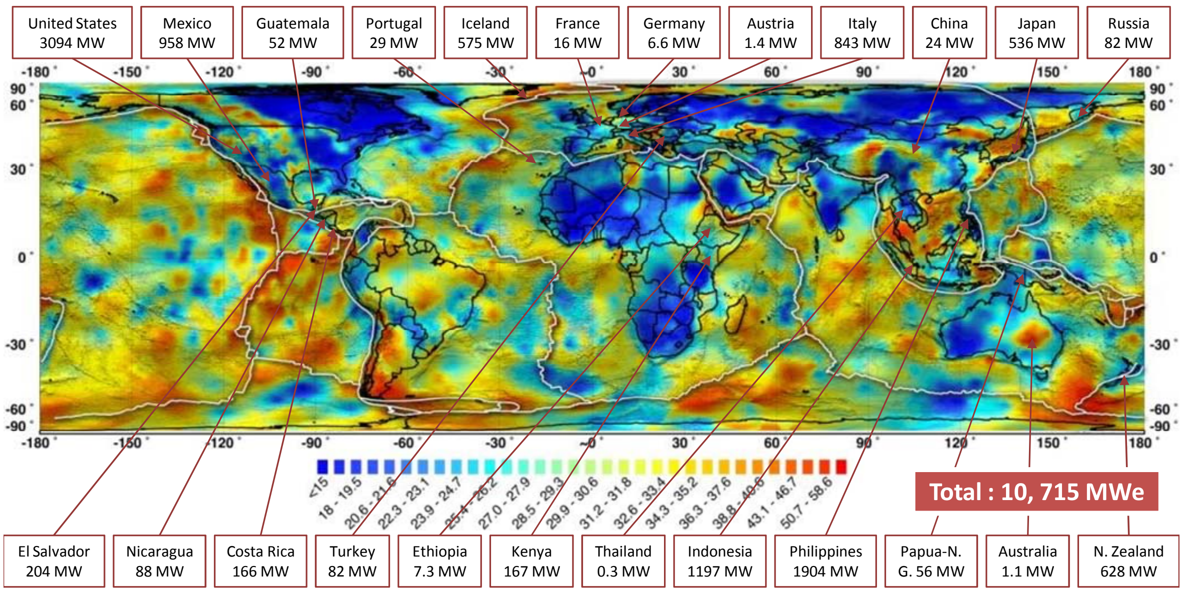


Figure TS 4.2 Geothermal-electric installed capacity by country in 2009. Figure shows worldwide average temperature gradients in °C/km and tectonic plates boundaries (data from Bertani, 2010).

The worldwide use of geothermal energy for power generation (predominantly from conventional hydrothermal resources) was 67.2 TWh/year in 2008 with a worldwide CF of 71% (Bertani, 2010). Conventional geothermal resources currently used to produce electricity are of high-temperature

(>180°C), utilised through steam turbines (condensing or back-pressure, flash or dry-steam), and of low-intermediate temperature (<180°C) used by binary-cycle power plants [4.4.1].

The average annual growth of worldwide geothermal-electric installed capacity over the last five years (2005-2010) is 4.7%, and over the last 40 years (1970-2010) is 7.0%. For geothermal direct uses (heat applications) the world average annual growth in 2005-2010 is 16.1%, and 11% in the last 35 years (1975-2010) [4.4.1].

EGS are still in the demonstration phase in Europe, the US and Australia, with two pilot projects already in operation in Germany and one commissioned in France. In Australia considerable investments of US$ 248 million by year-end 2008 have been made by private sector companies, and there are government grants to co-fund drilling, geophysical surveys and research totaling US$ 267 million. The US in its recent clean energy initiatives has included large EGS research, development, and demonstration components as part of a revived national geothermal program [4.4.2].

The world installed capacity of geothermal direct use is currently estimated to be 50.6 GWt (Table 4.2), with a total thermal energy usage of about 121.7 TWh_t/y (0.438 EJ/y), distributed in 78 countries, with an annual average capacity factor of 27.8%. The main types (and relative percentages) of direct applications in annual energy use are: space heating of buildings (63%, of which three quarters are from heat pumps), bathing and balneology (25%), horticulture (greenhouses and soil heating) (5%), industrial process heat and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%) (Lund et al., 2010) [4.4.3].

Cost Trends

Geothermal projects have typically high up-front costs (mainly due to the cost of drilling wells) and low operational costs. These operational costs vary from one project to another due to size and quality of the geothermal fluids, but are relatively predictable in comparison with power plants of traditional energy sources which are usually subject to market fluctuations in fuel price [4.7].

The capital cost (capex) of a typical geothermal-electric project is composed of the following components: a) Exploration and resource confirmation (10-15% of the total), b) Drilling of production and injection wells (20-35% of the total), c) Surface facilities and infrastructure (10-20% of the total), and d) Power plant (40-80% of the total). Current capex vary between 1800 and 5300 US$ (2005) per kWe [4.7.1].

Current geothermal-electric Operation and Maintenance (O&M) costs, including make-up wells, have been calculated to be between 19 and 30 (2005) US$/MWh. The present levelized costs (LCOE) of geothermal electricity are calculated to be 43-84 (2005) US$/MWh using the lowest (3%) and highest (10%) discount rates, which make it competitive in most power markets. There are no actual LCOE data for EGS, but some projections obtained values of 100-175 (2005) US$/MWh for relatively high-grade EGS resources (250-330°C, 5 km depth wells) assuming a base-case present-day productivity of 20 kg/s per well [4.7.2].

By 2050 LCOE are expected to low 15% (Fig. TS 4.3) due to a decreasing drilling cost derived from better technologic practices in the drilling industry and from economic competition resulting from a greater availability of drilling rigs, and an increasing worldwide average capacity factor (80% for 2020, 85% for 2030 and 90% for 2050 [4.7.3]). Projected LCOE values for EGS assuming improvements in technology and productivity are expected to low around 50% by 2050 [4.7.4].

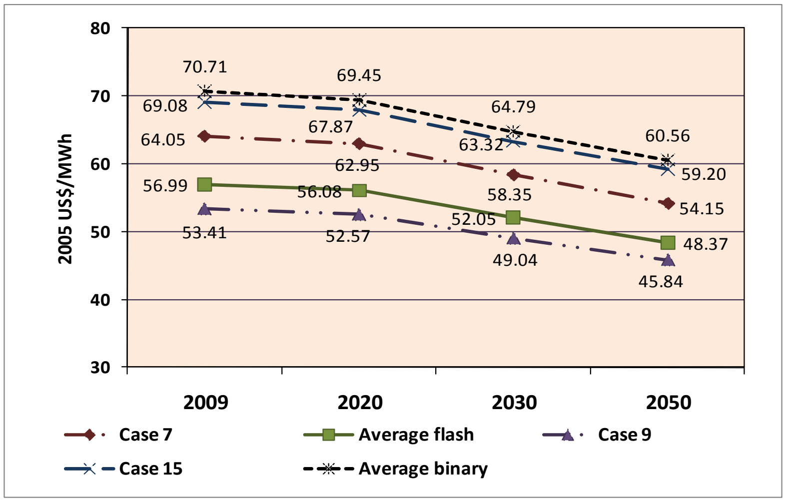


Figure TS 4.3 Present and projected LCOE in 2005 US$ for typical geothermal-electric plants at discount rate of 7% [Refer to 4.7.2 and 4.7.2 for explanation of cases 7, 9 & 15]. [TSU: reference?]

Cost of direct-use projects have a wide range, depending upon the specific use, the temperature and flow rate required, the associate O&M and labour costs, and the income from the product produced. In addition, costs for new construction are usually less than cost for retrofitting older structures. However, current costs of geothermal direct uses are also competitive and calculated to be between 75 (2005) US$/kW$_{th}$ for aquaculture ponds to 3900 (2005) US$/kW$_{th}$ for individual space heating. Current LCOE costs go from 35 (2005) US$/MWh (thermal) for aquaculture ponds to 170 (2005) US$/MWh (thermal) for individual space heating [4.7.5].

Environmental and Social Impacts

Geothermal is a renewable resource as the tapped heat from an active reservoir is continuously restored by natural conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by reinjection of the exhausted fluids. If managed properly, geothermal systems can be sustainable for the long term. Geothermal systems are natural phenomena, and typically discharge gases mixed with steam from surface features, and minerals dissolved in water from hot springs.

Direct CO_2 emissions average 120 g/kWh$_e$ for currently operating conventional flash and direct steam electric power plants and less than 1 g/kWh$_e$ for binary cycle plants with total reinjection. Corresponding figures for direct use applications are even lower.This emission is from natural CO_2 releases into the atmosphere, not created by any combustion process [ES, 4.5.1]. Over its full life-cycle, the CO_2-equivalent emissions range from 23-80 g/kWh$_e$ for binary plants and 14-202 g/kWh$_{th}$ for district heating systems and GHP [4.5.2].

Local hazards arising from natural phenomena, such as micro-earthquakes, hydrothermal steam eruptions and ground subsidence may be influenced by the operation of a geothermal field. Pressure or temperature changes induced by stimulation, production or re-injection of fluids can lead to geo-mechanical stress changes and these can then affect the subsequent rate of occurrence of these natural phenomena. Even though no buildings or structures within a geothermal operation or local community have been significantly damaged (more than superficial cracks) by shallow earthquakes originating from either geothermal production or injection activities, geological risk assessments can help avoid or mitigate these hazards [4.5.3].

Land use requirements range from 160 to 290 m²/GWh/y excluding wells and up to 900 m²/GWh/y including wells. Specific geothermal impacts on land use include effects on outstanding natural features such as springs, geysers and fumaroles. Despite good examples of unobtrusive, scenically-landscaped developments (e.g. Matsukawa, Japan), and integrated tourism/energy developments (e.g. Wairakei, New Zealand and Blue Lagoon, Iceland), land use issues in many settings (e.g. Japan, the US and New Zealand) can be a serious impediment to further expansion of geothermal development [4.5.5].

The successful realization of geothermal development projects often depends on the level of acceptance by the local people. Prevention or minimization of detrimental impacts on the environment, and on land occupiers, as well as the creation of benefits for local communities, is indispensable to obtain social acceptance. One of these benefits is that geothermal development often creates job opportunities for locals since drilling and plant construction must be done at the site. This can be helpful for poverty alleviation in developing countries, particularly in Asian, Central and South American, and African developing nations where geothermal developments are often located in remote mountainous areas [4.5.4].

Geothermal resources are environmentally advantageous and the net energy supplied more than offsets the environmental impacts of human, energy and material inputs. A good example of this is the city of Reykjavik, Iceland, which has eliminated heating with fossil fuels, significantly reducing air pollution, and avoided about 100 Mt of cumulative CO_2 emissions (i.e., around 2 Mt annually). Other examples are at Galanta in Slovakia, Pannonian Basin in Hungary, and Paris Basin in France [4.5.4].

Potential Deployment

Geothermal energy can contribute to near- and long-term carbon emissions reduction. In 2008 the worldwide geothermal-electric generation was 67.2 TWh_e [4.4.1, 4.7.3] and the heat generation from geothermal direct-uses was 121.7 TWh_t [4.4.3]. These amounts of energy are equivalent to 0.24 and 0.44 EJ/y, respectively, for a total of 0.68 EJ/y (direct equivalent method). This represents only ~0.13% of the global primary energy demand in 2007. However, on a global basis, by 2050 geothermal could supply 2.5-4.1% of the global electricity demand and almost 5% of the global demand of heat-cooling [4.8].

In the near-term (2015) and taking into account the geothermal-electric projects under construction or planned in the world, it is expected to reach 18,500 MWe of installed capacity (Bertani, 2010). For geothermal direct uses (heat applications) it is expected an annual growth rate between their historic average rate (11%) and the rate of the last 5 years (2005-2010: 16.1%), which results in 13.5% to reach 95,300 MW_{th} [4.8.1].

In the long-term (2050), it is assumed for electric power deployment that the average annual rate growth for 2015-2030 will be the historic rate (7%), and for 2030-2050 an annual rate growth of 5.9% is expected, including EGS projects deployment. For direct uses deployment, the assumed average annual rate growths are: 11% for 2015-2020 (historic rate 1975-2010), 9% for 2020-2030, 5.5% for 2030-2040 and 2.5% for 2040-2050 [4.8.2]. Thus, the expected deployments by regions in the near and long term are presented in Table TS 4.2, which is a compound of tables 4.10 and 4.12 of chapter 4 [4.8.1, 4.8.2].

Table TS 4.2 Regional near- and long-term forecasts of installed capacity for geothermal power and direct uses (heat) and global forecast of electric and direct uses (heat) generation [4.8.1, 4.8.2]. [TSU: Sources of tables 4.10 and 4.12 are missing]

REGION	Current capacity (2010)		Forecast capacity (2015)		Forecast capacity (2050)	
	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)
1. OECD North America	13.893	4.052	30.7	6.6	234.5	45.4
2. Latin America	0.808	0.509	1.2	1.1	10.2	8.5
3. OECD Europe	20.357	1.551	36.6	2.1	305.9	25.3
4. Africa	0.13	0.174	2.5	0.6	18.4	7.0
5. Transition Economies	1.063	0.082	1.8	0.2	10.2	4.8
6. Middle East	2.362	0	3.1	0.0	7.1	2.2
7. Developing Asia	0.052	3.158	2.1	6.1	20.4	35.2
8. India	0.265	0	1.2	0.0	10.2	2.8
9. China	8.898	0.024	12.3	0.1	127.5	13.7
10. OECD Pacific	2.755	1.165	3.7	1.8	86.7	15.7
TOTAL	**50.583**	**10.715**	**95.3**	**18.5**	**831.1**	**160.6**
Generation (current or expected, thermal and electric) in:	TWh_t/y	TWh_e/y	TWh_t/y	TWh_e/y	TWh_t/y	TWh_e/y
	121.7	67.2	250.4	121.6	2184.0	1266.4
	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y
	0.44	0.24	0.90	0.44	7.86	4.56

For power, practically all the new power plants expected by 2015 will be conventional (flash and binary) in hydrothermal resources, with only a marginal contribution of EGS projects. In general terms, the worldwide trends in development of EGS are estimated to be slow in the next 5-10 years, and then present an accelerated growth. In the long-term (2050) it is expected that half of the geothermal power plants in the world (160 GWe) will be of EGS type.

Projections of geothermal energy contribution to the global primary energy supply span a very broad range: up to 11.9 EJ/y in 2020, 21.3 EJ/y in 2030 and 50.1 EJ/y in 2050, taking the more stringent carbon mitigation policies (300-440 ppm in all years), and are sensitive to the carbon policy assumed by each projected year. Medians of all those scenarios are also sensitive to the carbon policy, ranging 0.39-0.68 EJ/y by 2020, 0.22-1.2 EJ/y by 2030 and 1.09-3.85 EJ/y by 2050, in all cases considering the baseline (600-1000 ppm) and the 300-440 ppm scenarios. These amounts are not completely comparable with the IPCC AR4 estimate by 2030, since this included only geothermal-electric generation without reference to the geothermal contribution for heat supply. But even so, it is clear that the 2.28 EJ/y of electric generation estimated by the AR4 by 2030 results well above the medians considered by 2030, but lies in the 25-75% percentile for the more restricted scenario [4.8.2]. It is clear, also, that the medians of all scenarios considered by Chapter 10 are feasible for 2020, 2030 and 2050 and even result conservative compared to the estimates provided in Table 4.2. What's more, even the highest estimates for long-term contribution of geothermal energy to the global primary energy supply (50.1 EJ/y by 2050), are well within the technical potentials (91 up to 1043 EJ/y for electricity and 10 up to 322 EJ/y for heat). Thus, technical resource potential is not likely to be a barrier to reach the most aggressive levels of geothermal deployment (electricity and direct uses) in a global or regional basis [4.8.2].

Evidence suggests that the global and regional availability of geothermal resources is enough to meet the results of the modelled scenarios, and also that projected market penetration seems to be reasonable. With its natural thermal storage capacity, geothermal is especially suitable for supplying base-load power, and thus is uniquely positioned to play a key role in climate change mitigation strategies [4.8.3].

Hydropower

Resource Potential

Hydropower is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. The annual global and *technically* feasible potential for hydropower generation is 14,368 TWh with a corresponding estimated total capacity potential of 3,838 GW; five times the current installed capacity. Undeveloped capacity ranges from about 70 percent in Europe and North America to 95 percent in Africa indicating large and well distributed opportunities for hydropower development worldwide (see Table TS 5.1). (5.2.1) Substantial potential is also available at existing weirs, barrages, canals and ship locks.

Table TS 5.1 Regional technically feasible, annual hydropower potential (TWh/yr) and capacity potential (GW) compared to annual generation in 2005/2006 (TWh) and installed capacity (GW); also shown are undeveloped capacity potential and average capacity factors in percent (%) (Source: (IJHD, 2005, 2007).

	Technical Potential (TWh/Yr)	**Capacity Potential (GW)**	**Annual Generation 2005/2006 (TWh)**	**Installed Capacity (GW)**	**Undeveloped Capacity Potential (%)**	**Capacity Factor [=Generation/ (Capacity*8760hrs)] (%)**
North America	1510	357	625	148	71	48
Latin America	2968	600	674	136	81	56
Europe	1140	360	539	170	68	36
Africa	1750	399	983	21	95	50
Asia	6800	1652	1061	258	87	47
Australasia/ Oceania	200	67	40	13	83	34
Total	14368	3845	3032	746	79	46

While the average capacity factors are in the order of 50%, the value for Europe (36%) and Australasia/Oceania is low probably due to the way hydro is used in the energy mix (more peaking than base-load). Increases in generation achievable by equipment renovation, uprates and operation optimization have generally not been assessed. (5.2.1)

The resource potential for hydropower may change due to a changing climate; both increasing and decreasing effects have been found in local and regional studies (5.2.2). Global effects on existing hydropower systems will probably be small, even if individual countries and regions could have significant positive or negative changes in precipitation and runoff (ES): Annual power production capacity for the present (2005) hydropower system in 2050 could increase by 2.7 TWh in Asia under the A1B scenario, and decrease by 0.8 TWh in Europe. (5.2.2.1.7)

Technology and Applications

Hydropower plants (HPP) are often classified in three main project types according to operation and type of flow: run of river (RoR), reservoir based and pumped storage type. (5.3.1)

RoR HPP only have small intake basins with no storage capacity. Some RoR HPP also have small storage and are known as pondage-type plants. Power production therefore follows the hydrological cycle in the watershed. For RoR HPP the generation varies as per water availability from rather intermittent in the small tributaries to base-load in large rivers with continuous water flow. Hydropower projects with a reservoir, alternatively called storage hydropower, deliver a broad range of energy services such as base load, peak, energy storage and act as a regulator for other sources. In addition they often deliver services that are going far beyond the energy sector such as flood control, water supply, navigation, tourism and irrigation. Pumped storage delivers its effect mainly on peaking consumption. (5.3.1, 5.4.4). Pumped storage is the largest-capacity form of grid energy storage now available. (5.3.1.3) Hydropower projects are usually designed to suit particular site conditions, and are classified by project type, head (i.e. the vertical height of water above the turbine), purpose (single or multi-purpose) and size (installed capacity). Size wise categories are different worldwide due to varying development policies in different countries.

Hydropower has the best conversion efficiency of all known energy sources (about 90% efficiency, water to wire). It also has the highest energy payback ratio (see Figure TS 5.1), considering the amount of energy required to build, maintain and fuel a hydropower plant compared with the energy it produces during its normal life span. (5.1.3) However, sedimentation is a problem that needs to be managed as it has a number of negative effects on HPP performance: depletion of reservoir storage capacity over time; increase in downstream degradation; increased flood risk ,; generation losses due to reduction in turbine efficiency, increased frequency of repair and maintenance; and reductions in turbine life-time and in regularity of power generation. The sedimentation problem may ultimately be controlled through land-use policies and the protection of vegetation coverage. The application of technical measures, such as the reduction of sediment load to the reservoirs, the removal of sediment from the storage reservoirs, and the design and operation of hydraulic machineries to resist effects of sediment, may also help to deal with the problem. (5.3.3)

Normally the life of hydro-electric power plant is 40 to 80 years. Electro-mechanical equipment may need to be upgraded or replaced after 30-40 years, while civil structures like dams, tunnels, etc usually function longer before it requires renovation. Uprating of hydropower plants calls for a systematic approach as there are a number of factors (hydraulic, mechanical, electrical and economic) that play a vital role in deciding the course of action. From a techno-economic viewpoint, uprating should be considered along with renovation & modernization/Life extension measures. Hydropower generating equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Most of the 746 GW of hydropower equipment in operation today will need to be modernised by 2030. Having existing hydropower plants refurbished will usually result in increased hydropower capacity and production both where present capacity is being renovated and/or uprated and where existing infrastructure (like barrages, weirs, dams, canal fall structures, water supply schemes) is being reworked to add new hydropower facilities. (5.3.4)

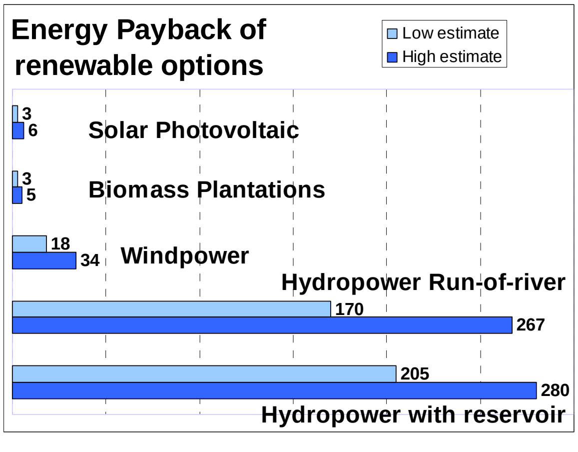


Figure TS 5.1 Energy Pay back Ratio (Source: Gagnon 2008).

Global and Regional Status of Market and Industry Development

Hydropower is a mature, predictable and price competitive technology. (ES) It currently provides approximately 16% of the world's total electricity production and 87% of electricity from renewable sources. (5.4.1) While hydropower contributes to some level of power generation in 159 countries, five countries make up more than half of the world's hydropower production: China, Canada, Brazil, the USA and Russia (5.4.1). The importance of hydroelectricity in the electricity matrix of these countries differs, however, widely. On one hand Brazil, Canada are heavily dependent on this source having a percentage share of the total of 83.2% and 58% respectively, whereas other hand, United States has a share of 7.4% only from hydropower. In Russia, the share is 17.6% and 15.2% in China. (5.4.1)

Hydropower projects are one of the main contributors to carbon credits. As of March 2010, 562 hydropower projects out of total 2062 projects are registered under CDM, representing 27% of CDM projects. A significant portion of these projects are based in China (67%), India (9%) and Brazil (6%). So far only 12 projects have been rejected by the CDM Executive Board on the grounds of not fulfilling the additionality criterion. However, there is uncertainty at present of the value of the Certified Emission Reductions (CERs) gained within the EU Emission Trading Scheme (ETS). With EU Member States having interpreted the conditions on the use of these credits differently in the past, European carbon exchanges have refused to offer the CERs for trade on their platforms as they may not be fully fungible. Initiatives to harmonise this procedure are underway. (5.4.5)

Carbon credits benefit hydropower projects by helping to secure financing and to reduce risks. As financing is a most decisive step in the entire project development, additional funding from carbon credit markets could be a significant financial contribution to project development (increase in return on equity and improve internal rate of return) which can be observed in several ways: 1) additional revenues from the credits, and 2) higher project status as a result of CDM designation (enhanced project's attractiveness for both equity investors and lenders). (5.4.5)

Many economically feasible hydropower projects are financially challenged. High up-front costs are a deterrent for investment. Also, hydropower tends to have lengthy lead times for planning, seeking various permits, and construction. In the evaluation of life-cycle costs, hydropower often has the best performance, with annual operating costs being a fraction of the capital investment and the energy pay-back ratio (= total energy produced during system's normal lifespan/ energy required to build, maintain and fuel the system) being extremely favourable because of the longevity of the power plant components. (5.4.6.1)

The development of more appropriate financing models is a major challenge for the hydropower sector, with optimum roles for the public and private sectors. The main challenges for hydropower relate to creating private-sector confidence and reducing risk, especially prior to project for seeking permits. Green markets and trading in emissions reductions will undoubtedly give incentives. Also, in developing regions, such as Africa, being emerging markets interconnection between countries and the formation of power pools is building investor confidence in these. Feasibility and impact assessments carried out by the public sector, prior to project execution, will ensure greater private-sector interest in future projects. (5.4.6.1)

Most of countries differentiate between small scale and large scale hydropower. There are different incentives used for small scale hydropower (feed-in tariffs, green certificates, easy permits and bonus) depending on the country, but no incentives are used for large scale hydro. For instance, France currently applies a legislation which provides a financial support scheme for renewable energy based on feed-in tariffs (FIT) for power generation. For renewable energy installations up to 12 MW, tariffs depend on source type and may include a bonus for some sources (rates are corrected for inflation). For hydropower the tariff duration is 20 years, and the FIT is 60.7 €/MWh, plus 5 to 25 €/MWh for small installations, plus up to 16.8 €/MWh bonus in winter for regular production. (5.4.6.2)

Integration into Broader Energy Systems

As the generating units of hydropower can be started or stopped almost instantly, it is the most responsive energy source for meeting peak demands and balancing unstable electricity grids. Techniques such as seasonal/multi seasonal storage or daily/weekly pondage can be used in many cases to make the distribution of stream flow better suitable to power demand patterns. (5.5.5) Storage hydropower is therefore ideal for backing up and regulating variable renewable sources like wind, solar and waves, thus allowing for a higher deployment of these sources in a given grid. The flexibility and short response time of hydropower could also facilitate nuclear and thermal plants to operate at their optimum steady state level thereby reducing their fuel consumption and emissions. (ES) Hence, in an integrated system, the hydropower plant is used as the peaking plant with thermal units functioning as base loads. (5.5.1) As such, hydropower has the potential to increase the output of power systems and smooth the output from variable output technologies. (5.5.) It can help to ensure reliable supplies and may help eliminate brownouts and blackouts caused by partial or total power failures. (5.5.4) Therefore, hydropower generation provides numerous ancillary services such as voltage regulation, operating reserves, black-start capability and frequency control, helping to maintain a reliable operation of the transmission system and to increase energy security. (5.5.6.4)

Hydropower can be served through the national and regional electric grid, mini grid and also in isolated mode. There are several hydro projects which are for captive use and have been since the very beginning of hydropower development. Water mills in England, Himalayan countries and many other parts of the world, for grinding the cereals, for water lifting and for textile industry constitute early instances where hydropower has been used as captive power in mechanical as well as electrical form. The tea and coffee plantation industry have used and still are using hydropower for their captive needs in isolated areas. (5.5.2) There has been a growing realisation in developing countries that small scale hydropower schemes have an important role to play in the socioeconomic development of remote rural, especially hilly, areas specially to provide power for industrial, agricultural and domestic uses. Small scale hydropower based rural electrification in China has been one of the most successful examples, building over 45,000 small scale hydro plants of 50,000 MW, producing 150 Billion kWh annually, and benefitting over 300 Million people (up to 2007). (5.5.3)

Environmental and Social Impacts

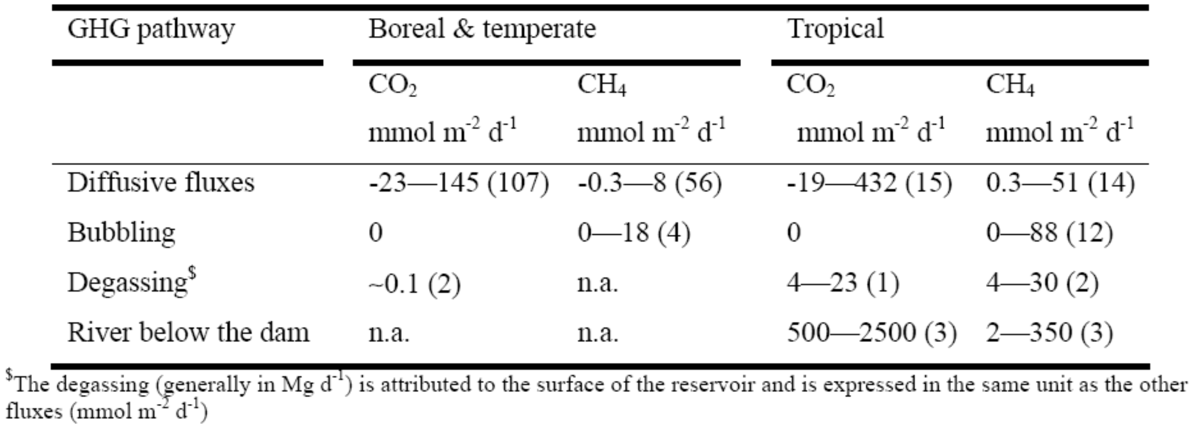
Like all other energy and water management options, hydropower projects do have up and down sides. On the environmental side, hydropower offers advantages on the macro-ecological level, but shows a significant environmental foot print on the local and regional level. With respect to social impacts, a hydropower scheme will often be a driving force for socio-economic development, yet a critical question remains on how these benefits are shared. (5.6)

Most environmental impacts of hydropower generation will be related to changes in the hydrological regime of the river, i.e. the physical and biological changes caused by variations in flow and water level. The magnitude of these changes can be mitigated by proper power plant operation and discharge management, regulating ponds, information and warning systems as well as access limitations. There is also a trend to incorporate ecological minimum flow considerations into the operation of water control structures as well as increasing needs for flood and drought control. Major changes in the flow regime may entail modifications in the estuary, where the extent of salt water intrusion depends on the freshwater discharge. Another impact associated with dam construction is decreased sediment loading to river deltas downstream from large reservoirs for example the Nile delta.

While not all hydropower plants do have a reservoir, it is the impoundment of land which has the most important adverse impacts. Water quality may be affected, with the absence of oxygen contributing, especially in warm climates, to the formation of methane in the first years after impoundment. Impacts on biological diversity and migratory fish species also require careful consideration during the project planning phase. For example, improvements in turbine design, spillway design or overflow design have proven to successfully minimize fish injury or mortality rates.

One of hydropower's main environmental advantages is that it creates no atmospheric pollutants or waste. Over its life cycle, a hydropower plant generally emits much less CO2 than most other sources of electricity. (5.6) Lifecycle assessments that evaluate GHG emissions of HPP during construction, operation and maintenance, and dismantling, estimate the amount of CO2 – equivalent emitted to be between 11-15g CO2eq/kWh. Such emission estimates, stemming from mainly temperate and Nordic reservoirs, rank very low compared to those of thermal power plants, which would typically be in the range of 500-1000 g CO2eq /kWh. However, all freshwater systems, whether they are natural or man made, emit greenhouse gases such as CO2 and methane (CH4) due to decomposing organic material (Table TS 5.2). While some natural water bodies and freshwater reservoirs may even absorb more GHG than they emit there is a definite need to properly assess the net change in GHG emissions induced by the creation of such reservoirs. The challenge is to improve the understanding of reservoir induced impacts, excluding unrelated anthropogenic sources as well as natural GHG emissions from the watershed. (5.6.3)

Table TS 5.2 Range of gross CO2 and CH4 emissions from hydroelectric freshwater reservoirs. Numbers in parentheses are the number of studied reservoirs (UNESCO-RED, 2008).



GHG pathway	Boreal & temperate		Tropical	
	CO_2 mmol m^{-2} d^{-1}	CH_4 mmol m^{-2} d^{-1}	CO_2 mmol m^{-2} d^{-1}	CH_4 mmol m^{-2} d^{-1}
Diffusive fluxes	-23—145 (107)	-0.3—8 (56)	-19—432 (15)	0.3—51 (14)
Bubbling	0	0—18 (4)	0	0—88 (12)
Degassing$^{\$}$	~0.1 (2)	n.a.	4—23 (1)	4—30 (2)
River below the dam	n.a.	n.a.	500—2500 (3)	2—350 (3)

$^{\$}$The degassing (generally in Mg d^{-1}) is attributed to the surface of the reservoir and is expressed in the same unit as the other fluxes (mmol m^{-2} d^{-1})

Hydropower has been a catalyst for economic and social development of several countries. According to the World Bank, large hydropower projects can have important multiplier effects creating an additional 40-100 cents of indirect benefits for every dollar of value generated. Hydropower can serve both in large centralized and small isolated grids. Small scale hydro can easily be implemented and integrated into local ecosystems and might be one of the best options for rural electrification for instance in isolated grids, while large urban areas and industrial scale grids need the flexibility and reliability of large scale hydro.

Thus on the positive side, hydropower often fosters socio-economic development, not only by generating electricity but also by facilitating through the creation of freshwater storage schemes along with other multiple water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries while protecting against floods and droughts. Yet, inevitably questions arise about the sharing of these revenues among the local affected communities, government, investors and the operators. Key challenges in this domain are the fair treatment of affected communities and especially vulnerable groups like indigenous people, resettlement if necessary and public health issues, as well as appropriate management of cultural heritage values. (5.6)

Each hydropower plant is a unique product tailored to the specific characteristics of a given geographical site and the surrounding society and environment. Consequently, the magnitude of environmental and social impacts as well as the extent of their positive and negative effects is rather site dependent. For this reason the mere size of a hydropower plant is not a relevant criterion to anticipate impacts. (5.6) Good experience gained during past decades in combination with new sustainability guidelines, innovative planning based on stakeholder consultations and scientific know-how is promising to secure a high sustainability performance in future hydropower projects. Transboundary water management, including hydropower projects, establishes an arena for international cooperation that may contribute to promote peace, security and sustainable economic growth. Ongoing research on technical and environmental issues may ensure continuous improvement and enhanced outcomes for future projects.

Prospects for Technology Improvement and Innovation

With hydropower being a mature technology, most components have been tested and optimised during long term operation. Large hydropower turbines are now close to the theoretical limit for efficiency, with up to 96% efficiency. Older turbines can have lower efficiency by design or reduced efficiency due to wear from sediments. It is therefore a potential to increase energy output by retrofitting new equipment with improved efficiency and usually also with increased capacity. Most of the existing hydropower equipment in operation today will need to be modernized during the next two decades, opening up for improved efficiency and higher power and energy output. (5.7)

There is much ongoing research aiming to extend the operational range in terms of head and discharge, and also to improve environmental performance, reliability and reduce costs. Some of the promising technologies under development are variable speed and matrix technologies, fish-friendly, hydrokinetic and abrasive resistant turbines, and tunnelling and dam technologies. Most of these new technologies under development aim at utilizing low (< 15m) or very low (< 5m) head, opening up many sites for hydropower that have not been possible to use by conventional technology. As most of the data available on hydropower potential is based on field work produced several decades ago, when low head hydro was not a high priority, existing data on low head hydropower potential may not be complete. (5.7)

Cost Trends

Hydropower requires relatively high initial investment, but has the advantage of very low operation costs and a long lifespan. Its life-cycle costs are deemed low and it is a cost competitive renewable energy source. For comparison to other energy sources (renewable and thermal) the Levelized Cost of Energy (LCOE) can be used.

The most important parameters for determining LCOE are: 1) Investment cost, 2) Load factor, 3) Operation and maintenance cost, 4) Depreciation period and 5) Interest rate. Investment costs are very site specific and ranges from as low as 500 $/kW to more than 5 000 $/kW.

Once built and put in operation, hydropower usually requires very little maintenance and operation costs can be kept low. O&M costs are usually given as % of investment cost per kW and may be taken typically as 2.5%. The load factor will depend on hydrological characteristics and regulation (storage) capacity, and values vary from below 40% to near 60%.

Depreciation period is the number of years (“Lifetime”) the station is expected to be fully operational and contributing to production and income. For hydropower, and in particular large hydropower, the largest cost components are civil structures with very long lifetime, like dams, tunnels, canals etc. Electrical and mechanical equipment, with much shorter lifetime, usually contributes less to the cost. For large hydro a typical lifetime ranges from 40 to 80 years.

Interest rate on investment is a critical parameter, in particular for renewable technologies where the initial investment costs dominates in the calculation of LCOE.

There is still a large untapped potential for new hydropower development up to the assumed economic potential of ca. 9000 TWh/year. It is reasonable to assume that in general projects with low cost will be developed first, and as the best projects have been developed, increasingly costly projects will be used. Very expensive project will usually have to wait and possibly be used at a later stage.

Considering the investment cost structure distribution for mostly large projects and mixture of small and medium size projects (5.8.1), it seem reasonable to assume a gradually increasing cost from today and up to 2050. A typical investment cost can be 1500 $/kWh in 2010 (range 1000 to 2000 $/kW), increasing to 2000 $/kWh in 2030 and 2500 $/kWh in 2050, as the more favorable projects have been developed. A summary of the results are given in Table TS 5.3 below:

Table TS 5.3 [TSU: Table caption missing].

Interest rate/Depreciation period	Investment cost in US$/kW	O&M cost in %	Full load hours	LCOE cent/kWh	Comments
3% interest rate 40 year depreciation period	1500 $/kW in 2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5% 2.5%	3950 3950 3950	2.6 3.5 4.3	Projects with lowest cost implemented first Increasing cost for remaining projects
7% interest rate 40 year depreciation period	1500 $/kW in 2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5% 2.5%	3950 3950 3950	3.8 5.1 6.3	Projects with lowest cost implemented first Increasing cost for remaining projects
10% interest rate 40 year depreciation period	1500 $/kW in 2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5% 2.5%	3950 3950 3950	4.8 6.4 8.1	Projects with lowest cost implemented first Increasing cost for remaining projects

These values are well within the range of cost estimates given by WEO 2000/2004 and the various analyses published by IEA and other (Table 5.6 in 5.8.1).

For hydropower stations serving multi-purpose like irrigation, flood control, navigation, roads, drinking water supply, fish, and recreation, the cost, especially for the reservoir, should be shared with the other users/purposes. Many of the purposes cannot be served alone due to consumptive nature and different priority of use. (5.8.2, 5.10)

Potential Deployment

In addition to mitigate global warming, hydropower with storage capacity can also mitigate freshwater scarcity by providing water security during lean flows and drought in dry regions of the world. By 2035, it is projected that 3 billion people will be living in conditions of severe water stress. Water, energy and climate change are inextricably linked. Water storage facilities have an important role in providing energy and water for sustainable development. It is anticipated that climate change will lead to modifications of the hydrological regimes in many countries, introducing additional uncertainty into water resources management. In order to secure water and energy supply in a context of increasing hydrological variability, it will be necessary to increase investment in infrastructure sustaining water storage and control.

Renovation, modernisation & upgrading (RM&U) of old power stations is cost effective, environmentally friendly and requires less time for implementation(5.3.4). There is a substantial potential for adding hydropower generation components to existing infrastructure like weirs, barrages, canals and ship locks.

So far, only one third of the economically feasible hydropower potential has been developed across the world (e.g. 3 000 TWh/year out of ~9 000 TWh/year). The different long term prospective scenarios propose a significant increase for the next decades. For the near-time projections (2015) it is estimated a growth to between 3692 and 3887 TWh/year. For 2030, the global hydropower generation capacity is projected between 4 680 TWh to more than 6 454 TWh as an annual generation, depending on assumptions regarding carbon mitigation scenarios. For 2050, estimates of potential deployment of new hydropower range from 3000 to 6000 TWh/year, compared to present level (5.9.2).

The European Union has developed most of its feasible potential but there are however several possibilities to increase its hydropower capacity: rehabilitation and refurbishment of the existing units, development of small hydropower, and possible new large plants to fulfil the EU RES targets. In Eurasia the remaining potentials are mostly located in Russia and Turkey. (5.9.4)

In North America, even though a large amount of the feasible potential has been developed so far, Canada (and also United States of America) is likely to continue to develop their potential considering national laws on RES, and GHG constraints. In South and Central America**,** the growth will be mainly driven by Brazil, but also several other countries such as Peru, Ecuador, Chile and Colombia will contribute to the increase. (5.9.4)

In Africa, less than 10% of the feasible potential has been developed. The development will rely mainly on countries such as the Democratic Republic of Congo, Ethiopia, Cameroon, Sudan, Uganda, Zambia and Mozambique. In the Asia Pacific region, growth will be mainly driven by China and India. There will also be a significant increase in the Mekong basin (Laos, Myanmar, etc.) and in the Himalaya area (Bhutan and Nepal). (5.9.4)

To achieve these levels there are no real technical and markets challenges, compared to other non mature RES technologies. Even the highest estimates for long-term hydro production are within the global resource estimates presented in section 5.2, suggesting that technical resource potential is unlikely to be a barrier to hydro deployment. On a regional basis, however, higher deployment levels may begin to constrain the most economical resource supply in some regions. (5.9.4).

While efforts may be required to ensure an adequate supply of labour and materials during a long period (for instance more than 40 GW were installed in 2008, which is equivalent to the highest annual long-term IEA forecast scenario in its 450 ppm scenario WEO-2008), no fundamental long-term constraints to materials supply, labour availability, or manufacturing capacity are envisioned if policy frameworks for hydro are sufficiently attractive. (5.9.5)

Integration into water management system

Water, energy and climate change are inextricably linked. These issues must be addressed in a holistic way and it is not practical to look at them in isolation. Providing energy, food and water for sustainable development requires global water governance. As it is often associated with the creation of water storage facilities, hydropower is at the crossroads of these stakes and has a key role to play in providing both energy and water security. Therefore hydropower development is part of water management systems as much as energy management systems, both of which are increasingly climate driven. (5.10)

In order to increase security of supply for water and energy, both within the current climate and in a future with increasing hydrological variability, it will be necessary to increase investment in infrastructure for water storage and control. This is stated in one of the main messages in the World Bank Water Resources Sector Strategy. The need for climate driven water management is often repositioning hydro development as a component of multipurpose water infrastructure projects. (5.10.1)

Creating reservoirs is often the only way to adjust the uneven distribution of water in space and time that occurs in the unmanaged environment. Reservoirs add great benefit to hydropower projects, because of the possibility to store water (and energy) during periods of water surplus, and release the water during periods of deficit, making it possible to produce energy according to the demand profile. This is necessary because of large seasonal and year-to-year variability in the inflow. Such hydrological variability is found in most regions in the world, and it is caused by climatic variability in rainfall and/or air temperature. Most reservoirs are built for supplying seasonal storage, but some also have capacity for multi-year regulation, where water from two or more wet years can be stored and released during a later sequence of dry years. The need for water storage also exists for many other types of water-use, like irrigation, water supply, navigation and for flood control. Reservoirs, therefore, have the potential to be used for more than one purpose. About 75% of the existing 45,000 large dams in the world were built for the purpose of irrigation, flood control, navigation and urban water supply schemes. Only about 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multi-purpose reservoirs (5.10.2).

Since the majority of dams do not have a hydropower component, there is a significant market for increased hydropower generation in many of them. A recent study in the USA indicated some 20 GW could be installed by adding hydropower capacity to the 2500 dams that currently have none. New technology for utilizing low heads also opens up for hydropower implementation in many smaller irrigation dams (5.10.2).

Ocean Energy

Resource Potential

Ocean Energy can be defined as energy derived from technologies, which utilize sea water as their motive power or harness the chemical or heat potential of sea water. The renewable energy resource in the ocean comes from five distinct sources, each with different origins and each requiring different technologies for conversion. These resources are:

Wave energy – derived from wind energy kinetic energy input over the whole ocean. The total theoretical wave energy resource is 32,000 TWh.

Tidal rise and fall – derived from gravitational forces of the earth-moon-sun system. The world theoretical tidal power potential is in the range of 1 -3 TW located in relatively shallow waters (Charlier and Justus, 1993). The world's largest ocean energy power plant is the 240 MW La Rance Barrage in Brittany. A 254 MW tidal barrage is due to open at Sihwa Lake in the Republic of Korea later in 2010. At least 21 GW of tidal barrage developments are under consideration worldwide.

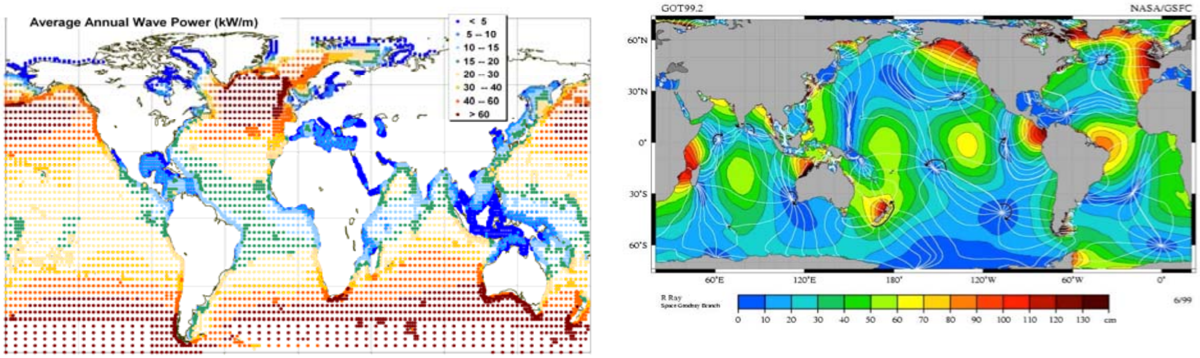
Tidal and ocean currents – derived from tidal energy or from wind driven (thermo-haline) ocean circulation. A total of 106 promising locations for utilization of tidal currents have been identified in Europe alone and it was estimated that, using present-day technology, these sites could supply 48 TWh/y to the European electrical grid network. In China it has been estimated that 7,000 MW of tidal current energy are available. Locations with high potential have also been identified in the Philippines, Korea, Japan, Australia, Northern Africa and South America. The best-characterized system of ocean currents is the Gulf Stream, of which the Florida Current has potential for 25 GW of electricity generation.

Ocean thermal energy conversion (OTEC) – derived from solar energy stored as heat in ocean surface layers centres. An optimistic estimate of the global resource is 30,000 to 90,000 TWh. Submarine geothermal energy – hydrothermal energy at mid-ocean ridges - may be a future source of ocean heat energy.

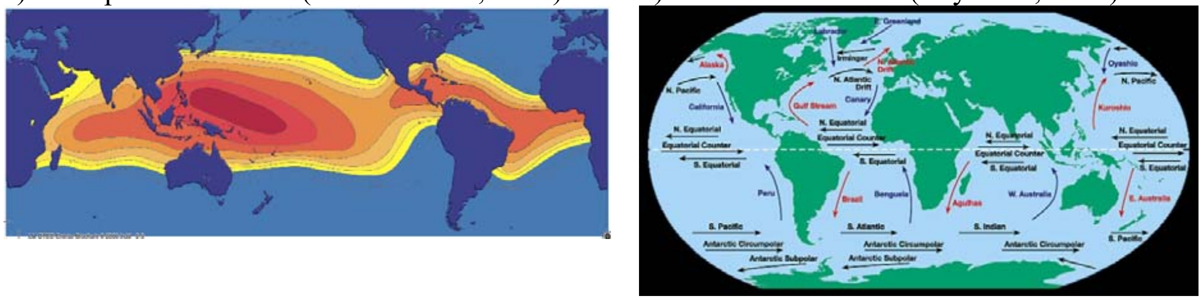
Salinity gradients – derived from salinity differences between fresh and ocean water at river mouths (also called 'osmotic power'). The annual generation potential of osmotic power has been calculated as 1,650 TWh. In Europe alone there is a potential to generate 180 TWh (6.1, 6.2).

The energy resources contained in the world's oceans easily exceed present human energy requirements and the energy could be used not only to generate and supply electricity but also for direct potable water production. Some potential ocean energy resources, such as ocean currents or osmotic power from salinity gradients, are globally distributed, other forms have a complementary distribution. Ocean thermal energy is principally distributed in the Tropics around the Equator (0° - 35°), whilst the highest annual wave power occurs between latitudes of 40° - 60°. Wave power in the Southern Hemisphere undergoes smaller seasonal variation than in the Northern Hemisphere. Ocean currents, ocean thermal energy, osmotic power and, to some extent, wave energy are consistent enough to generate base load power.

The following maps the description of global annual spectral wave power (in kW/m of wavefront, global energy distribution, global tidal rise and fall, global ocean thermal energy resources (in °C) and distribution of global surface ocean currents (Figures TS 6.1a-d).



a) Wavepower in kW/m (Barstow et al., 2008) b) Tidal Rise and Fall (Ray et al., 2009)



c) Ocean Thermal Energy (Lockheed-Martin, 2009) d) Ocean Currents – warm in red, cold in blue (UCAR, 2009)

Figure TS 6.1 Description of a) global annual wavepower, b) global energy distribution, c) global ocean thermal energy resources and d) global ocean currents distribution.

Technology and Applications

There is presently no convergence on a single design for ocean energy converters due to botht he range of different resources, immaturity of present technologies and a fundamental lack of operating experience (6.3.1). Given the range of options for harnessing different forms of ocean energy, there will never be a single device design, as there is for wind energy.

Wave energy technologies can be classified into three groups: oscillating water columns (shore-based, floating), oscillating body (surface buoyant, submerged), and overtopping devices (shore-based, floating). Oscillating water columns use wave motion to trap a volume of air and compress it in a closed chamber, where then exhausts through a specialized air turbine generating electricity. Oscillating bodies are commonly devices, which use swell wave movements to generate differential motions between two bodies of different mass, from which motion power can be generated. Overtopping devices collect surging waves into a water reservoir at a level above the free water surface, which then drains down through a conventional low-head hydraulic turbine (6.3.2).

Tidal rise and fall energy can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations, where a barrage encloses an estuary, which creates a single basin reservoir behind it. The barrage may generate electricity on both the ebb and flood tides. Some future barrages may have multiple-basin mode to enable continuous generation. The most recent technical advances are stand-alone offshore "tidal lagoons" (6.3.3).

Technologies to harness power from rivers and tidal/ocean currents are also under development but tidal energy converters are more advanced. Some of the tidal/ocean current energy technologies are similar to mature wind turbine generators but submarine turbines must also account for reversing flow, cavitation at blade tips and harsh underwater marine conditions (e.g., salt water corrosion, debris, fouling, etc). Tidal currents tend to be bidirectional, varying with the tidal cycle, and relatively fast-flowing, compared with ocean currents, which are usually unidirectional, slow-moving but continuous. The main difference river and ocean current turbines generally deal with currents flowing in a single direction, whilst tidal current turbines must deal with reversing flow directions two or four times per day during ebb and flood cycles. Usually, they are classified based by their principle-of-operation into axial flow turbines, cross flow turbines and reciprocating devices (6.3.4).

Ocean thermal energy conversion (OTEC) plants use temperature differences of seawater from different depths (warm water from the surface, cool water (from >1,000 m depth) to produce electricity. Open-cycle OTEC systems use seawater as the circulating fluid, whilst closed-cycle systems use heat exchangers and a secondary volative working fluid to drive a turbine. They are believed to present the best solution in terms of thermal performance (6.3.5). Hybrid systems use both open- and closed-cycle systems.

The salinity gradient between freshwater from rivers and seawater can be utilised as a source of power. At least two concepts for converting this energy into electricity are under development: Reversed Electro Dialysis (RED) and Pressure Retarded Osmosis (PRO), also known as ‘osmotic power’. The Reversed Electro Dialysis (RED) process is a concept where the difference in chemical potential between two solutions is the driving force. The PRO or osmotic power process utilises naturally occurring osmosis – a hydraulic pressure potential, caused by the tendency of fresh water to mix with seawater by the difference in salt concentration of salt (6.3.6).

Global and Regional Status of Markets and Industry Development

Excepting tidal barrages, all ocean energy technologies are conceptual or are presently under research and development. The most mature technologies have reached pre-commercial prototype stage. Consequently, there is no present commercial market for ocean energy technologies. Nevertheless, worldwide developments of devices are accelerating with, for instance, well over 100 prototype wave and tidal current devices under development.

The principal investors in ocean energy R&D and deployments are national, federal and state governments, followed by major national energy utilities and investment companies. By contrast, the principal form of device developer is a private small- or medium-scale enterprise (SME). There is encouraging uptake and support from these major investors into the prototype products being developed by the SMEs.

National and regional governments are particularly supportive of ocean energy through a range of financial, regulatory and legislative initiatives to support developments, including:

1. Targets for installed capacity or contribution to future supply
2. R&D funds, capital grants and financial incentives, including prizes
3. Market incentives, including feed-in tariffs and supply obligations
4. Research and testing facilities and infrastructure
5. Permitting/space/resource allocation regimes, standards and protocols (6.4.7).

Presently northwestern European coastal countries lead development of ocean energy technologies with North American, northwestern Pacific and Australasian countries also involved (6.4.2.1).

Industrial development of ocean energy is at a very early stage and there is no true manufacturing industry for ocean energy technologies at present. But the growth of interest may lead to the transfer of capacity, skills and capabilities from related industries, combine with the development of new skills and capabilities (6.4.1.2). One unusual feature of ocean energy is the development of national marine energy testing centres, as exemplified by the European Marine Energy Centre (EMEC)[1]. These centres are becoming foci not only for device testing and certification but also for R&D.

Ocean energy technologies for power production range mostly from the conceptual stage to the prototype stage, but few technologies have matured to commercial availability (Table TS 6.1). Over the past four decades, other marine industries (primarily petroleum industry) have enabled significant advances in the fields of offshore materials, offshore construction, corrosion, undersea cables, data and communications. Ocean energy can directly benefit from these advances (6.3.1).

Table TS 6.1: Selected ocean energy devices in operation/under development [TSU: Reference is missing]

Type of Ocean Energy Technology	Subtype	Size of Device	Name of Device	Device Developer	Country	Operational Since	Notes
Wave Energy	shore-based OWC				Portugal	1999	occasionally operational
			LIMPET	Wavegen	Scotland	2000	almost continously operational
	offshore OWC			Energetech/ Oceanlinx	Australia	2006	prototype scale, one device per company
				OE Buoy	Ireland	2007	prototype scale
	OB	750 kW	Pelamis Wavepower	Pelamis	Scotland/Portugal		most advanced OB, device sold as part of commerical project, next device under development
		40 - 150 kW	Power Buoy	Ocean Power Technologies	Hawaii, US eastern seabord, north Spanish coast		vertical axis type, one device in each location
			Wavebob		Ireland	-	under development
				Wave Energy Technology	New Zealand	-	under development
	OT		Wave Dragon		Denmark		prototype scale
			WavePlane		Denmark		prototype scale
Tide Rise and Fall	estuarine barrage	240 MW	LaRance		France	1996	24 x 10 MW bulb-type turbines
		3.2 MW			China	1980	
		20 MW			Canada	1984	
		0.5 MW			Russia	2004	
		254 MW	Sihwa		Korea	2010 (tbc)	retrofit to an existing 12.7 km sea dyke
	estuarine barrage, tidal lagoon (offshore basin)	5 - 11,400 MW (total over 47 GW)	16 projects		Australia, Canada, India, Korea, Russia, UK	planned	
Tidal and Ocean Currents	tidal turbine		SeaGen		Northern Ireland		most advanced tidal turbine
OTEC	floating OTEC		2 devices		India		mainly fresh water production, fuelled by diesel
	land-based OTEC				Kavaratti, India??		fresh water production
	floating, closed cycle	53 kW (18 kW in operation)	Mini-OTEC		USA	1979	
		1 MW (rated)	OTEC-1		USA	1981 (four month)	no turbine
	open-cycle OTEC	205 kW (peak production 103 kW)			USA (Hawaii)	1993 - 1998	
	closed-cycle (Freon)	120 kW (peak production 31.5 kW)			Japan (Nauru)	for several month	
		several smaller			Japan	not kept operational long-term	
	hybrid OTEC	30 kW			Japan	during 2006	able to produce electricity
	land-based, hybrid OTEC	10 MW		Sea Solar Power			under development, closed-cycle (propylene), open-cycle for fresh water production
	floating, hybrid OTEC	100 MW		Sea Solar Power			under development, closed-cycle (propylene), open-cycle for fresh water production
Salinity Gradient	Osmotic Power			Statcraft	Norway	2009	demonstration plant

Environmental and Social Impacts

General environmental concerns about ocean energy devices include the effects of deployment, operation and maintenance (O&M) and decommissioning on local flora and fauna and the alteration of the physical environment. Noise/vibration and hydrodynamic impacts are more specific issues, as are electromagnetic fields, produced by cables transmitting power to shore (6.5.1).

Ocean energy technologies do not generate greenhouse gases in operation – a substantial benefit for climate change mitigation.

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[1] www.emec.org.uk

The key social impact will be competition for and potential loss of space for other uses around deployment sites, including fishing, navigation and recreational activities (6.5.1, 6.5.3). Each ocean power technology has its own set of environmental and social impacts.

Tidal barrages are usually located across estuaries, which are complex, dynamic and potentially fragile environments. Although the La Rance estuary was closed during construction of the La Rance barrage, biodiversity - comparable to that of neighbouring estuaries - was restored within 10 years after commissioning, thanks to the responsible operating mode at the power station. The environmental impacts of the Sihwa Lake tidal power plant should be limited since the tidal flow will refresh an increasingly brackish lake (6.5.3). A barrage is a massive construction and not easily removed. Coast-attached wave energy devices also face this challenge of reversibility (6.5.1).

A key concern with tidal current technologies is that they have moving parts (blades), which may harm marine life. To date there is no evidence of harm to marine life from such devices, probably due to slow rotational speeds (relative to escape velocities of the marine fauna) and the passive nature of the rotating device.

Full-scale commercial deployments of open-ocean current electric generating systems could present certain environmental risks. These can be grouped into four broad categories: the physical environment (the ocean itself), benthic (ocean-bottom) communities, pelagic marine life (in the water column), and commerce. None of these has been fully evaluated, since no prototype ocean current devices have yet been deployed (6.5.4.2).

The principal environmental impacts of ocean energy thermal conversion (OTEC) plants will be the outflow of significant volumes of exotic cold water (OTEC) from these plants (6.5.1). Other social and environmental impacts from OTEC include: chemical pollution (biocides, working fluid leaks, corrosion), structural effects (on artificial reef, nesting/migration), social effects (6.5.5).

Similarly, the principal environmental impact of osmotic power will be the mixing of freshwater and seawater at the power plant, which are likely to be built at large river mouths, with sufficient volumes of freshwater. However, the volume of mixed brackish water produced osmotic power plants will be considerably smaller than the natural mixing that occurs at river mouths (6.5.6).

The social benefits of ocean energy are potentially high, rejuvenating shipping and fishing industries, supplying electricity and/or drinking water to remote communities at small-scale or utility-scale deployments with transmission grid connections to displace aging fossil fuel generation plants. Social benefits may be national – the creation of new industries, redirection of resources from declining industries; regional – industry rejuvenation, developments of business clusters, and individual - new employment opportunities, training for new skills and development of new capabilities (6.5.1).

Prospects for Technology Improvement, Innovation and Integration

Ocean energy technology developers are keen to gain operating experience, so that engineering practices and technology development can advance. Performance improvements and increased reliability are key for most ocean energy technologies. Future developments are likely to focus on up-scaling to the largest practical machine size, minimizing downtime, operation and maintenance (O&M) efforts, reducing installation and decommissioning costs and limiting mooring and substructure requirements. Device design and materials selection to limit or resist degradation by corrosion, cavitation, water absorption, bio-fouling and debris impacts are of crucial importance (6.6.1, 6.6.3, 6.6.4).

Rotor diameters of ocean and tidal current technologies are likely to increase to maximize swept area and thus power extraction. New operating control strategies will be developed to resist extreme loads and mitigate fatigue damage. Axial-flow water current turbines, which harness energy from water currents have operating principles similar to widely-used horizontal-axis wind turbines (6.6.3). They may have developmental advantage over other designs, e.g., cross-flow turbines or reciprocating devices). Enhancing energy extraction from bidirectional flows directions will improve tidal current turbine performance (6.6.2, 6.6.3).

Tidal rise and fall power projects differ from most other ocean energy technologies because they are based on proven hydroelectric technologies, albeit built and operated in an estuarine rather than a riverine environment. Nonetheless are improvements can still be achieved by:

1. Construction of very large offshore facilities
2. Use of multiple basins to increase the value of projects by reducing the intermittency of generation, and
3. Improvements of general turbine efficiency and, more specifically, generation efficiency in both flow directions.

Technologies may be further improved with gears, permitting different rotation speeds for the turbine and the generator, or with variable frequency generation, creating better outputs for the various operating ways and heads (6.6.2).

The heat exchanger system and cold-water inlet pipe are the most important components of the closed-cycle ocean thermal energy conversion (OTEC) power plants. Most research efforts are directed toward some special subjects related to the heat exchanger, in particular its construction material and working fluid, because its share of total plant cost of 20 - 40%. The cold-water inlet pipe is also critical but experience obtained in the last decade with risers for oil & gas production is being transferred to design of these large diameter pipes (6.6.4).

Research in osmotic power will mainly be focussed on membrane modules, pressure exchanger equipment and power generation equipment (i.e., the turbine and generator) to increase efficiency. There will also be a focus on further development of control systems, water pre-treatment equipment, as well as infrastructure around the water inlets and outlets (6.6.5).

Cost Trends

It is difficult to accurately assess the economic viability of most ocean energy technologies, because none but tidal barrages are mature and very little experience is available for validation of demonstration/prototype devices. Future cost reductions can only be demonstrated theoretically, since there are few operating devices and little operating experience.

Present capex costs can be determined directly from prototypes in the water but these are higher than commercial capex costs (6.7.1). Realistic performance (energy capture) estimates and operation and maintenance (O&M) costs (6.7.2) are difficult to estimate for lack of experience. Levelized cost of energy (LCOE) projections by technology developers are frequently unreliable (6.8.1). Future LCOE estimates rely on learning curve reductions experienced in other sectors, such as the wind energy sector. The following table (Table TS 6.2) shows estimates of the costs of various ocean energy technologies.

Reliable cost estimates for ocean power generation are therefore unavailable. However, cost trends should closely follow that of tidal current technology (6.7.4). Concrete estimates for costs of estuarine barrages, tidal lagoons are also missing. Nonetheless, it can be said that upfront costs are high due to expensive construction in marine environments and long construction times (6.7.3).

Table TS 6.2: Cost estimates from various studies for different ocean energy technologies

		Current Cost Parameters[1]					Future Cost Parameters			
Source of Cost Data	**Type of Ocean Energy Technology**	**Capex (US$/kW)**	**O&M Costs (US$/kW)**	**Discount Rate in %**	**Capacity Factor in %**	**LCOE (US¢/kWh)**	**LCOE (US¢/kWh)**	**Required Cumulative Capacity in MW**	**Learning Rate**	**Notes**
Vega (2002)	OTEC	12,300	NA	-	-	0.22	-	-	-	100 MW closed-cycle, 400 km from shore
SERI (1989)		12,200	NA	-	-	-	-	-	-	40 MW plant planned at Kahe Point, Oahu
Cohen (2009)		8,000 - 10,000	NA	-	-	0.16 - 0.20	0.08 - 0.16	-	-	100 MW early commercial plant
Francis (1985)		5,000 - 11,000	NA	-	-	-	-	-	-	-
Lennard (2004)		9,400	NA	-	-	0.18 (0.11)	-	-	-	10 MW closed-cycle; LCOE in parenthesis apply if also producing potable water
SERI (1989)		7,200	NA	-	-	-	-	-	-	Onshore, open-cycle
Vega (2002)		6,000	NA	-	-	0.10	-	-	-	100 MW closed-cycle, 100 km from shore
Vega (2002)		4,200	NA	-	-	0.07	-	-	-	100 MW closed-cycle, 10 km from shore
Scråmestø et al., 2009	Salinity Gradient Power	High	-	-	70%	5 - 10	-	-	-	
CEC (2009)	Tidal Current	-	-	-	-	10 - 30	-	-	-	Cost estimate for California
Callaghan (2006)		8,571 - 14,286	-	-	-	16.1 - 32.1	0.046	2,800	-	Prototype, cost assessment for UK
Callaghan (2006)	Wave Energy	7,679 - 16,071	-	-	-	21.4 - 78.8	-	-	-	PSrototype and pre-commercial devices, cost assessment for UK
Previsic (2004)		2620	123	7.5	38%	-	13.4 (2020)	-	-	106.5 MW capacity, 213 devices x 500 kW, 20-year life, 95% availability, R&D improvement

[1] Cost estimates for OTEC technologies are in different-year dollars and cover a range of different technologies and locations. Many are also highly speculative.

The Marine Energy Challenge study by the UK Carbon Trust demonstrated that the initial LCOE of tidal stream-generated electricity in the UK could be high with 14.3 US¢/kWh but this cost could reduce to 4.46 US¢/kWh by the time installed capacity had reached 2,800 MW.

Potential Deployment

Full-size floating wave energy prototypes are being deployed at specific test sites in various countries, including Norway, UK, Ireland, France, Spain and Portugal. Government-funded financial support is fundamental to facilitating the construction and testing of full-scale prototypes in open sea (6.8.1).

The world's largest tidal power plant (254 MW) is currently under construction at Sihwa in Republic of Korea. Korea has also announced other larger tidal plants, for example, a 520 MW barrage planned for Garolim Bay. In the United Kingdom the 14 m tidal range in the Severn Estuary has long been considered, as one of the greatest tidal sources to be harnessed. The British Government is currently considering ten proposals from a public call for proposals in May 2008 ranging from 624 MW to 14.8 GW. (6.8.2).

A number of other large tidal stream developments are planned over the next five years, based on 1 to 1.5 MW turbines from different manufacturers. Despite little convergence in design options to harness energy from tidal and ocean streams, submarine current devices are beginning to dominate. The deployment of tidal current devices is likely to be areally restricted. The best locations for such deployments include Canada (Bay of Fundy, Vancouver Island), Scotland (Pentland Firth), Wales (Anglesey), Korea (Uldulmok) and New Zealand (Cook Strait). Ocean currents are much more widespread than tidal currents but generally operate at slower speeds, which may be too slow for most early devices (6.8.3).

For the near-to-mid-term, the potential to use OTEC power is concentrate near appropriate markets, rather than any constraints on the resource. Larger floating-platform OTEC plants sending electricity to shore by submarine cable are likely to be limited to locations with large seawater temperature differentials close to shore and large coastal populations nearby. In the long term, ‘grazing’ plant ships could conceivably begin to approach resource limits but more likely would be limited by ability of economies to utilize ammonia or other “high-energy products” directly or indirectly for transportation fuel or other purposes (6.8.4).

The Statkraft prototype osmotic power plant, which became operational in October 2009, is an important milestone following several years of research & development (R&D). The operational prototype plant will be used as a basis to develop a pilot plant with an installed capacity between 1 - 2 MW within 2 - 5 years, bringing the technology one step nearer to commercialisation and development of full-scale plants. Given continued technology development and declining prices for components, osmotic power is a realistic technology with worldwide potential for renewable energy generation (6.8.5).

Wind Energy

Introduction

Wind energy has been used for millennia in a wide range of applications. The use of wind energy to generate electricity on a commercial scale, however, began in earnest only in the 1970s. Though different wind energy technologies remain available within a range of applications, the primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either on-shore or off-shore (smaller wind turbines, high-altitude wind electricity, and the use of wind energy in mechanical and propulsion applications are briefly discussed in 7.1). [7.1]

Wind energy offers significant potential for near- and long-term carbon emissions reduction. The wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050 if ambitious efforts are made to reduce carbon emissions and to mitigate the other barriers to increased wind energy deployment. On-shore wind energy is already being deployed at a rapid pace in many countries, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. Moreover, though average wind speeds vary considerably by location, ample technical potential exists in most regions of the world to enable significant wind energy development. In areas with particularly good wind resources, the cost of wind energy can be competitive with fossil generation but, in most regions of the world, policy measures are required to make wind energy economically attractive. Nonetheless, continued advancements in both on- and off-shore wind energy technology are expected, further reducing the cost of wind energy and improving wind energy’s carbon emissions mitigation potential.

Resource potential

The global resource potential for wind energy is not fixed, but is instead related to the status of the technology, the economics of wind energy, and the assumptions made regarding other constraints to wind energy development. Nonetheless, a growing number of global wind resource assessments have demonstrated that the world’s technical potential for wind energy exceeds global electricity demand. [7.2]

The IPCC (2007) has estimated the technical potential for on-shore wind energy at 180 EJ/y, almost three times greater than global electricity demand in 2007. Other estimates of the global technical potential for wind energy range from a low of 70 EJ/y (excluding off-shore) to a high of 1,000 EJ/y (including on- and off-shore); estimates of the potential for off-shore wind energy alone range from 15 EJ/y to 130 EJ/y. This overall range equates to between one and 14 times global electricity demand, and may understate the potential for wind energy due to several of the studies relying on outdated assumptions; the exclusion of off-shore wind energy in a number of the studies; and methodological and computing limitations. As visual demonstration of the impact of advances in assessment methods, Figure TS 7.1 presents two global wind resource maps, one created in 1981 another in 2009. [7.2.1]

Although further advancements in wind resource assessment methods are needed, the technical potential for the resource itself is unlikely to be a limiting factor on global wind energy development. Instead, economic constraints associated with the cost of wind energy, the institutional constraints and costs associated with transmission access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute global resource limit is encountered. [7.2.1]

In addition, ample technical potential exists in most regions of the world to enable significant wind energy development. The wind resource is not evenly distributed across the globe, however, nor uniformly located near population centres, and wind energy will therefore not contribute equally in meeting the needs of every country. The on-shore wind resource in North America and Eastern Europe/CIS, for example, is often found to be particularly sizable, while some areas of Asia and OECD Europe appear to have more limited on-shore potential. Recent, detailed regional assessments have generally found the actual size of the wind resource to be greater than estimated in previous assessments. [7.2.2]

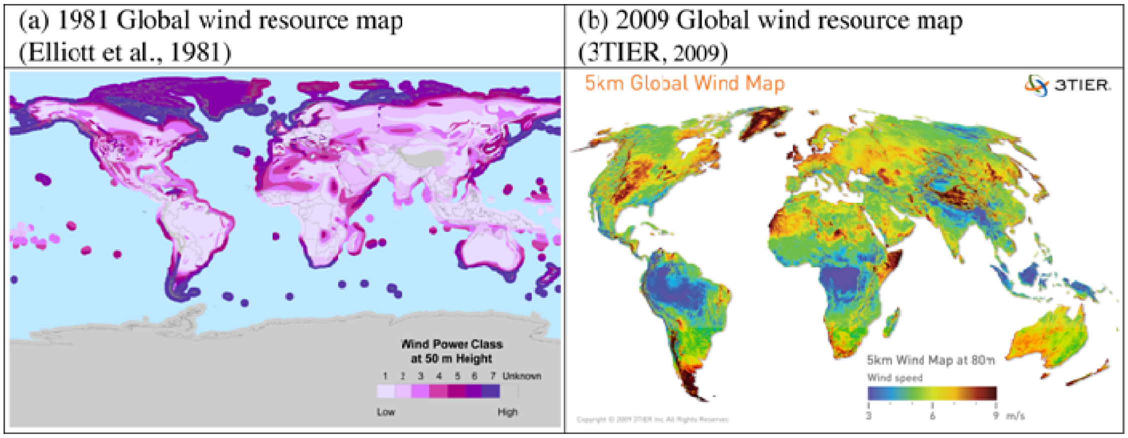


Figure TS 7.1 Example global wind resource maps from 1981 and 2009.

There is increasing recognition that global climate change may alter the geographic distribution and/or the inter- and intra-annual variability of the wind resource, or alter the prevalence of extreme weather events that may impact wind turbine design and operation. Though research in this field is nascent and additional research is warranted, it appears unlikely that multi-year annual mean wind speeds and energy densities will change by more than a maximum of ±25% over most of Europe and North America during the present century. As a result, research to date suggests that, while global climate change will alter the geographic distribution of the wind resource, those effects are unlikely to be of a magnitude to greatly impact the global potential for wind energy to reduce carbon emissions. [7.2.3]

Technology and applications

Modern grid-connected wind turbines have evolved from small, simple machines to large, highly sophisticated devices. Scientific and engineering expertise, as well as computational tools and design standards, have supported these technology developments. [7.3.1]

Generating electricity from the wind requires that the kinetic energy of moving air be converted to electrical energy, and the engineering challenge for the wind industry is to design efficient wind turbines to perform this conversion. Though a variety of wind turbine configurations have been investigated, turbine design now centres on horizontal axis machines with 3-blades positioned upwind of the tower. In order to reduce the levelized cost of wind energy, over the past 30 years, average wind turbine size has grown significantly (Figure TS 7.2), with the largest fraction of land-based wind turbines installed globally in 2009 having a rated capacity of 1.5 MW to 2.5 MW. As of 2010, such turbines typically stand on 50-100 meter towers, with rotors that are often 50-100 meters in diameter; even larger machines are in use and under development. As a result of these developments, on-shore wind energy technology is already viable for large-scale commercial deployment. [7.3.2]

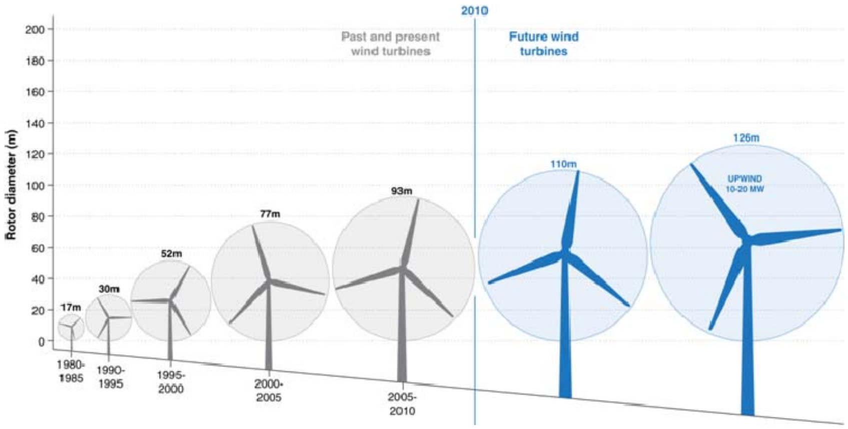


Figure TS 7.2. Growth in size of commercial wind turbines. Source: NREL [TSU: date?]

The off-shore wind energy sector remains relatively immature, but considerable interest exists in the EU and, increasingly, in other regions. This interest is the results of the higher-quality wind resources located at sea; the ability to use larger and more-flexible wind turbine designs; a potential reduction in long-distance, land-based transmission; the ability to build larger power plants; and the potential mitigation of siting controversial. To date, off-shore wind turbine technology has been very similar to on-shore designs, with some modifications and with special foundations. Wind energy technology specifically tailored for off-shore applications will become more prevalent as the off-shore market expands, and it is expected that larger turbines in the 5-10 MW range may come to dominate this market segment. [7.3.2]

Alongside the evolution of wind turbine design, improved testing methods have been codified in International Electrotechnical Commission (IEC) standards. Certification agencies rely on accredited design and testing bodies to provide traceable documentation demonstrating conformity with the standards in order to certify that turbines, components, or entire wind power plants meet common guidelines relating to performance, safety, and reliability. [7.3.3]

From an electric system reliability perspective, an important part of the wind turbine is the electrical conversion system. For new turbines, variable speed machines now dominate the market, allowing for the provision of real and reactive power control and some fault ride-through capability, but no intrinsic inertial response; wind turbine manufacturers have recognized this latter limitation, and are pursuing a variety of solutions. [7.3.4]

Global and regional status of market and industry development

The wind energy market has developed rapidly, demonstrating the commercial and economic viability of the technology and industry. Wind energy deployment has been concentrated in a limited number of regions, however, and further expansion, especially in regions with little wind energy development to date and in off-shore locations, is likely to require additional policy measures. [7.4]

Wind energy has quickly established itself as part of the mainstream electricity industry. From a cumulative capacity of 14 GW by the end of 1999, the global installed capacity increased twelve-fold in ten years to reach almost 160 GW by the end of 2009. The majority of the capacity has been installed on-shore, with off-shore installations focused on Europe and totalling a cumulative 2.1 GW. The countries with the highest installed capacity by the end of 2009 were the United States. (35 GW), China (26 GW), Germany (26 GW), Spain (19 GW), and India (11 GW). Total investment in wind power installations in 2009 alone equalled roughly US$57 billion, while worldwide direct employment in the sector in 2009 has been estimated at 500,000. [7.4.1, 7.4.2]

In both Europe and the U.S., wind energy represents a major new source of electric capacity additions. From 2000 through 2009, wind energy was the second-largest new resource added in the U.S. and EU, while in 2009 roughly 39% of all capacity additions in the U.S. and the EU came from wind energy; in China, 16% of the net capacity additions in 2009 came from wind energy. On a global basis, wind energy represented 11% of net electric capacity additions from 2000 through 2009; in 2009 alone, that figure was likely more than 20%. As a result, a number of countries are beginning to achieve relatively high levels of wind electricity penetration in their respective electric systems. By the end of 2009, wind power capacity was capable of supplying electricity equal to roughly 20% of Denmark's electricity demand, 14% of Portugal's, 14% of Spain's, 11% of Ireland's, and 8% of Germany's. [7.4.2]

Despite these trends, wind generated electricity remains a relatively small fraction of worldwide electricity supply. The total wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand. Additionally, though the trend over time has been for the wind energy industry to become less reliant on European markets, with significant recent expansion in the United States and China, the market remains concentrated regionally: Latin America, Africa and the Middle East, and the Pacific regions have installed relatively little wind power capacity (Figure TS 7.3). [7.4.1, 7.4.2]

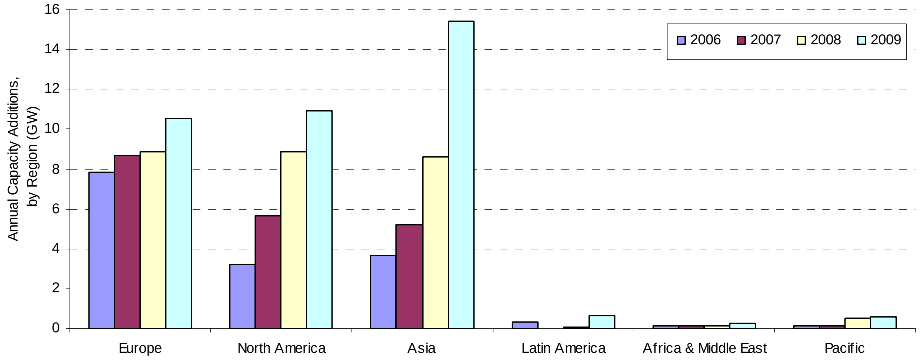


Figure TS 7.3. Annual wind power capacity additions by region (GWEC, 2010a).

The deployment of wind energy must overcome a number of barriers, including: the relative cost of wind energy compared to fossil-fuel generation options; concerns about the impact of wind energy's variability; challenges to building new transmission; cumbersome and slow planning, siting, and permitting procedures; the relative immaturity and therefore high cost of off-shore wind energy technology; and lack of institutional and technical knowledge in regions that have not yet experienced substantial wind energy development. As a result, growth is affected by and responsive to a wide range of government policies. [7.4.4]

Near-term integration issues

As wind electricity penetration levels have increased so too have concerns about the integration of that energy into electric systems. The nature and magnitude of the integration challenge depends on the characteristics of the existing electric system and the level of wind electricity penetration. Nevertheless, the existing literature generally suggests that, at low to medium levels of wind electricity penetration (under 20% of total electricity demand), the integration of wind energy is technically and economically manageable, though institutional constraints will need to be overcome. Concerns about (and the costs of) wind energy integration will grow with wind energy deployment and, even at medium penetration levels, integration issues must be addressed both at the local and system levels through stability and balancing requirements. Even higher levels of penetration may depend on the availability of additional flexible options to maintain a balance between supply and demand. [7.5.1]

Wind energy has characteristics that pose new challenges to electric system planners and operators, including: the localised nature of the wind resource with implications for new transmission; the variability of wind power output; and the lower levels of predictability than is common with conventional power plants. The variability and predictability of wind power output depends, in part, on the degree of correlation in the output between geographically dispersed wind power plants: generally, the output of wind power plants that are further apart are less correlated, and variability over shorter time periods (minutes) is less correlated than variability over longer time periods (multiple hours). Forecasts of wind power output are also more accurate shorter time periods, and when multiple plants are considered together. [7.5.2]

Electric system planners must ensure that generation and transmission are adequate for the reliable operation of the electric system. To do so, planners need computer-based simulation models that accurately characterize wind energy. Additionally, as wind power capacity has increased, so too has the need for wind power plants to become more active participants in maintaining the operability and power quality of the electric system, and minimum interconnection requirements have been implemented to prevent wind power plants from adversely affecting the electric system during normal operation and contingencies. Accurate transmission adequacy evaluations, meanwhile, must account for the location dependence of the wind resource, and significant new transmission infrastructure, both on-shore and off-shore, would be required to access areas with the best wind resource conditions. The institutional challenges of transmission expansion can be substantial. Finally, planners need to account for wind power output variability in assessing the contribution of wind energy toward the long-term reliability of the electric system. The contribution of wind energy to resource adequacy depends on the correlation of wind power output with the periods of time when electric system reliability is at greatest risk, typically periods of high electricity demand. Wind power plants are typically found to have a ‘capacity credit’ of 5-40% of nameplate capacity, with the credit generally decreasing as wind electricity penetration levels rise. The relatively low average capacity credit of wind power plants suggests that electric systems with large amounts of wind energy will also tend to have significantly more total nameplate generation capacity to meet the same peak load than will electric systems without large amounts of wind energy. Some of this generation capacity will operate infrequently, however, and the mix of conventional generation will therefore increasingly shift towards “peaking” resources and away from “baseload” resources. [7.5.3]

[Authors: Need to add some text to explain what the capacity credit means, in layman: something on needing sufficient capacity to serve loads at times of system stress.]

The unique characteristics of wind energy also hold important implications for electric system operations. Because wind electricity is generated with a near-zero marginal operating cost, it is typically used to meet demand when it is available; conventional generators are then dispatched to meet demand minus any available wind energy (i.e., “net demand”). As wind electricity penetration grows, the variability of wind energy results in an overall increase in the magnitude of changes in net demand, and also a decrease in the minimum net demand. As a result of these trends, wholesale electricity prices will tend to decline when wind power output is high, and conventional generating units will be called upon to operate in a more flexible manner than required without wind energy. At low to medium levels of wind electricity penetration, the increase in minute-to-minute variability is expected to be relatively small. The more significant operational challenges relate to the need to manage changes in wind power output over 1 to 6 hours. Incorporating wind energy forecasts into electric system operations can reduce the need for flexibility and operating reserves, but even with high-quality forecasts system operators will need a broad range of strategies to actively maintain the supply/demand balance, including the use of flexible power generation technologies, wind energy output curtailment, and increased coordination and interconnection between electric systems; demand-side management, energy storage technologies, and geographic diversification of wind power plant siting will also become increasingly beneficial as wind electricity penetration rises. Despite the challenges, actual operating experience in different parts of the world demonstrates that wind energy can be reliably integrated into electric systems, and in some countries wind energy already supplies in excess of 10% of annual electricity demand. [7.5.4]

In addition to actual operating experience, a number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed. The results of these studies demonstrate that the cost of integrating up to 20% wind electricity into electric systems is, in most cases, modest but not insignificant. Specifically, at low to medium levels of wind electricity penetration, the literature suggests that the additional costs of managing electric system variability and uncertainty, ensuring resource adequacy, and adding new transmission to accommodate wind energy will generally not exceed 30% of the generation cost of wind energy. The technical challenges and costs of integration are found to increase with wind electricity penetration. [7.5.5]

Environmental and social impacts

Wind energy is already reducing net GHG emissions, and has the potential for far greater emissions reductions. Moreover, attempts to measure the relative impacts of various electricity supply technologies suggest that wind energy generally has a comparatively small environmental footprint. As with other industrial activities, however, wind energy has the potential to produce some detrimental impacts on the environment and on human beings, and many local and national governments have established planning, permitting, and siting requirements to minimize those impacts. [7.6]

Although the major environmental benefits of wind energy result from displacing electricity generated from fossil-fuel based power plants, estimating these benefits is somewhat complicated by the operational characteristics of the electric system and the investment decisions that are made in new power plants. In the short-run, increased wind energy will typically displace the operations of existing fossil plants. In the longer-term, however, new generating plants may be needed, and the presence of wind energy will influence future plant selection. The emissions arising from the manufacture, transport, installation, and decommissioning of wind turbines should also be considered, and have been estimated by a number of studies to be small compared to the energy generated and emissions avoided over the lifetime of wind power plants (the carbon intensity of wind energy is estimated to range from 4.6 to 27 gCO_2/kWh, whereas energy payback times are between 3 to 9 months). Similarly, managing the variability of wind power production has not been found to significantly degrade the carbon emissions benefits of wind energy. [7.6.1]

Other studies have considered the local ecological impacts of wind energy deployment. Specifically, the construction and operation of both on- and off-shore wind power plants impacts wildlife through bird and bat collisions and through habitat and ecosystem modifications, with the nature and magnitude of those impacts being site- and species-specific. Bird and bat fatalities through collisions with wind turbines are among the most publicized environmental concerns. Though much remains unknown about the nature and population-level implications of these impacts, avian fatality rates have been reported at between 0.95 and 11.67 per MW per year; raptor fatalities, though much lower in absolute number, have raised special concerns in some cases. Bat fatalities have not been researched as extensively, but fatality rates ranging from 0.2 to 53.3 per MW per year have been reported; the impact of wind power plants on bat populations is of particular contemporary concern. Wind power plants can also impact habitats and ecosystems through avoidance of or displacement from an area, habitat destruction, and reduced reproduction.

The impacts of wind power plants on marine life have moved into focus as offshore development has increased. Potential negative impacts include underwater sounds, electromagnetic fields, physical disruption, and the establishment of invasive species. The physical structures may, however, create new breeding grounds or shelters and act as artificial reefs or fish aggregation devices. Additional research is warranted on these impacts, but they do not appear to be disproportionately large compared to on-shore wind energy. [7.6.2]

Surveys have consistently found wind energy to be widely accepted by the general public. Translating this broad support into increased deployment, however, often requires the support of local host communities and/or decision makers. To that end, in addition to ecological concerns, a number of concerns are often raised about the impacts of wind power plants on local communities. Perhaps most importantly, modern wind energy technology involves large structures, so wind turbines are unavoidably visible in the landscape. Other impacts of concern include land and marine usage, proximal impacts such as noise, flicker, health, and safety, and property value impacts. Appropriate siting of wind turbines is important in minimizing the impact of wind energy development on local communities, and engaging local residents in consultation during the planning stage is often an integral aspect of the development process. Though some of the concerns can be readily mitigated, others - such as visual impacts - are more difficult to address. In part as a consequence, complicated and time-consuming planning and siting processes are key obstacles to wind energy development in some countries and contexts. Efforts to better understand the nature and magnitude of the remaining impacts, together with efforts to minimize and mitigate those impacts, will therefore need to be pursued in concert with increasing wind energy deployment. [7.6.3]

Prospects for technology improvement and innovation

Over the past three decades, innovation in the design of grid-connected wind turbines has led to significant cost reductions, while the capacity of individual turbines has grown markedly. Public and private R&D programmes have played a major role in the technical advances seen in wind energy over the last decades, leading to system and component-level technology advancements, as well as improvements in resource assessment, technical standards, grid integration, wind energy forecasting, and other areas. From 1974 to 2006, government R&D budgets for wind energy in IEA countries totalled $3.8 billion, representing around 10% of RE R&D budgets, and just 1% of total energy R&D expenditure. [7.7.1]

Though on-shore wind energy technology is reasonably mature, continued incremental advancements are expected to yield improved design procedures, increased reliability and energy capture, reduced O&M costs, and longer component life. In addition, as off-shore wind energy gains more attention, new technology challenges arise, and more-radical technology innovations are possible. Sophisticated design approaches are required to systematically evaluate and optimize wind turbine concepts, and studies have identified a number of areas where technology advancements could result in changes to the capital cost, annual energy production, reliability, O&M, and grid integration of wind energy. [7.7.2]

At the component level, a range of opportunities are being pursued, including: (1) advanced tower concepts that reduce the need for large cranes and minimize materials demands; (2) advanced rotors and blades through better designs, coupled with better materials and advanced manufacturing methods; (3) reduced energy losses and improved availability through advanced turbine control and condition monitoring; (4) advanced drive trains, generators, and power electronics; and (5) manufacturing learning improvements. [7.7.3]

In addition, there are several areas of possible advancement that are more-specific to off-shore wind energy, including O&M strategies, installation and assembly schemes, support structure design, and the development of larger turbines, possibly including new turbine concepts. Foundation structure innovation, in particular, offers the potential to access deeper waters, thereby increasing the potential wind resource available. Off-shore turbines have historically been installed in relatively shallow water, up to 30 m, on a mono-pile structure that is essentially an extension of the tower, but gravity-based structures have become more common. These approaches, as well as other concepts that are more appropriate for deeper water depths, including floating platforms, are depicted in Figure TS 7.4. [7.7.3]

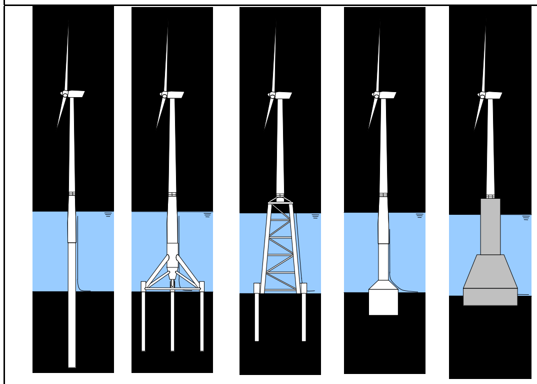
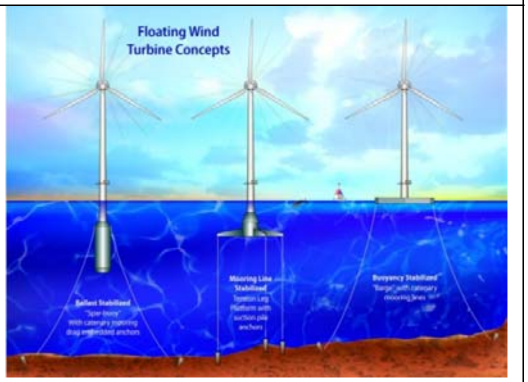
(a) Near-term off-shore foundation concepts	**(b)** Floating off-shore turbine concept
	
Source: UpWind.eu [TSU: date?]	Source: NREL [TSU: date?]

Figure TS 7.4. Off-shore wind turbine foundation designs.

Wind turbines are designed to withstand a wide range of conditions with minimal attention. Significant effort is therefore needed to further advance the fundamental knowledge of the wind turbine operating environment in order to assure a new generation of reliable, safe, cost-effective wind turbines, and to further optimize wind power plant siting and design. Research in the areas of aeroelastics, unsteady aerodynamics, aeroacoustics, advanced control systems, and atmospheric science, for example, can lead to improved design tools, and thereby increase the reliability of the technology and encourage further design innovation. Fundamental research of this nature will be essential for improving: wind turbine design, wind power plant performance estimates, wind resource assessments, short-term wind energy forecasting, and estimates of the impact of large-scale wind energy deployment on the local climate, as well as the impact of potential climate change effects on wind resources. [7.7.4]

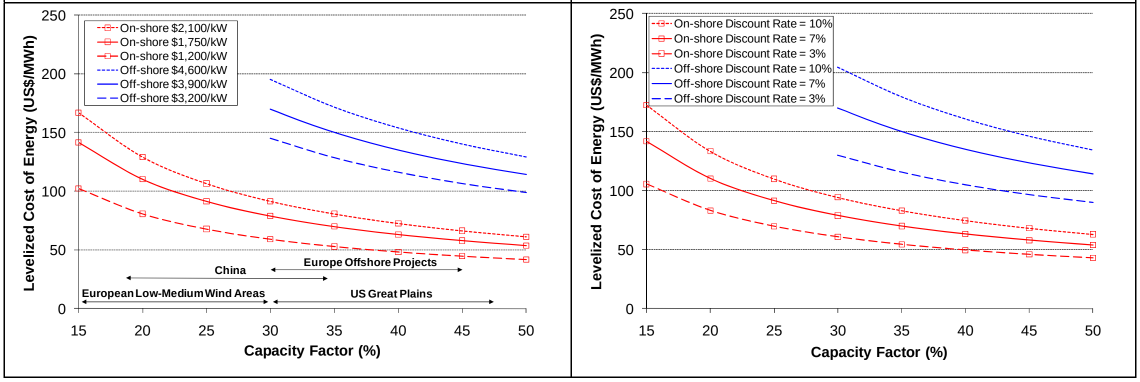
Cost trends

Though the cost of wind energy has declined significantly since the 1980s, in most regions of the world, policy measures are required to make wind energy economically attractive. In areas with particularly good wind resources or particularly costly alternative forms of power supply, the cost of wind energy can be competitive with fossil generation. Moreover, continued technology advancements are expected, supporting further cost reduction. [7.8]

The cost of both on-shore and off-shore wind energy is affected by five fundamental factors: annual energy production, installation costs, O&M costs, financing costs, and the assumed economic life of the power plant. [7.8.1]

From the 1980s to roughly 2004, the installed capital cost of on-shore wind power plants dropped. From 2004 to 2009, however, capital costs increased, the primary drivers of which were: escalation in the cost of labour and materials inputs; increasing profit margins among turbine manufacturers and their suppliers; the relative strength of the Euro currency; and the increased size of turbine rotors and hub heights. In 2009, the average cost for on-shore wind power plants installed worldwide was roughly US$1,750/kW, with a typical range of US$1,200-2,100/kW. The installed costs of off-shore wind power plants have historically been 50% to more than 100% higher than for on-shore plants; O&M costs are also greater for off-shore plants. Recently built or planned off-shore plants have ranged in cost from roughly US$3,200/kW to $4,600/kW. The performance of wind power plants is primarily governed by local wind conditions, but is also impacted by wind turbine design optimization, performance, and availability, and by the effectiveness of O&M procedures. Performance therefore varies by location, but has also generally improved with time. Off-shore wind power plants are often exposed to better wind resources. [7.8.2, 7.8.3]

The resulting levelized cost of on- and off-shore wind energy in 2009 varies substantially, depending on assumed capital costs, energy production, and discount rates (Figure TS 7.5). For on-shore wind energy, levelized costs in good to excellent wind resource regimes average US$50-100/MWh, and can reach US$150/MWh in lower resource areas. Off-shore wind energy is generally more expensive than on-shore, with typical levelized costs that range from US$100/MWh to US$200/MWh; where the exploitable on-shore wind resource is limited, however, off-shore plants can sometimes compete with on-shore plants. [7.8.3]



(a) Cost of wind energy as a function of capacity factor and capital cost*

(b) Cost of wind energy as a function of capacity factor and discount rate**

* Discount rate assumed to equal 7%

** On-shore capital cost assumed at US$1,750/kW, and off-shore at US$3,900/KW

Figure TS 7.5 Estimated levelized cost of on-shore and off-shore wind energy, 2009.

Based on a review of the learning curve and engineering literature, it is estimated that continued R&D, testing, and operational experience could yield reductions in the levelized cost of on-shore wind energy, relative to 2009 levels, of roughly 7.5-25% by 2020, and 15-35% by 2050. The available literature suggests that off-shore wind energy has greater potential for cost reductions: 10-30% by 2030 and 20-45% by 2050. The levelized cost of on-shore wind energy is therefore projected to range from roughly US$30-110/MWh by 2050, depending on the wind resource, installed cost, and the speed of cost reduction. Off-shore wind energy is likely to experience somewhat deeper cost reductions, with a range of expected levelized costs of US$60-140/MWh by 2050. [7.8.4]

Potential deployment

Given the commercial maturity and cost of on-shore wind energy technology, increased utilization of wind energy offers the potential for significant near-term carbon emission reductions: this potential is not conditioned on technology breakthroughs, and related integration challenges are manageable. As a result, in the near-term, the rapid increase in wind power capacity from 2000-2009 is expected by many studies to continue. [7.9.1]

Moreover, a number of studies have assessed the longer-term potential of wind energy in the context of carbon mitigation scenarios. Based on a review of this literature, and as summarized in Figure TS 7.6, wind energy could play a significant long-term role in reducing global carbon emissions. By 2050, the median contribution of wind energy in the two carbon stabilization scenarios across a wide range of studies is 22-26 EJ/y, increasing to 45-50 EJ/y at the 75th percentile, and to more than 100 EJ/y in the highest study. To achieve this contribution would require wind energy to deliver around 13% of global electricity supply in the median case, and 21-26% at the 75th percentile. Other scenarios published by wind energy and RE organizations are consistent with this median to 75th percentile range. [7.9.2]

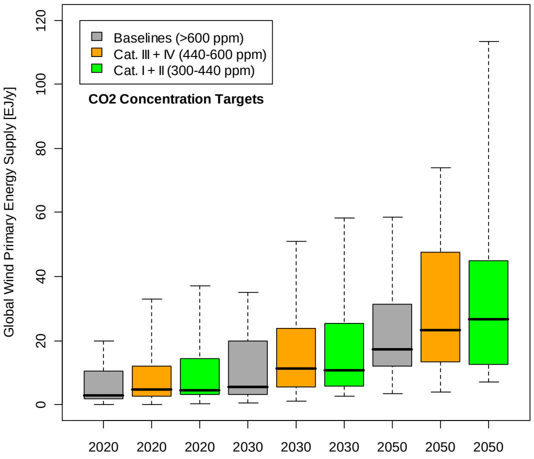


Figure TS 7.6 Global total primary energy supply of wind energy in carbon stabilization scenarios (median, 25th to 75th percentile range, and absolute range).

Achieving the higher end of this range of global wind energy utilization would likely require not only economic support policies of adequate size and predictability, but also an expansion of wind energy utilization regionally, increased reliance on off-shore wind energy in some regions, technical and institutional solutions to transmission constraints and operational integration concerns, and proactive efforts to mitigate and manage social and environmental concerns. Though R&D is expected to lead to incremental cost reductions for on-shore wind energy, enhanced R&D expenditures may be especially important for off-shore wind energy technology. Finally, for those markets with good wind resource potential but that are new to wind energy deployment, both knowledge and technology transfer may help facilitate early wind power installations. [7.9.2]

Integration of Renewable Energy into Present and Future Energy Systems

Integration of renewable energy into supply systems

To enable RE systems to provide a greater share of heating, cooling, transport fuels and electricity will require the modification of conventional energy supply systems so that they can accommodate greater supplies of RE than at present (Figure TS 8.1).

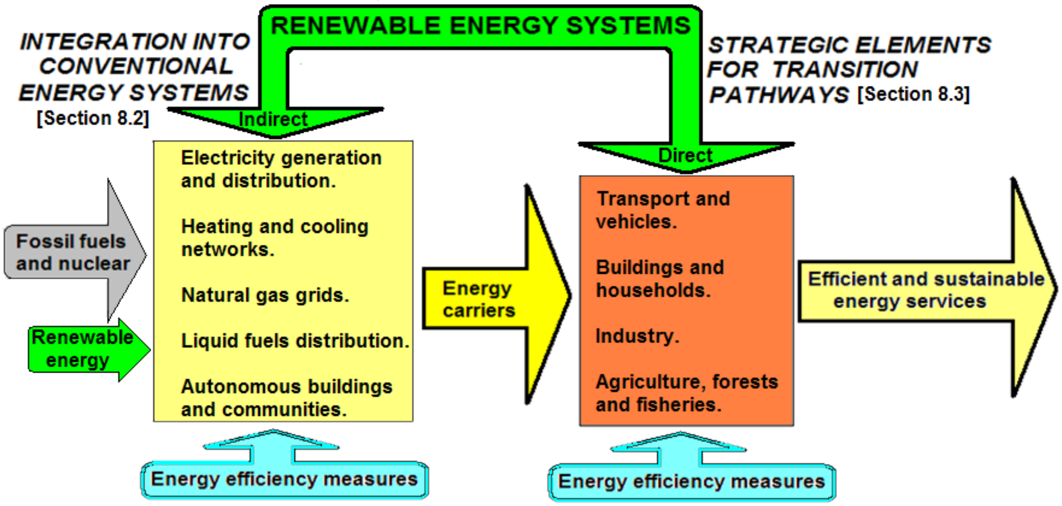
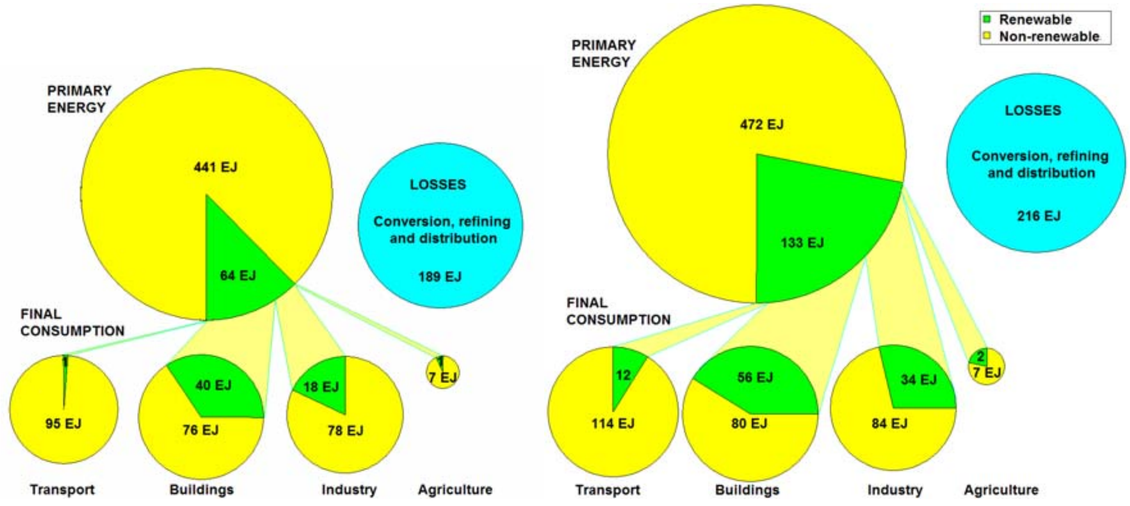


Figure TS 8.1 RE sources, additional to those presently being utilised in conventional energy systems, can be deployed *indirectly* through enhanced integration into energy carriers or *directly* on site by end-use sectors.

Conventional energy systems have evolved over many decades to enable efficient and cost-effective distribution of energy carriers so as to provide useful energy services to end-users. Increasing the deployment of RE systems requires their integration into existing systems by overcoming the associated technical, economic, environmental and social barriers. The various energy systems operating in countries and regions around the world differ markedly and are complex. RE integration approaches will vary as a result. In some regions, electricity systems could possibly become the backbone of future RE-based energy supply if the heating and transport sectors increase electricity demand due to the substitution of coal, natural gas and oil products by “green” electricity.

In order to achieve GHG atmospheric concentration stabilisation around 450 ppm, global energy supply will need to undergo a major transition. As part of this, RE technologies will all need to continue to increase market shares out to 2030. The necessary transition can be illustrated by many scenarios (Chapter 10), the one used here as an example being the IEA’s “450 Policy Scenario” (Figure TS 8.2). This would require the rate of increase in annual deployment of primary RE to double from today’s level to around 3.0 EJ/yr by 2030.



2007 **2030**

Figure TS 8.2 RE shares of primary energy and final consumption in the transport, buildings, industry and agriculture sectors in 2007, and an indication of the increasing shares needed by 2030 in order to aim for a 450 ppm stabilization target (based on IEA, 2009a). Notes: Area of circles approximately to scale. "Non-renewable" energy includes coal, oil, natural gas (with and without CCS by 2030) and nuclear power. Energy efficiency improvements included in the 2030 projection. RE in the buildings sector includes traditional solid biomass fuels used for cooking and heating as used, along with coal, by 3 billion people in developing countries (UNDP, 2009). Traditional biomass may be replaced, at least in part, by more modern bioenergy systems by 2030.

In order to gain greater RE deployment in each of the sectors, strategic elements need to be better understood, as do the non-technical issues. Transition pathways for each technology could facilitate a smoother integration of RE with the conventional energy systems. Multiple benefits for energy end-users should be the ultimate aim.

RE technologies have continued to evolve and there has been increased deployment due to improved cost-competitiveness, more supporting policies, and increased public concerns at the threats of energy security and climate change. For each sector, the current status of RE use will vary as will possible integration pathways to enhance increased adoption; transition issues yet to be overcome, and future trends. There are also regional variations, particularly for the building sector where deploying RE technologies is vastly different in commercial high-rise buildings and apartments in mega-cities compared with small towns of mainly individual dwellings; in wealthy suburbs compared with poor urban areas; in established districts compared with new sub-divisions; and in farming and fishing communities in OECD countries compared with small village settlements in developing countries that have limited access to energy services.

The aims of the Integration chapter (8.1) are to provide a good understanding of current global energy supply systems and to develop a coherent integration framework in preparation for higher levels of RE penetration. Conventional power supply systems, natural gas grids, heating/cooling schemes and petroleum transport fuel supply and distribution networks as well as vehicles, can be adapted to accommodate greater supplies of RE than at present, ranging from mature technologies to those at the early-concept demonstration stage. They rely on improved cost-effectiveness, social acceptance, reliability, and political support at national and local government levels in order to gain greater market share. The optimum combination of technologies and social mechanisms to enable RE integration at high levels of penetration varies with the limitations of specific site conditions, available RE resources, and local energy demands. How conventional energy supply and demand systems can be adapted and developed to accommodate high penetration of RE, particularly for the electricity sector, together with the additional costs involved for RE integration, remain unclear and further study is required.

Taking a holistic approach to the whole energy system can be a prerequisite for efficient and flexible RE integration. It includes achieving mutual support between different energy sectors, and an intelligent control strategy, together with coherent long-term planning, that would enable electricity, heating, cooling and mobility to be inter-linked.

Electric Power Systems

A feature of RE power generation is greater variability as most RE resources have variable characteristics (Figure TS 8.3.). Since an electric power system has to remain in supply/demand balance at all times, this variability makes achieving a high penetration of RE cost-effectively a significant technical, but not insurmountable, challenge for many transmission system operators (TSOs). To maintain reliability could require fundamental changes to be made in the ways that generation plants, grids and electrical loads are designed and operated.

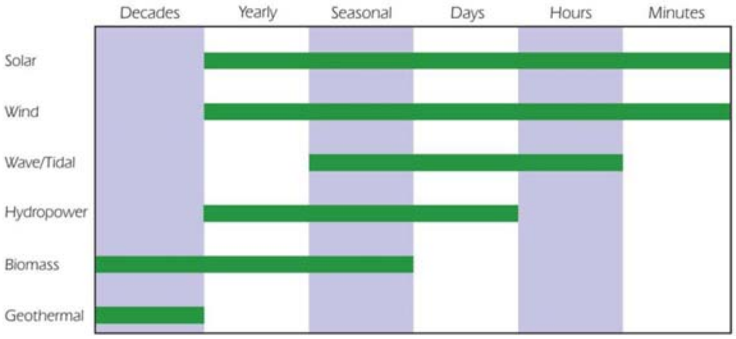


Figure TS 8.3 Time-scale of the natural variability cycles of some RE sources (IEA, 2008).

Within a power supply system, some RE technologies (such as reservoir hydro, bioenergy, geothermal) are dispatchable whereas others (such as wind, solar PV, concentrating solar power (CSP) without storage, small and run-of-the-river hydro, tidal and wave energy systems) are non-dispatchable[2] as their potential output fluctuates with the local RE resource flux. Efficient integration of large shares (above 30%) of these variable RE sources into an existing system will require a paradigm shift rather than minor adjustments. It will require a transition from a conventional system (with zero or limited shares of variable generation and an inflexible load demand), to a more innovative system encompassing flexible generation and demand. For any given system, increasing the penetration[3] of RE varies with the existing plant and infrastructure, operation, flexibility and market design.

In the electricity sector, international experience with the integration of variable RE, mainly wind, shows that high levels of penetration are feasible and can be economically beneficial. Integration is facilitated by strong networks, interconnection, and by methods and investments that increase the flexibility of conventional power supply such as system control and operation over the network, demand-side response, energy storage, more flexible thermal power plants and an enabling

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[2] The term non-dispatchable should be interpreted with care. In this report it denotes the characteristics of a variable RE source that at the system level can be dispatched to a major extent only by decisions of the system operator (for delivering positive and negative regulating power) if primary energy (wind or solar) is spilled (not used). Equally, if variable RE resources are not used in a must-run mode, primary energy will be spilled. There is always, however, a portion of "non-dispatchable" sources that can be dispatched, especially when used at a large scale, due to the correlation between load demand and the resource.

[3] Penetration of RE in a power system is the share it provides of the total gross annual electricity consumption.

electricity market framework. Base load options are feasible using mature and relatively non-variable hydro, geothermal and bioenergy combined heat and power (CHP) technologies.

It is difficult to standardise on a transition strategy to move from a traditional electricity system to a highly flexible one as each system, large or small, has its own particular governance, inter-connection, technology, market and commercial issues to deal with. To increase the penetration of RE resources, stakeholders associated with a given electricity system will probably need to determine their own future pathway, whether the industry serves a village or a continent. The transition to an increased share of RE will need to be carefully managed over many years which could be a challenge for countries without long-term political stability. On a system wide level, RE plants generate electricity just like any other power plant, but many have distinctive features compared to conventional generation.

- *Planning and operation.* Power systems should be designed to provide a reliable supply of electricity for minimal costs. One approach is by using a large number of different generation sources. The benefits of aggregation that this permits are obtained by means of a strong network of transmission/distribution lines and a communication infrastructure that allows for the transfer of power and coordination throughout the network. To avoid voltage fluctuations and blackouts, the system must be able to maintain supply/demand balance even with RE variability and a degree of unpredictability in both demand and generation. In real-time operations, to maintain a near-instantaneous supply/demand balance TSOs, or equivalent market processes, commit and schedule flexible generation capacity and responsive demand to provide reserves that can be available in minutes to compensate for possible loss of generation or transmission or inaccurate forecasts or schedules. When planning ahead, power system planners or participants in equivalent market processes use complex models of the current operation and expected evolution of the system to evaluate the need for investment in generation, network or responsive demand resources.

- *Variability and predictability.* The outputs of variable RE generation can be predicted with various levels of accuracy but may not correlate well with the fluctuating power demand. Depending on the share of the total demand covered by variable RE, the increased variability and uncertainty in the power system may necessitate changes in system operation (8.2.1.3, 8.2.1.4). Over large areas, the correlation of output among variable RE plants is often small due to variations in the RE resource at any given moment. As a consequence the aggregated output of multiple RE generators usually fluctuates less in fractional terms than that of individual plants (8.2.1.2). Experience has shown that integration and accommodation of variable RE resources in a system can become more manageable from the technical and economic perspectives if methods of predicting variability over short time scales (from a few hours to a few days ahead) are sufficiently accurate.

- *Resource location.* The locations of RE sources have consequences for distribution and transmission network infrastructure (8.2.1.3). Small-scale RE systems can often be installed at or near the location of demand. Such distributed generation can bring some advantages for networks if near capacity, but can also pose new challenges that could be resolved by better controls, smart meters and intelligent grids. In other cases, the RE resource can be remote such as for large scale solar PV and CSP plants located in deserts so that substantial new transmission infrastructure may be required.

- *Electrical characteristics.* Electrical conversion of variable RE systems differs from conventional constant speed, synchronous generator systems, but as RE generation designs evolve, the differences are narrowing in terms of power quality characteristics. New technology and innovation enable wind and other variable RE power plants to function more like conventional power plants by meeting a major part of the control requirements made on traditional power plants, and by delivering ancillary services. The cost of delivering a specific ancillary service, or, more generally, to participate in the power market, can be a constraint. Experience shows that RE generators can contribute to sound power system operation, especially by the grouping of small generation plants to create a virtual power plant (VPP) (8.2.1.6). Understanding these characteristics and their interaction and impacts with other parts of the power system, is the basis for proper system integration of RE.

Short-term and long-term impacts. Short-term effects can be caused by balancing the system at the operational time scale (minutes to hours), and by the interaction of variable RE systems with grid voltage and stability. Long-term effects are related to the contribution that RE can make to the adequacy of the system in terms of its capability to meet peak load situations with high reliability. Impact studies on various power systems, both in time and scale, have been undertaken, mainly represented by wind but with more general applicability (Figure TS 8.4). For any given power system, the ability to integrate higher levels of RE depends upon whether the impacts can be identified in advance and successfully dealt with (8.2.1.3).

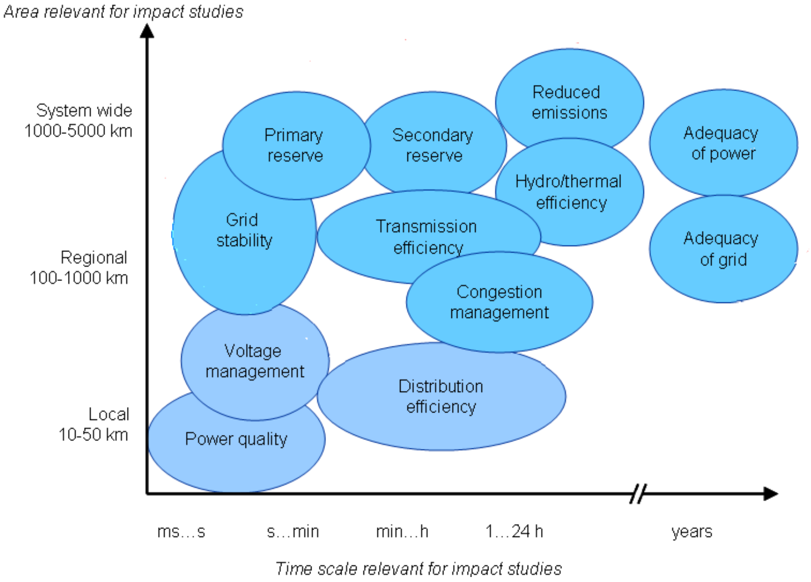

Figure TS 8.4 Impacts of wind power penetration on power systems by time scale and geographic area (Holttinen, 2009a), are representative of similar impacts from other variable renewables.

Analyzing and forecasting RE variability on different time scales, at different levels of geographical aggregation (3.5.4, 7.5.2, 8.2.1.2) and for different RE technology portfolios is necessary to understand and deal with RE impacts on the power system. There is practical experience of large power systems with wind penetration levels of up to 20% and integration issues up to 50% levels have been analysed in system studies. Better controls, smart meters and intelligent grids can help reduce impacts. These impacts identify the challenges of integrating variable and distributed RE systems and highlight the need to address specific aspects of a power system. The main experience with wind energy has relevance to other variable RE sources because it represents a challenging case in view of its relatively high variability and high penetration levels. There remains, however, a knowledge gap on integration issues, particularly for RE penetration levels higher than 20-30%.

From experience to date, the main technical, economic, management and institutional challenges are to be found in:

- power system design, stability and operation, including frequency and voltage regulation;
- network reinforcement, extension and interconnection of national and regional networks;

- network connection requirements for RE generation;
- system adequacy with high penetration of RE due to the low capacity value[4] of several variable RE technologies; and
- electricity market design and corresponding market rules.

Facilitating RE integration. Options to facilitate integration include making power systems more flexible and interconnected (8.2.1.4). Specific engineering approaches that could help solve integration issues include:

- alleviation of the overloading of transmission components through an appropriate combination of power system operation, system expansion, voltage regulation and power flow regulation technologies;
- consideration of energy storage requirements, although this option is likely to be more cost-effective in isolated power systems with high variable RE penetration than those interconnected;
- the time-shifting of power demand in response to an institutional incentive to improve the demand/supply balance as a response to variations in RE generation; and
- more effective energy management at the centralized or decentralized system level, including variable RE generation analysis and forecasting to support more frequent and wider variations of RE generation, better monitoring of the system, the realization of more robust power system controls, and improving system performance including recovery from various system disturbances.

Policy-level initiatives to facilitate RE integration include the review of electricity industry decision-making frameworks (governance, security, commercial and technical regimes) to assess their effectiveness at high levels of RE penetration. They include traditional long-term energy planning of a regulated, monopoly electricity industry, whereas in a competitive industry, such investment decisions may be delegated to a commercial regime with long-term derivative markets supported by advisory functions. In either type of industry, systematic and coherent institutional decision-making can facilitate the integration of high-levels of RE generation.

Costs and benefits. The investment and operating costs associated with integration of RE generation arise from network augmentation to accommodate fluctuating electricity flows associated with variable RE generation. Network extension to connect new RE power plants add costs as does investment in, and operation of, complementary electricity generation, storage and end-use technologies that can respond in a flexible and efficient manner to the additional fluctuating energy flows associated with non-storable RE forms (8.2.1.5). There is a lack of information in the literature on the costs of large-scale RE grid integration other than for wind power which is the most advanced in this regard.

Carefully chosen policies and commercial incentives may be required to bring forward an appropriate mix of "complementary resources" including generation, networks, storage and flexible end-uses, and to maximise the benefits that non-storable RE resources can bring whilst minimising the integration costs. For any given power supply system, the resulting generation mix, and the effectiveness of such a strategy, will be context-specific and evolve over time.

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[4] The capacity value (also known as capacity credit) of variable RE generation in a power system is equal to the amount of conventional generation capacity that can be replaced by this capacity without diminishing the security of supply level (Giebel, 2007).

Future power supply systems. In the long term, the aim to develop a truly sustainable energy supply system could see electricity becoming the main energy carrier, including for the heat and transport sectors. The necessary transition will be in the context of increasing demand for energy services, partly driven by bringing populations within developing countries out of poverty. Integration of electricity from RE sources could become a dominant component of this transition. If so, challenges to the sector will be way beyond current knowledge or experience (8.2.1.6).

A number of speculative approaches to future power system design and operation have been suggested (8.2.1.7). These commonly involve a combination of more highly connected power systems with greatly extended transmission infrastructure; ensuring loads are temporally responsive to supply availability; making greater use of distributed data, communications and controls; employing adapted unit commitment, economic dispatch methods and short-term forecasts; and modifying market structures to combine balancing solutions and to provide incentives for flexible generation in the necessary time frames. The concept of 'intelligent grids' still needs clearer definition, analysis and demonstration but several approaches for the design and operation of such future electricity systems dominated by RE generation have been examined in the literature. These range between large-scale, grid-integrated systems using high voltage direct current (HVDC) transmission over distances of 1000s of kilometres to small-scale distributed generation (DG) embedded in the local, low-voltage network, or to building-integrated systems with the power produced either for use on-site or export. The possibility of DG completely taking over from centralised generation is unlikely to happen even in the long term, but integration of DG into an existing supply system could be technically feasible, as could small autonomous DG mini-grids in remote rural areas or small islands. Depending on the further development of the technologies and associated cost reductions, DG could make a substantial contribution to future total global power generation.

Integration of renewable energies into heating and cooling networks

A district heating (DH) or district cooling (DC) network allows multiple energy sources to be connected to many energy consumers by pumping hot or cold water energy carriers, and sometimes steam, through insulated underground pipelines (8.2.2). Occupiers of buildings connected to a network can avoid operation and maintenance of individual heating/cooling equipment and rely on a professionally managed central system. Several high latitude countries have a district heating market penetration of 30-50%, although in Iceland, the share using geothermal resources, has reached 96%. World annual district heat deliveries have been estimated at around 11 EJ but heat data and statistics are uncertain.

Centralised heat production can facilitate the use of low cost and/or, low grade RE heat sources such as from geothermal, solar thermal, or combustion of a variety of biomass (including refuse-derived fuels and waste by-products) that are not suitable for use in individual heating systems. Waste heat from CHP generation and industrial processes can also be used. This flexibility facilitates competition among various heat sources, fuels and technologies. Centralised production also facilitates application of cost-effective measures to reduce local air pollution.

DH systems can also provide electricity, through CHP system designs. Demand response options also facilitate increased integration of RE in power systems. This includes using electricity for heat pumps and electric boilers for DH schemes, with thermal storage used where excess electricity is generated. Thermal storage systems can bridge the gap between variable, discontinuous or non-synchronised heat supply and demand (8.2.2.3). For short term storage (hours and days) the thermal capacity of the distribution system itself can be used for storage. The capacities of thermal storage systems using different materials and corresponding storage mechanisms, range from a few MJ up to several TJ; the storage time from hours to months; and the temperature between 20°C and 1000°C. Combined production of heat, cold and electricity (trigeneration), as well as the possibility for diurnal and seasonal storage of heat and cold, mean that high overall energy efficiency can be obtained.

There are many geothermal and biomass heating or CHP plants integrated into DH systems that are successfully operating under commercial conditions. Several large scale solar thermal systems with collector areas of around 10,000 m^2 have also been built (e.g. in Denmark). The best mix of heat and cold sources, and heat transfer technologies, depends strongly on local conditions, including demand patterns. As a result, the energy supply mix varies widely between different countries and also between systems.

Modern building designs and uses have tended to increase the demand for cooling but reduced the demand for heating. This trend has been amplified by recent warmer summers in many areas that have increased the cooling demand to provide comfort (8.2.2.4). Cooling load reductions can be achieved by the use of passive cooling options and active RE solutions. As for DH, the uptake of energy efficiency, deployment of other cooling technologies and structure of the market will determine the viability of developing a DC scheme. Modern DC systems from 5 to 300 MW$_{th}$ have been operating successfully for many years using natural aquifers, waterways, the sea or deep lakes as the source of cold, and therefore are classed as a form of RE.

Establishing or expanding a DHC scheme involves high up-front capital costs for piping networks. Distribution costs alone represent roughly half of the total DH cost but are subject to large variations depending on heat density and the local conditions for building the insulated piping network. Network capital costs and distribution losses per unit of heat delivered are lower in areas with high heat densities. Corresponding heat distribution losses can range from less than 5% to more than 30%. The extent to which losses are considered a problem, however, depends on the source and cost of the heat.

DH schemes have typically been developed in situations where strong planning powers have existed, e.g., centrally planned economies, American university campuses, Western European countries with multi-utilities, and urban areas controlled by local municipalities. Expanding the use of DHC systems could facilitate a higher share of RE sources such as deep geothermal and biomass CHP that often require a large heat sink to be viable. Some countries are therefore supporting investments in DH networks as well as providing incentives for using RE.

Integration of renewable energies into gas grids

The gas grid system consists of gas production plants, transmission and distribution pipelines, gas storage, and industrial or private gas consumers. The basic design of a gas system depends on the type and source of energy, the location of demand, and the desired heating value, pressure, and purity depending on the use. Bio-methane or synthesis gas (8.2.3) can be injected into existing gas pipelines for distribution on a national, regional or local level. Large local and regional differences in existing infrastructure (and in gas production and consumption) make planning difficult for RE integration.

Over the past 50 years large integrated natural gas networks have been developed in several parts of the world including USA, Europe, and Japan. Over the past decade there has been an increased interest to “green” existing natural gas grids. Gaseous fuels from RE sources originate largely from biomass and may be produced either thermo-chemically to give synthesis gas (mainly H_2 and CO) or by anaerobic digestion (AD) to produce biogas (mainly CH_4 and CO_2) (8.2.3.1). Gas utilisation can be highly efficient when combusted directly for heat, or converted to a range of liquid fuels using various processes, or used in gas engines or turbines to produce heat and electricity. For example, biomethane, from biogas or landfill gas, can be combusted on-site to produce electricity and/or heat, or after cleaning and upgrading to natural gas quality, distributed to filling stations for use in dedicated or dual gas-fuelled vehicles, or fed into natural gas grids (Figure TS 8.5). Most of the biogas produced around the world has been distributed either in local gas systems primarily dedicated for heating purposes, or, in some cases transported via trucks to filling stations for gas vehicles. However, the biogas business is growing rapidly and several large gas companies are now making plans to upgrade large quantities of biogas and feed them at the required quality into national/regional transmission gas pipelines. As the heating value of synthesis gas is less than that of biomethane, the existing natural gas grid would need modifying to accept synthesis gas directly due to its different flow and combustion properties.

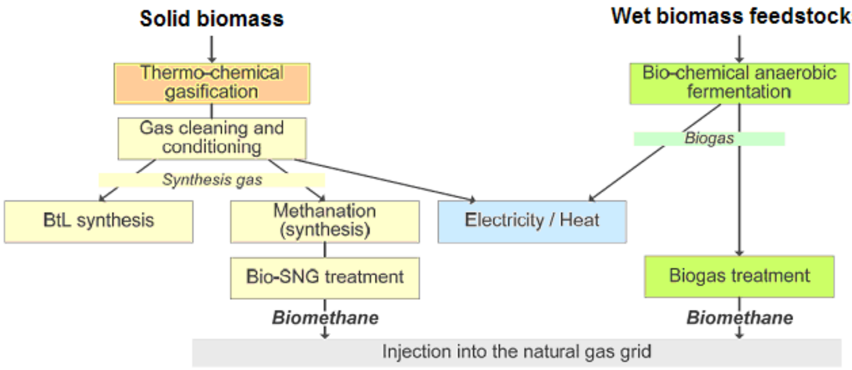

Figure TS 8.5 Injection into the natural gas grid of RE gases produced from solid or wet biomass feedstocks such as green crops or organic wastes (Müller-Langer et al., 2009).

Technical challenges relate to gas source, composition, and quality. Only gases of a specified quality can be injected directly into existing natural gas grids hence gas clean-up is a critical step for both biogas and syngas use. This process removes water, carbon dioxide (thereby increasing the heating value) and additional products from the gas stream. The cost of upgrading varies according to the scale of the facility (3-6% of the energy content).

RE gas systems are likely to require significant storage capacity to account for variability and seasonality of supply. The size and shape of storage facilities and the required quality of the gas will depend on the primary energy source of production and its end use.

Hydrogen may be produced from RE by several routes including the reformation of biogas or water electrolysis. The potential RE resource base for hydrogen is greater than for biogas or biomass-derived syngas. Future production and distribution of hydrogen will depend significantly on the interaction with existing electricity systems. For the short term, blending of hydrogen with natural gas (up to 20%) and transporting it long-distances in existing natural gas grids could be an option, while, in the long term, the construction of pure hydrogen pipelines would require different steels to reduce leakage. The rate limiting factors for deploying hydrogen are likely to be the capital and time involved in building a new hydrogen infrastructure and the added cost for storage when incorporating variable RE sources.

In order to blend RE gases into the gas grid, the gas source needs to be located near to the existing system to avoid high costs. In the case of remote biogas plants it may be better to use the methane on-site to avoid the need for transmission. Similar considerations apply to hydrogen and syngas produced from biomass (8.2.3.5).

Integration of renewable energies into liquid fuels

Most of the projected demand for liquid biofuels is for transport purposes, though industrial demand could emerge for bio-lubricants and bio-chemicals, such as methanol, used in chemical industries. In addition, large amounts of traditional solid biomass used for cooking and heating could eventually be replaced by more convenient, safer and healthier liquid fuels such as dimethyl ether (DME) or ethanol gels.

The biomass-to-liquid fuel process comprises production (agricultural phase), preparation and conversion (industrial phase), distribution, and final consumption (Figure TS 8.6). Biofuels can take advantage of existing infrastructure components already used by the petroleum-based fuels for storage, blending, distribution and dispensing (8.2.4.1) although sharing oil-product infrastructure (storage tanks, pipelines, trucks) with biofuels, especially ethanol, can give problems of water contamination and corrosion, and may require new materials to preserve the lifetime of the equipment.

Decentralized biomass production, seasonality and remote agricultural locations not necessarily near existing oil refineries or fuel distribution centres can impact on the logistics and storage of biofuels (8.2.4.3). The type of fuel storage and delivery system will vary depending with the properties of the biofuel and its compatibility with the existing petroleum fuel system. Technologies continue to evolve to produce biofuels that are more compatible with the existing petroleum infrastructure. Quality control procedures need to be implemented to ensure that biofuels meet all applicable product specifications (8.2.4.4).

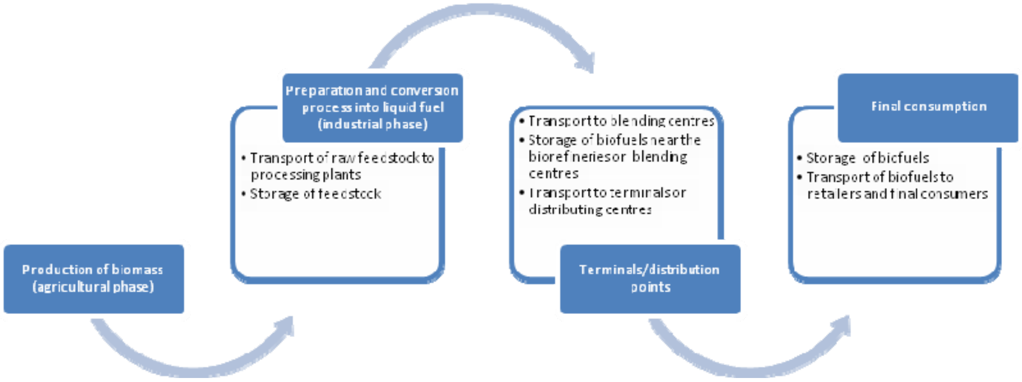

Figure TS 8.6 The typical biofuel process, blending and distribution system [TSU: Reference is missing]

Integration issues are challenging for biofuels. For example, replacing a substantial proportion of gasoline with blends of neat ethanol requires investment in infrastructure including additional tanks and pumps at the service stations. Although the cost of delivery is a small fraction of the overall cost, the logistics and capital requirements for widespread expansion could present many hurdles if they are not well planned. Ethanol and ethanol/gasoline blends cannot be easily stored, transported and delivered in the existing petroleum infrastructure because of the incompatibility of some materials and water absorption by ethanol in the pipelines (8.2.4.1). Moreover, ethanol has only around two-thirds of the volumetric energy density of gasoline, so larger storage systems, more rail cars or vessels, and larger capacity pipelines would be needed to store and transport the same amount of energy, thereby increasing the fuel storage and delivery cost. Although pipelines would, in theory, be the most economical method of delivery, and trial pipeline shipments of ethanol have been successfully achieved, a number of technical and logistical challenges remain. Current ethanol demand volumes are usually considered too low to justify the cost and operational challenges (8.2.4.3).

Autonomous systems

In order to be sustainable, and depending on whether the energy carrier is electricity, hydrogen, or liquid, gaseous or solid fuels, an energy system needs to maintain the demand-supply balance over various time frames. When a system is small, the demand-supply balance problem readily emerges so that the energy system has autonomy for balancing (8.2.5.1). The integration of several RE conversion technologies, energy storage options and energy use technologies in a small-scale energy system depends on site-specific availability of RE resources and the energy demand due to geology, climate, and lifestyle. This creates several types of autonomous power supply systems including: 1) on an island (often including fossil fuel generators as part of a small, mini-grid system); 2) in rural areas of a developing economy (generally a hybrid RE system for remote, off-grid, communities); 3) for individual buildings (including zero-emission designs) that could generate more electricity and heat energy than they consume through the use of energy efficient technologies and on-site heat and power generation.

An autonomous RE power system could involve the limited deployment of a single type of RE generation technology such as solar power, or incorporate a portfolio of technologies. The capacity of the RE generation can be increased by the addition of more generation units of similar type, or by adding other types of RE generation technologies to enhance operational flexibility. Fossil fuel generation to maintain the desired supply reliability and flexibility of system operation could, in the future, be displaced by increased flexibility and the integration of energy storage (8.2.5.2).

Energy storage and efficient utilization technologies could become essential where the integration of RE technologies changes from a niche to a major role. Major constraints can arise from the difficulty of appropriate planning, designing, construction and maintenance of autonomous systems (8.2.5.3). In order to avoid these factors, establishing standardization and certification of the products, integrating planning tools, developing a database and capacity building are important, as are building local capacity and market establishment for low capital and operation costs.

Electricity generated in an autonomous system is usually more costly than that from an existing network where grid connection is available. However, integration of different kinds of RE may improve the economy and reliability of the supply and the economic viability should be evaluated including factors such as the possible future constraints of fossil fuel supplies, avoidance of infrastructure construction, technology innovation and projected cost reductions.

Strategic elements for transition pathways

Since the IPCC 4th Assessment Report in 2007, RE technology developments have continued to evolve and there has been increased deployment due to improved cost-competitiveness, increased public concern at the threats of energy security and climate change, and more supporting policies, including public R&D investment particularly for the transport and building sectors. In order to achieve greater RE deployment in these sectors as well as industry and agriculture (that includes forestry and fishing) (Fig. y.y), both technical and non-technical issues have a role to play.

For each sector, the current status of RE use, possible pathways to enhance increased adoption, the transition issues yet to be overcome and future trends are discussed (8.3). Regional variations exist due to differences in the energy system and related infrastructure currently in place as well as varying national and local ambitions and cultures.

Transport

The direct combustion of fossil fuels for transport consumes around 19% of global primary energy use and produces around 23% of GHG emissions, plus a significant share of air pollutant emissions. Light duty vehicles (LDVs) account for over half of transport fuel consumption worldwide, with heavy duty vehicles (HDVs) 24%, aviation 11%, shipping 10%, and rail 3%. Demand for mobility is growing rapidly with the number of motorized vehicles projected to triple by 2050 and a similar growth in air travel. Energy supply security is therefore a serious concern for the transport sector with about 94% of transport fuels presently coming from petroleum, mostly as imported products.

Improving the efficiency of the transport sector, and decarbonising it, have been identified as being critically important to achieving long-term, deep reductions in carbon emissions. The approaches to reducing transport-related energy use, and hence GHG emissions, are a reduction of travel demand, increased vehicle efficiency, shifting to more efficient modes of transport, and replacing petroleum-based fuels with alternative low or near-zero carbon fuels including biofuels, electricity or hydrogen produced from low carbon primary energy sources (8.3.1.1). Recent scenario studies strongly suggest that a combination of approaches will be needed to accomplish 50-80% reductions in GHG emissions by 2050 (compared to current rates) while meeting the growing transport energy demand.

There are a number of possible fuel/vehicle pathways beginning with the primary energy source, conversion to an energy carrier (or fuel) and use including in advanced internal combustion engine vehicles (ICEVs), electric battery vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and hydrogen fuel cell vehicles (HFCVs) (Figure TS 8.7) (8.3.1.2).

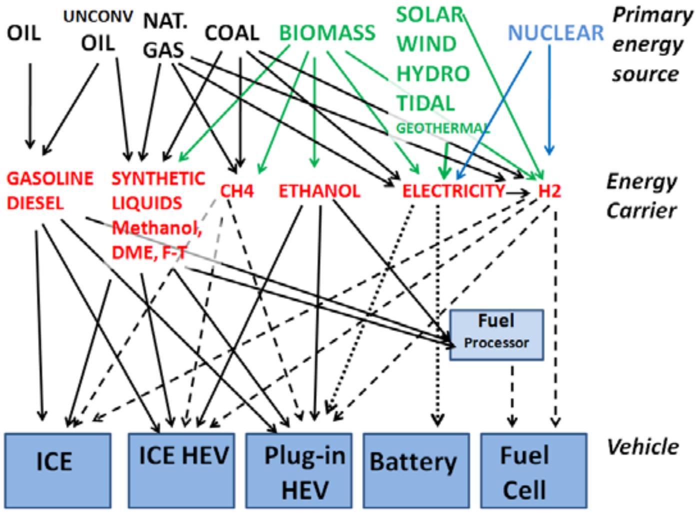

Figure TS 8.7 Possible fuel/vehicle pathways, from primary energy sources (top), through energy carrying fuels (red) to vehicle options (bottom) showing renewable resources (green). Notes: F-T= Fischer-Tropsch process. ICE= internal combustion engine. HEV=hybrid electric vehicle. [TSU: Reference is missing]

Present use of RE in transport is only a few per cent of the total demand, mainly through electric rail and blending liquid biofuels with petroleum products. Millions of LDVs capable of running on liquid biofuels are already in the fleet and biofuel technology is commercially mature (as is the use of compressed biomethane). Costs and lifetimes of present battery technologies are a major barrier to both battery only EVs and PHEVs. The latter are undergoing rapid development, spurred by recent policy initiatives worldwide, and several companies have announced plans to commercialize them starting in 2010. Consumer acceptance associated with battery range and recharging time is also an issue. One strategy is to introduce PHEVs initially while developing and scaling up battery technologies. Many hydrogen fuel cell vehicles have been demonstrated, but are unlikely to be commercialized until at least 2015-2020 due to barriers of fuel cell durability, cost, on-board hydrogen storage and hydrogen infrastructure availability.

Transition issues vary for biofuels, hydrogen, and electric vehicles (Table TS 8.1). No one option is seen to be a clear “winner” and all will take several decades to implement at the large scale.

Table TS 8.1 Transition issues for biofuels, hydrogen, and electricity (Bandevedakar et al., 2008)

Technology Status	**Biofuels**	**Hydrogen**	**Electricity**
Vehicles	Millions of flex-fuel vehicles using ethanol, but conventional vehicles still limited to low concentration blends of ethanol (< 10%) or biodiesel (< 5%)	Demonstration HFCVs. Commercial HFCVs: 2015-2020	Limited current use of EVs. Demonstration PHEVs, Commercial PHEVs :2010-15. Commercial EVs: 2015-2020.
Fuel production	1st generation: Ethanol from sugar and starch crops, biomethane, biodiesel. 2nd generation: ethanol / diesel/green fuels from cellulosic biomass, biowastes, bio-oils, and algae - after at least 2015.	Fossil H_2 commercial for large-scale industrial applications, but not competitive as transport fuel. Renewable H_2 generally more costly.	Commercial power available. RE electricity generally more costly.
Cost (vs. gasoline vehicles) Incremental vehicle price compared to future gasoline ICEV (USD2005) Fuel cost (USD /km)	Similar vehicle cost to gasoline. Fuel cost per km competes, if biofuel price per unit energy ~ gasoline price per unit energy.	HFCV experience price increment compared to gasoline ICEV >USD 5300 (2035) Fuel cost per kg for H_2 at \$3-4/kg (target for mature H_2 infrastructure; may prove optimistic) used in HFCV competes with gasoline at USD 0.40-0.53/l used in gasoline ICEV, assuming HFCV has 2x fuel economy of gasoline ICEV. Renewable H_2 at least 1.5-3x more expensive.	Experience price increment compared to gasoline ICEV >USD 5900 (2035) (PHEVs) >USD 14,000 (2035) (EVs). Electricity cost per km competes with gasoline cost per km for electricity costs \$0.10-0.30/kWh when gasoline costs \$0.3-0.9/l (assuming EV has fuel economy 3x gasoline ICEV)
Compatibility with existing infrastructure	Partly compatible with existing petroleum distribution system. Separate distribution and storage infrastructure can be needed for ethanol.	New H_2 infrastructure needed, as well as renewable H_2 production sources. Infrastructure deployment must be coordinated with vehicle market growth.	Widespread electric infrastructure in place. Need to add in-home and public chargers, RE generation sources, and upgrade transmission and distribution (especially for fast chargers).
Consumer acceptance	Fuel cost: alcohol vehicles have shorter range than gasoline. Potential cost impact on food crops and land use. Land and water issues can be a factor.	Vehicle and fuel costs. Safety of on-board gaseous H_2 storage. Fuelling station availability in early markets.	Vehicle initial cost. High electricity cost of charging on-peak. Limited range unless PHEV. Modest to long recharge time, but home recharging possible. Significantly degraded performance in extreme climates (cold winters, hot summers).
Existing and potential primary resources	Sugar, starch, oil crops. Cellulosic crops; forest, agricultural and solid wastes. Algae and other biological oils.	Fossil fuels, nuclear, all RE-potential RE resource base is large but inefficiencies and costs of converting to H_2 an issue.	Fossil fuels, nuclear, all RE – potential RE resource base is large.
GHG emissions	Depends on feedstock, pathway and land use issues. Low for fuels from waste residues, and sugarcane. Near-term can be high for corn ethanol. 2nd generation biofuels lower.	Depends on H_2 production mix. Compared to future hybrid gasoline ICEVs, WTW GHG emissions for HFCVs using H_2 from natural gas are slightly more to slightly less depending on assumptions used. WTW GHG emissions can approach zero for RE pathways.	Depends on grid mix. Using coal-dominated grid mix, EVs, and PHEVs have WTW GHG emissions similar or higher than gasoline HEV. With larger fraction of RE and low carbon electricity, WTW emissions are lower.

Petroleum consumption	Low	Very low	Very low
Environmental and sustainability issues			
Air pollution	Similar to gasoline. Additional issues for ethanol due to permeation of volatile organic compounds (VOCs) through fuel tank seals. Aldehyde emissions.	Zero emission vehicle	Zero emission vehicle.
Water use	More than gasoline depending on feedstock and irrigation needs.	Potentially very low but depends on pathway.	Potentially very low but depends on pathway.
Land use	Might compete with food-for cropland.	Depends on pathway.	Depends on pathway.
Materials use		Platinum in fuel cells. Neodymium and other rare earths in electric motors.	Lithium in batteries. Neodymium and other rare earths in electric motors.

Note: Costs quoted do not always include payback of incremental first vehicle costs.

An advantage of liquid biofuels is their relative compatibility with the existing liquid fuel infrastructure (8.3.1.2). They can be blended with petroleum products and most ICE vehicles can be run on blends or some even on 100% biofuel. They are similar to gasoline or diesel in terms of vehicle performance and refuelling times, though have limits on the concentrations that can be blended and typically cannot be easily distributed using existing fuel pipelines without modifications. Although liquid biofuels would likely need their own distribution and storage systems, this would be less of a radical change than the supply chains required to provide either electricity, hydrogen or even biomethane where such a network is not yet in place. Sustainable biomass resource availability is, however, a serious issue for some biofuels (Chapter 2).

For RE electricity to serve large transport markets, several innovations must occur such as development of batteries and low cost supply available at the time of recharging EVs. With night-time off-peak recharging, new capacity would not be needed and there may be a good temporal match with wind or hydropower resources, although not necessarily to solar. Energy storage may also be needed to balance vehicle electric demand with RE sources.

Hydrogen has the potential to tap vast new energy resources to provide transport with zero or near-zero emissions (8.3.1.2). Hydrogen from RE sources has near-term cost barriers rather than technical feasibility or resource availability issues. Initially RE and other low carbon technologies will likely be used to generate electricity, a development that could help enable zero-carbon hydrogen that might be co-produced with electricity in future energy complexes. Unlike electricity, natural gas, gasoline and biofuels, hydrogen is not widely distributed to consumers today. Electricity is used more efficiently in an EV or PHEV but hydrogen might be preferred where a larger vehicle with a longer range and faster refuelling time is needed. Bringing hydrogen to large numbers of vehicles would require building a new refuelling infrastructure that could take several decades to construct. The first steps to provide hydrogen to test fleets and demonstrate refuelling technologies in mini-networks have begun.

It is also possible to lower emissions and introduce RE options in other transport sectors including HDVs, aviation, maritime and rail. The use of biofuels is key for increasing the share of RE but engines would probably need to be modified to operate on high biofuel blends above 80% (8.3.1.5). Compared to other transport sectors, aviation has less potential for fuel switching due to safety needs and to minimize fuel weight and volume. Various aircraft have flown demonstration test flights using several biofuel blends, but significantly more processing is needed than for road fuels to ensure that stringent aviation fuel specifications are met. For rail transport, as 90% of the industry was powered by diesel fuel in 2005, greater electrification and the increased use of biodiesel are the two primary options for introducing RE.

Recent trends and projections show strong growth in transport demand, including a strong projected growth in number of vehicles. Meeting this demand whilst achieving a low carbon, secure energy supply will require strong policy initiatives, rapid technological change, monetary incentives and, or, the willingness of customers to pay additional costs. Many uncertainties and cost reduction challenges remain concerning future technologies, source of the energy carriers and the related infrastructure. Given these uncertainties and the long timeline for change, it is important to maintain a portfolio approach that includes behavioural changes (to reduce vehicle km travelled or km flown), more efficient vehicles, and a variety of low-carbon fuels.

Buildings and households

The buildings and household sector in 2007 accounted for ~116 EJ, or about 30 % of total global final energy demand. Around 40 EJ of this total was from combustion of traditional biomass for cooking and heating. By 2030, the total demand could rise to ~136 EJ. The sector is paramount for providing a variety of energy services to support the livelihoods and well-being of people living in both developed and developing countries.

The present use of fossil fuels to provide heating and cooling can be replaced economically in many regions by RE systems using e.g., district heating and cooling, modern biomass and enclosed stoves, ground source heat pumps, or solar thermal and solar sorption systems. Building-integrated electricity generation technologies provide the potential for buildings to become energy suppliers rather than energy consumers. Integration of RE into existing urban environments, combined with efficient “green building” designs, is key to further deployment. For household and commercial building sub-sectors, energy vectors and energy service delivery systems vary depending on the local characteristics of a region and its wealth.

In *urban settlements in developed countries*, most buildings are connected to electricity, water and sewage distribution schemes (8.3.2.1). The features and conditions of energy demand in an existing or new building and the prospects for RE integration differ with location and from one building design to another. Assuming a low stock turnover of buildings of around 1% per year, retrofitting of existing buildings will play a significant role for energy efficiency and RE integration. Where buildings are connected to electricity grids, gas grids or district heating and cooling systems it facilitates indirect integration of RE to provide energy services. Many energy efficiency and RE technologies, although economically viable, involve relatively high up-front investments and long pay-back periods. Examples include district heating and cooling systems, solar water heaters and ground source heat pumps. This barrier can be overcome through planning and regulation as well as economic incentives and financial arrangements.

In *urban settlements in developing countries*, energy consumption patterns often include the non-rational use of biomass, particularly from forest resources located close to urban consumption centres. In some areas, grid electricity is available, although limited. A major challenge is to reverse the current consumption patterns by providing access to modern energy carriers and services, while increasing the share of RE.

Energy consumption patterns in *rural settlements in developed countries* greatly resemble those in urban areas (8.3.2.3). In such areas there are good opportunities for local RE resources to be developed to meet local demand and, in some cases, to generate surplus electricity that can be delivered to the grid. Financial and institutional barriers, including lack of awareness, are among key barriers to mobilizing RE on a large scale in rural areas.

Only a small fraction of *rural settlements in developing countries* have access to modern energy services, which is also a major constraint to eradicating poverty (8.3.2.4). Rural households rely on traditional biomass (mainly crop residues, fuel-wood and charcoal) for their basic cooking and heating energy needs. Lighting demands is often met by kerosene lamps, torches and candles. The key challenge for rural communities is to improve energy access and quality through deploying a range of modern RE technologies for providing basic energy services.

Industry

Manufacturing industries account for about one-third of global energy use although the share differs markedly between countries. The sector is highly diverse but perhaps 85% of industrial energy use is by energy intensive industries: iron and steel, non-ferrous metals, chemicals and fertilizers, petroleum refining, minerals, and pulp and paper. Key measures to reduce carbon dioxide emissions include energy efficiency, materials recycling, CCS, in addition to integrating higher shares of RE and substitute fossil feedstock. In addition, industry can provide demand-response facilities that are likely to achieve greater prominence in future electricity systems with more variable supply.

There are no severe technical limits to the increased direct and indirect use of RE in industry in the future. But integration in the short term may be limited by factors such as space constraints or demands for high reliability and continuous operation. The main opportunities for RE integration in industry include:

- direct use of biomass derived fuels and residues for on-site biofuels, heat and CHP production and use (Chapter 2);
- indirect use of RE through increased use of RE-based electricity, including electro-thermal processes;
- indirect use of RE through other purchased RE-based energy carriers, e.g., liquid fuels, biogas, heat and hydrogen (section 8.2.3);
- direct use of solar thermal energy for process heat and steam demands (Chapter 3); and
- direct use of geothermal for process heat and steam demands (Chapter 4).
- The current direct use of RE in industry is dominated by biomass in the pulp and paper, sugar and ethanol industries where biomass by-products are important sources of co-generated heat and electricity mainly used for the process. Biomass is also an important fuel for many small/medium enterprises (SMEs) such as brick-making, notably in developing countries (8.3.3.1). Industry is not only a potential user of RE but also a potential supplier as a co-product.

Possible pathways for increased use of RE in *energy-intensive industries* vary between different industrial sub-sectors (8.3.3.2). Biomass can replace fossil fuels in boilers, kilns and furnaces and there are alternatives for replacing petro-chemicals through switching to bio-based chemicals and materials. However, due to the scale of operations, access to sufficient volumes of biomass may be a constraint (Chapter 2). Direct use of solar technologies is constrained for the same reason. For many energy-intensive processes the main option is indirect integration of RE through switching to electricity and hydrogen. The broad range of options for producing carbon neutral electricity and its versatility of use implies that electro-thermal processes could also become more important in the future for replacing fuels in a range of processes.

Non-energy intensive industries, although numerous, account for a smaller share of total energy use than energy-intensive industries (8.3.3.3). They include food processing, textiles, light manufacturing of appliances and electronics, automotive assembly plants, wood processing, etc. Much of the energy demand in these industries is for installations similar to energy use in commercial buildings such as lighting, space heating, cooling and ventilation and office equipment.

In general, they are more flexible and offer greater opportunities for the integration of RE than energy-intensive industries.

The potentials and costs for increasing the direct use of RE in industry are poorly understood due to the complexity and diversity of industry and various geographical and climatic conditions. Improved utilisation of processing residues and CHP in biomass-based industries and substitution for fossil fuels offer near-term opportunities. Solar thermal technologies are promising but further development of collectors, thermal storage, back-up systems and process adaptation and integration is needed. Indirect integration using electricity generated from RE sources and facilitated through electro-technologies may have the largest impact both in the near and long-term. Direct use of RE in industry has difficulty competing at present due to relatively low fossil fuel prices and low or zero energy and carbon taxes for industry. RE support policies in different countries tend to focus more on the transport and building sectors than on industry and consequently potentials are relatively un-charted.

Agriculture, forestry and fishing

Whether large corporate-owned farms or subsistence farmers, agriculture is a relatively low energy consuming sector, with pumping of water for irrigation and indirect energy for the manufacture of fertilisers accounting for the greatest consumption.

RE sources including wind, solar, crop residues and animal wastes, are often abundant for the landowner to utilise locally or to earn additional revenue from exporting useful energy carriers such as electricity or biogas off the farm. In many regions, land under cultivation could simultaneously be used for RE production (8.3.4.2). Multi-uses of land for agriculture and energy purposes is becoming common, such as wind turbines constructed on grazing land, on-farm biogas plants used for treating pig manure and recycling the nutrients, streams used for small- and micro-hydropower systems, straw residues collected and combusted for heat and power, and crops grown and managed specifically to provide both food or fibre and liquid biofuel co-products (8.3.4.3).

Despite barriers to greater deployment including high capital costs, lack of available financing and remoteness from energy demand, it is likely that RE will be used to a greater degree by the global agriculture sector in the future to meet energy demands for primary production and post-harvest operations at both the large and small scales, using a wide range of conversion technologies. Since RE resources often abound in rural areas, their capture and integration into traditional farming operations to become an additional form of revenue for landowners has good future potential.

Conclusions

RE has the potential in the longer term to provide a much greater share of global energy than at present. Indeed some communities are already close to achieving 100% RE supply, including for local transport. Over the long-term and through measured system integration, there are few, if any, technical limits to the level of penetration of RE in the many parts of the world where abundant RE resources exist. In the future RE could provide the full range of energy services to large and small communities in both developed and developing countries. However, the necessary transition to a low carbon future will require considerable investments in new technologies and infrastructure, including flexible and intelligent electricity grids, energy storage, novel transport methods and distributed energy systems, as well as improved energy efficiency on both the supply-side and during final end-use consumption.

In the short-term, integration of higher shares of RE in the present energy supply systems than at present can enhance system reliability, energy security, electricity and gas network security, GHG mitigation, sustainable development and access to energy services for all. The full range of RE sources could become available for integration by end-use sectors, including electric vehicles, building integrated solar systems, industry use of bioenergy co-fired with coal, and small wind and small hydro projects for agriculture. Integration strategies that could increase the deployment of RE in both urban and rural areas will depend upon the local and regional RE resources, energy demand patterns, project financing methods and existing energy markets.

The general and specific requirements for better integration of RE into heating and cooling networks, electricity grids, gas grids, transport fuel supply systems and autonomous buildings or communities are reasonably well understood. However, analysis of the additional costs for integration of RE options has not been found in the literature and therefore future research is needed including to provide accurate data for modelling scenarios. For example, how the possible projected trend towards decentralised energy supply systems might affect future costs and demand for large, centralised systems has not been assessed. Other risks and impacts involving the integration and deployment of RE in a sustainable manner, including the increased use of materials, capacity building, technology transfer, and financing, also need further analysis.

Regardless of the energy systems presently in place, whether in energy-rich or energy-poor communities, increased RE integration with the existing system is desirable. The rate of penetration will depend on an integrated approach, including policy framing, life-cycle analysis, comparative cost/benefit evaluations, and recognition of the social co-benefits that RE can provide.

Renewables in the Context of Sustainable Development

Introduction

Development is a concept frequently associated with economic growth, still in many cases disregarding income distribution, physical limits from the environment and the external costs of impacts caused by some and borne by others. Climate change is one of these most relevant impacts, with externalities present at global level. (9.1)

Sustainable Development (SD) is a relatively recent concept, aiming to consider such impacts. There are several definitions of SD, but probably the most important came up in 1987, with an influential report published by the United Nations, entitled “Our Common Future” (or “The Brundtland Report”). In this publication, sustainable development is a principle to be pursued, in order to meet the needs of the present without compromising the ability of future generations to meet their own needs. The report recognized that poverty is one of the main causes of environmental degradation and that equitable economic development is a key to addressing environmental problems. (9.1)

Energy for sustainable development has three major pillars: (1) more efficient use of energy, especially at the point of end-use, (2) increased utilization of renewable energy, and (3) accelerated development and deployment of new and more efficient energy technologies. The questions of renewable and sustainable energy have their roots in two distinct issues: while renewability is a response to concerns about the depletion of primary energy sources (such as fossil fuels), sustainability is a response to environmental degradation of the planet and leaving a legacy to future generations of a reduced quality of life. Both issues now figure prominently on the political agendas of all levels of government and international relations. (9.1)

Interactions between Sustainable Development and Renewable Energy

Much of the discourses on SD have historically focused on economic and environmental dimensions of renewable energy technologies and their implementation. Social and institutional dimensions have not received the same degree of attention. With growing interest in the two-way relationship between SD and renewable energy, the latter two dimensions need to be given the same level of importance. After all, increased penetration of RE can have positive or negative local impacts on air, water, land, health and socio-economic development, and could impact attaining the Millennium Development Goals. Positive impacts include reduced air pollution, improved energy access and supply security, higher employment, enhanced lifestyles and gender equality, whereas negative ones may involve higher costs, land competition, impacts on biodiversity and displacement of people.

In most respects, consumers of energy services are focused on whether those essential services are abundant, reliable, and affordable – not on where the energy comes from. However, judging from the availability of renewable energy technologies other than large-scale hydropower, it is difficult to conceive of significant urban/industrial development based on renewable energy sources. Where current renewable energy niches in either electricity production or transportation fuels are now on the order of four to eight percent, increasing them to twenty or thirty percent is a profound challenge to scalability because of the magnitude of the needs. In addition, many renewable energy sources are based on continuous energy sources, such as water flow or plant growth, but some are based on intermittent energy sources, such as solar radiation or wind. Where the sources are intermittent, the only ways that they can meet continuing needs for energy services are either by energy storage or by using other energy sources as supplements, either of which tends to increase costs and reduce net benefits. Finally, energy costs and their affordability constitute a complex issue for renewable energy. At a local scale, in many cases renewable energy options offer a prospect of reduced energy costs. But for larger-scale energy needs for development, fossil energy sources – or intermediate sources dependent on them – are considerably less expensive at present (except for hydropower), and efforts to promote clean energy by increasing the cost of fossil energy can be a threat to development. (9.1.1)

Different forms of human settlement will each pose their own challenges in providing adequate access to energy. In rural settlements, electrification to promote development (and reduce pressures for rural to urban migration) has been a development priority for many decades. In most cases, the preferred approach has been to combine local renewable resource endowments (such as solar radiation or biomass) with institutional innovations. There have been notable early successes, such as the development of solar cells in rural villages in the Dominican Republic in the early 1980s. Often, however, rural electrification efforts have been so subsidized that they are not themselves sustainable, which can be worse for overall sustainability than not introducing those changes at all. In many urban areas in developing countries, on the other hand, the major energy access issues are (a) the lack of reliability of electricity supply and (b) air pollution associated with local industrial, transportation, and energy production, which affect rich and poor alike. But even where it is generally available, the poor often lack ready, affordable access to electricity, as urban electricity supply institutions emphasize supplies to relatively large customers who can pay. In many cases, traditional renewable energy sources such as wood or charcoal for cooking and heating and passive solar energy for food preservation are used as the only affordable options, but urban wood and charcoal consumption often poses threats to the sustainability of regional biomass energy supply capacities. (9.2.1)

One of the most attractive features of increasing the use of local renewable energy sources, especially if local populations either control or share in the control, is their contribution to energy security, as risks for external trading factors to cause sudden, disruptive supply shortages or price increases are reduced. (9.2.3)

Environmental and Social Impacts: Global and Regional Assessment

Renewables have consequences (positive and adverse) to environmental resources and qualities at regional and global level with implications for mitigating and adaptive capacity. Apart from hydropower, windpower and bioenergy, literature describing the impacts of other RE technologies on land, water, air, ecosystems and biodiversity, human health and built environment is limited. In the following paragraphs, some of the most crucial aspects are described. (9.3)

RE technologies have many *similar* positive environmental and social impacts that make them attractive compared to their fossil and nuclear counterparts. On the other hand, the adverse environmental and social issues that affect their deployment and limit development opportunities are more *technology-specific* and in some cases *site specific*. There are mitigative options for the adverse impacts and their implementation can improve and in many cases ensure sustainability of the technologies. Details of the most significant environmental and social impact topics, positive and negative, are shown in Table TS 9.1.

Land use and population: Renewable energy technologies offer a way to improve the use of degraded or desert lands that otherwise may have few productive uses. In addition, small RE power plant sites can coexist with minimal side effects on farming, forestry, and other land uses. RE offer decentralized options, reducing the impacts on land use from ducts and transmission lines.

There are several adverse impacts and conflicts with RE land use especially on lands that are being currently used for food crop production. In addition, there are risks such as land subsidence or soil contamination near geothermal plants, population displacement through the setting up of hydro reservoirs and competition with fishing in oceans. (9.3.1)

Air and Water: Most RE technologies have little or no direct local and global atmospheric emissions, which serves as a strong mitigation mandate. Exceptions include release of methane from hydro reservoirs and biomass burning, in crops or in poorly controlled industrial processes. Even so, such releases are less toxic compared to those from poorly controlled fossil fuel combustion or even with nuclear material accidents. Small bioenergy, solar PV, hydro and other RE plants serve as a valuable resource for local (rural) ground water extraction and supply of basic energy services to communities. Wind farms offer a way to amortize strong winds. (9.3.1)

Similar to fossil fuel sources, however, many types of RE technologies can adversely affect water sources. The need for cooling RE power plants in water-short arid areas, risk of water contamination through geothermal generation, thermal pollution, water quality degradation and health impacts from hydro reservoirs, swell/waves and tidal/ocean currents are established examples of water impacts. (9.3.1)

Ecosystem and Biodiversity: RE plants offer limited direct benefit to ecosystem and biodiversity. Shaded solar reflectors may improve micro-climate and ocean energy sources may increase biodiversity in some locations. On the other hand, loss of biodiversity and disruption of ecosystem structure is a major concern mainly for bioenergy and hydropower. Impacts due to monoculture originating from bioenergy sources, loss of biodiversity and obstacle to fish migration through hydro units, ecological modification of barrages, bird and bat fatalities due to wind farms are classic examples of such problems. Recent projects utilizing modern technologies, following adequate guidelines and providing due environmental compensation have mitigated significantly these adverse effects. (9.3.1)

Human Health: Human health can benefit through low and less toxic emissions from renewable energy sources. Steady and clean water supply from reservoirs serve as recreational and entertaining facilities, as well as for fishing and irrigation. By the same token, uncontrolled bioenergy combustion can increase indoor and outdoor air pollution, manufacturing and disposal of PV modules can generate toxic waste, hydro reservoirs can spread vector borne diseases and noise at wind farms can be a nuisance. (9.3.1)

Built Environment: Not unlike fossil and nuclear plants, RE infrastructure provides socio-economic benefits to local communities through creation of jobs and facilitation of local development. Ocean energy provides additional benefit through protection of coastal erosion. Changes in bioenergy plant landscape, induced local seismicity near geothermal plants, risks from dam bursts or wind tower breakdown, as well as changing conditions at ocean discharge sites are illustrations of concerns about the built environment. (9.3.1)

The environmental impacts associated with RE clearly vary by technology, location, availability of resources (e.g., water), the potential for human exposure, and local ecological susceptibilities. Proper assessments and comparisons of such issues typically require a life-cycle assessment (LCA) approach. Ideally, an LCA will characterize the flows of energy, resources, and pollutants across the life-cycle of an RE technology, which includes activities related to raw materials acquisition, manufacturing, transportation, installation and maintenance, operation, and decommissioning. The ecological and human impacts associated with such flows are further characterized across a range of impact metrics (e.g., global warming potential, human health damages, ecotoxicity, and land use). As such, LCA provides a framework for assessing and comparing RE technologies in an analytically-thorough and environmentally-holistic manner. (9.3.1)

Table TS 9.1: Environmental and Social Benefits (+) and Concerns (-) Associated with Renewable and Conventional Energy Sources

From/ on		Bioenergy	Direct Solar	Geothermal	Hydropower	Ocean Energy	Wind Energy	Nuclear	Fossil Fuels
Land Use and Population	+	positively intensified land uses (e.g. degraded land)	decentralized energy allowing better land use (e.g. degraded or desert)	decentralized energy allowing better land use	stored water for irrigation and other uses (fisheries, domestic use, recreation)	decentralized energy allowing better land use	decentralized electricity co-existing with farming, forestry, etc.	low land use from power plants	some fuels (LPG, kerosene) allow decentralized energy avoiding deforestation
	-	competition with food supply; threats to small landowners	land use (mostly urban) for large installations	risks of land subsidence and/or soil contamination	population displacement / impacts on cultural heritage	competition for areas (e.g., fishing and navigation)	competition for areas, landscape alterations	accidents may affect large areas; mining; decommissioning sites	land occupation and degradation (e.g. mining),
Air and Water	+	decentralized electricity for water extraction and supply; lower GHG emissions	no direct atmospheric emissions; water pumping from PV electricity	no direct atmospheric emissions	low GHG emissions in most cases; impounded water can be used for irrigation, fisheries and domestic uses	no direct atmospheric emissions	no direct emissions; improved water pumping, amortization of strong winds	no direct atmospheric emissions under normal operation	
	-	water usage for crops; fertilizers nitrate pollution; risk of fires; GHG emissions from land clearing	(limited) life cycle pollution; water for cooling CSP plants in arid areas	water usage by power plants in arid areas; risk of water contamination	risks of water quality degradation and associated health impacts; potential high methane emissions in some cases	swell/waves & tidal/ocean currents: possible effects on pollution	nuisances from noise	risks of leakages and accidents releasing toxic material	significant atmospheric emissions (GHG, other pollutants); risks of water spills, leakages, accidents, fires
Ecosystem and Biodiversity	+	possible integration between crops and with bio-corridors/ conservation units	no harm and some benefits (reflectors shade improving micro-climate)	-	-	increase of biodiversity for some constructions	-	no or little impact under normal operation	-
	-	Biodiversity loss; impacts from monoculture, burning practices and habitat land clearing and landscape diversity; invasive species; use of agrochemicals	risks from large scale projects (disruption of ecosystem structure); CSP may affect birds	water contamination effects	loss of biodiversity from inundation, new hydrological regimes; obstacle to fish migration and introduction of alien species	ecological modification from barrages	bird and bat fatalities, impacts from noise	short to long-term effects in case of contamination	loss of biodiversity from pollution and spills; change of vegetation and wildlife in mining and waste-fields
Human Health	+	lower and less toxic air pollutant emissions improving human health	virtually no pollution	cleaner air and improved public health; hot water for spa resorts	virtually no air pollution; water supply from reservoirs can contribute to improved health	virtually no pollution	virtually no pollution	virtually no pollution	-
	-	indoor pollution from traditional biomass burning; health effects from crop burning practices (e.g. sugarcane)	toxic waste from manufacturing and disposal of PV modules	some risks of contaminations	risk of spreading vector borne diseases in tropical areas; odor in isolated cases	-	nuisance effects (e.g., noise)	very significant impacts from potential accidents	effects from pollution (occupational, local, regional, global); significant impacts from potential accidents
Built Environment	+	high level of socio-economic benefits from new infrastructure (e.g. jobs, local development.)	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure; wave power protects coast from erosion	socio-economic benefits from new infrastructure; (some) turbines attractiveness e	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure
	-	changes in landscape, negative visual aspects		induced local seismicity (EGS hydrofracturing); impact on scenic quality and use of natural areas	existing infrastructure damage due to inundation; risks from dam bursts; impacts from induced occupation	changing conditions at discharge sites (OTEC/osmotic power); irreversibility (tidal barrages)	impacts of wind turbines on radar systems; visibility of wind turbines	changes in landscape; necessary escape routes	large mining and processing structures; risks of accidents; impacts from induced occupation

Socio-economic Impacts: Global and Regional Assessment (energy supply security)

Sustainable Development (SD) can be translated in a set of socioeconomic goals applicable to different energy sources and technologies. Some of the most relevant are: poverty reduction; water security; sanitation; food security; energy security; energy access; energy affordability; infrastructure; governance; land use and rural development. Compared to conventional fossil fuels, nuclear energy and large hydropower projects – which have overall highly concentrated and capital intensive production, transformation and distribution chains – renewables have an important role in rural development. Relatively simple systems such as solar panels, improved cookstoves or micro hydropower plants can provide the necessary lighting, heat or electricity to pump water, prepare food, refrigerate vaccines and medicines, or allow education during the night period. (9.2.1)

However, access to modern forms of energy, especially electricity for all purposes and clean fuels for cooking, heating and lighting to the billions of people without them today and in the future is a major challenge in itself. Making the joint achievement of promoting access while simultaneously making a transition to a cleaner and secure energy future is a challenging task. It requires a sustained effort that includes awareness raising, capacity building, policy changes, technology innovation and investment. The shift towards a sustainable energy economy also requires sound analysis of the options by policymakers, good decisions and the sharing of experience and knowledge of individuals and organizations involved in the many practical challenges that such a transition presents. These activities, and the resulting changes, are needed in industrial as well as developing countries (9.4).

Providing relevant and carefully targeted information to the different stakeholders including the general public in order to respond to concerns over climate change related issues, and to the private sector to leverage commercial interest and investments in RE, is found to be key and is already happening in many countries. (9.5.3)

[Authors: Table with quantitative data will be inserted once Chapter 9 Appendix table has been cross-checked with numbers from other chapters].

To create and strengthen institutional capacity, there are a variety of policy instruments, measures, and activities relevant for policy makers and governmental institutions at the national level to further this aim. The adoption of such policies may be directed towards supporting various stages in the RE promotion process from basic R&D at universities, private companies, or non–profit institutions, to demonstration, commercialization, and full deployment stage. Experiences from countries that have effectively promoted private investments in renewable energy show that national strategies, policies and targets are key elements. Most existing successful national renewable energy strategies have wider goals, such as security of energy supplies, environmental protection, climate change mitigation, renewable energy industry development, and ultimately sustainable development (enhancing energy access, alleviating poverty, addressing gender and equity issues, etc). (9.5.3)

Information, data and capacity constraints is often a barrier both for the setting of broad policy priorities and for drafting actual sector-specific legislation. The same constraints may also prevent the private industries, including finance companies, from estimating more accurately the risks of cleaner energy technology investments, and stifles more widespread adoption of cleaner energy technologies by industry esp. in many developing countries. (9.5.3)

Decision making and policy implementation has also in many countries changed from solely being the responsibility of certain government levels to increasingly involving various private sector stakeholders, NGO's, and civil society. This shift is incorporated in the inclusive concept of governance, which reflects the need to involve and give influential mandate to relevant parties in order to reach desired and successful outcomes. (9.5.3)

Overall, policies can be grouped into seven main categories i) research, development and demonstration incentives; ii) investment incentives; iii) tax measures; iv) incentive tariffs; v) voluntary programs; vi) mandatory programs or obligations; and vii) tradable certificates. The evolution of these policies since the 1970s reflects among other things, an increased market orientation or policies moving from regulation towards economic policy tools. Presently, feed-in tariffs, obligations and tradable green certificates are emerging as the main policy instruments in many developed and increasingly some developing countries. Investment incentives and various tax measures do, however, remain important mechanisms to stimulate renewable energy investment, and it remains to be seen if the current financial crisis will affect policy tools in a potential move back towards more direct government regulation. (9.5.3)

The gradual shift from regulatory approaches towards more economic and market oriented policy tools also has implications for the expertise required to develop and implement policies reflecting back on the need for new approaches on the capacity building side. This links in many developing countries with broader shift of the whole perception of RE implementation from niche applications and demonstration projects to having targets and policies at national level (Table TS 9.2). (9.5.3)

In most cases, the proprietary ownership of RE technologies is in the hands of private sector companies and not in the public domain and the diffusion of technologies also typically occurs through markets in which companies are key actors. This necessitates a need to focus on the capacity of these actors to develop, implement and deploy RE technologies in various countries, especially in firms in late-industrialising or emerging economies. (9.5.4)

Table TS 9.2 Renewable Energy Markets in Developing Countries

Old Paradigm		New paradigm
Technology assessment	⇨	Market assessment
Equipment supply focus	⇨	Application, value-added, and user focus
Economic viability	⇨	Policy, financing, institutional, and social needs and solutions
Technical demonstrations	⇨	Demonstrations of business, financing, institutional and social models
Donor gifts of equipment	⇨	Donors sharing the risks and costs of building sustainable markets
Programs and intentions	⇨	Experience, results, and lessons

Source: Eric Martinot. et al (2002)

Capacity building and technical support by or for the public sector can usefully address issues that facilitate more rapid development and implementation of RE by private companies and can for example cover issues like data on resources and technology performance, strict testing and licensing procedures and increased investments in research and development of renewable energies. (9.4.3.3)

Implications of (Sustainable) Development Pathways for Renewable Energy

It is widely accepted that energy is linked with more or less all aspects of sustainable development. It is an engine for growth and poverty reduction, and therefore it has to be accorded high priority and this has to be reflected in policies, programs and partnerships at national and international levels. The provision of energy in a sustainable way, guaranteeing the availability of resources, security of supply, environmental, economic and social compatibility and low-risk production, is therefore pivotal to the aim of achieving sustainable development. (9.4)

However, the reverse relationship whereby development that is sustainable can create conditions in which renewables mitigation can be effectively pursued is equally important and needs to be highlighted in future development pathways. Most development pathways already focus on SD goals such as poverty alleviation, water and food security, access to energy, reliable infrastructure, etc. How to make these pathways more sustainable such that GHG emissions are reduced is critically important for permitting an increased role for renewable energy technologies.

Future scenarios of renewables for different regions, different end-user sections and different energy sources need to consider a broad spectrum of possible RETs, as well as the associated risks, the affordability and limitations of the proposed technologies. Furthermore, to achieve low stabilisation targets, not only all technology options have to be evaluated, but also all sources of CO_2 and non-CO_2 emissions have to be considered. When assessing different future scenarios for renewable energy in the context of sustainable development, questions like how are we going to deal with a conventional baseline in terms of equity, trade, security, environment, as well as the impact of subsidies, need to be addressed. What will be possible outcomes in the medium to long-term? And how will this impact on how development pathways are determined. (9.4.1)

To facilitate a global transition to renewable energy will require large investment in national, regional and local energy infrastructures in developing as well as developed countries and economies in transition. These investments will need to come from the public and the private sectors and will have to take many forms, including financial incentives from government, loans and capital investment from banks, private investors, venture capital funds and communities, as well as new innovative markets that contribute to the benefits of renewable energy and energy efficiency. (9.4.2)

While some developing countries have the opportunity to leapfrog the more polluting fossil fuel based technologies and industries and move directly to more advanced renewable energy technologies, they cannot afford to be dependent on technology transfer and foreign supply to sustain their technological progress. Instead, technology transfer needs to be coupled with capacity building. This requires finance mechanisms that are appropriate for the specific conditions within which they are applied. (9.4.2)

On the global level there is a recognized need for the international community to strengthen its commitment to the scaling up of renewable energy development and use, especially in developing countries. There is a range of international and national institutions that play an important role in building capacity and improving financing and transfer of technology know-how for renewable energies. In addition, numerous international and regional initiatives and efforts, such as WSSD, the G-8 Gleneagles Summit and the European Union energy policy, are strongly involved in the advancement of renewable energy technologies. On the national level, government institutions can stimulate technical progress and speed up the technological learning processes so that RETs will be able to compete with conventional technologies, once the environmental costs have been internalised. (9.4.8)

Gaps in Knowledge and Future Research Needs

As noted in the introductory section, there is a two-way relationship between sustainable development and renewables. Renewable sources can reduce emissions that will help to better manage the process of climatic change but this reduction may not be adequate to lower temperature increases to tolerable levels. Sustainable development pathways can help achieve these reductions by lowering the overall need for energy particularly fossil fuel supply. Pathways that improve energy access and infrastructure in rural areas for example can lead to less-carbon-intensive energy demand thus reducing the need for overall energy supply. Identifying, documenting and quantifying such pathways and their impact on renewables is a critical need.

A related important step is to identify non-climate policies that affect GHG emissions and sinks, and ways these could be modified to increase the role of renewable energy sources. Often such policies have to be context specific requiring research and analysis that is local or regional.

The current set of global models has rarely looked at development paths with non-climate policies. Development of such models requires a broader set of researchers with strong quantitative SD background who can help define and understand various development paths. This applies to both industrialized and developing countries.

Future research will need to examine the role of renewable energy and its implications on the pursuit of sustainable development goals. Several chapters in this report provide information on the implications of renewable energy sources on various SD attributes. Missing is a complete understanding of the life-cycle analysis (LCA) of the implications of the use of renewable energy and so far methods, tools and data sources are lacking sufficient quality and comparability. Future work will need to focus on this important aspect of renewable energy, which in some cases has minor or no direct GHG emissions but may have significant indirect emissions.

Mitigation Potential and Costs

Introduction

The implementation of mitigation technologies is triggered, amongst others, by cost effects or specific policy incentives (IEA 2008b). The uncertain future is reflected in the wide, and growing, range of emissions pathways across emission scenarios in the literature,(Calvin et al, 2009) as was well reflected in the most recent IPCC assessment report (IPCC, 2007).AR 4 focused on the behaviour of the overall energy system and, as such, discussion of single technologies as a matter of course had to be rather short. One of the main questions in that context is the role renewable energy sources (RE) are likely to play in the future and how they can particularly contribute to GHG-mitigation pathways.

RE, following the investigated scenarios, is expected to play an important, and increasing, role in achieving ambitious climate mitigation targets but already even without setting any climate protection goals. Although some RE technologies already belong to competitive technologies (e.g. large hydropower) and many others are becoming increasingly market competitive, there are still innovative technologies in the field of RE under the given frame conditions have a long way to go before becoming mature alternatives to non-renewable technologies.

Behind this background, this chapter discusses the mitigation potentials and related costs of RE technologies based on an assessment of the most recent scenario literature available on the subject. An in-depth analysis of selected scenarios is used to come to a technological and regional breakdown. Underlying assumptions about scenario based supply curves are also stressed as so far as given data allows costs for commercialization and deployment. A discussion about social and environmental cost and benefits closes the section.

Synthesis of Mitigation Scenarios for Different Renewable Energy Strategies

A total of 162 recent medium- to long-term scenarios from large-scale, integrated, energy-economic and integrated assessment models are reviewed to provide context for understanding the role of RE in climate mitigation. Although this set of scenarios is by no means exhaustive of recent work on mitigation scenarios, it is large enough and extensive enough to provide robust insights. The full set of scenarios covers a large range of CO_2 concentrations (350-1050 ppm atmospheric CO_2 concentration by 2100), some of which represent scenarios of aggressive action to address climate change and other of which represent no-policy, or baseline, scenarios. The full set of scenarios also covers time horizons 2050 to 2100, and all of the scenarios are global in scope.

These scenarios reflect the most recent understanding of key underlying parameters and the most up-to-date representations of the dynamics of the underlying human and Earth systems. The scenarios also include a relatively large number of "2nd-best" scenarios which cover less optimistic views on international action to deal with climate change (delayed participation) or address consequences of limited mitigation portfolios (technology failure). Although scenarios assuming idealized climate policy approaches and full technology availability ("1st-best scenarios") have historically dominated the mitigation scenario literature, 2nd-best scenarios have received growing attention in recent years.

The statistical perspective applied gives a comprehensive overview about the full range of mitigation scenarios and tries to identify the major relevant driving forces and system interactions (e.g. competing technologies) for the resulting RE deployment in the market and the specific role of these technologies in mitigation paths. One focus is to assess the robust evolutions of RE as a whole and single technologies reflecting different sets of assumptions.

Following the scenario analysis, increasing demand for energy, and for low-carbon energy in particular, if the world chose to reduce greenhouse gas emissions, could lead to a great variation in the deployment characteristics of individual technologies (**Error! Reference source not found.** and Figure TS 10.2).

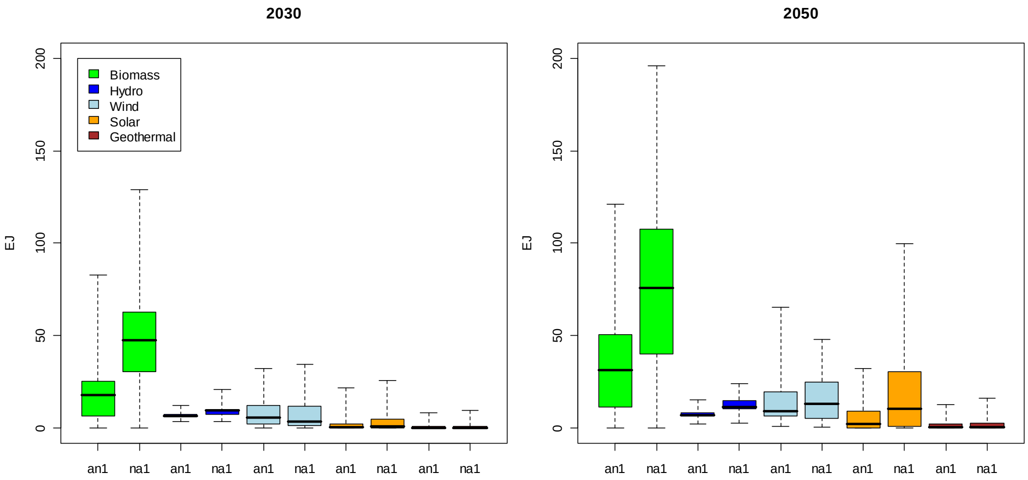

Figure TS 10.1 Renewable primary energy consumption by source in Annex I (an1) and Non-Annex I (na1) countries in the long-term scenarios by 2030 and 2050. [The thick black line corresponds to the median, the colored box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios.]

Several dimensions of this variation bear mention. First, the absolute scales of deployments vary considerably among technologies, representing differing assumptions about long-term potential. Bioenergy deployment is of a dramatically higher scale over the coming 40 years than any of the other RE technologies, although it should be noted that the figures include traditional biomass which contributes close to 40 EJ in the base year with a modest decline over time in most scenarios. By 2050, wind and solar constitute a second tier of deployment levels. Hydroelectric power and geothermal power deployments fall into a lower tier. The variation in these deployment levels represents assumptions by the scenario developers regarding the cost, performance, and potential of these different sources. They indicate, for example, that the consensus among scenario developers is that solar power, bioenergy, and wind power are the most likely large-scale contributors in the 2050 time frame and beyond; there is room for growth in hydroelectric power and geothermal power, but the potential for this growth is limited.

Second, the time-scale of deployment varies across different RE sources, in large part representing differing assumptions about technological maturity. Hydro, wind and biomass show a significant deployment over the coming one or two decades in absolute terms. These are the most mature of the technologies. Solar energy is deployed to a large extent beyond 2030, but at a scale that is surpassing that of the other RE sources apart from biomass, capturing the notion that there is substantial room for technological improvements over the next several decades that will make solar largely competitive and increase the capability to integrate solar power in the electricity system. Indeed, solar energy deployment by 2100 is on the same scale at bioenergy production. Direct biomass use in the end-use sectors is largely stable or even slightly declining across the scenarios. It should be noted that direct use is dominated by traditional, non-commercial fuel use in developing countries which is typically assumed to decline as economic development progresses.

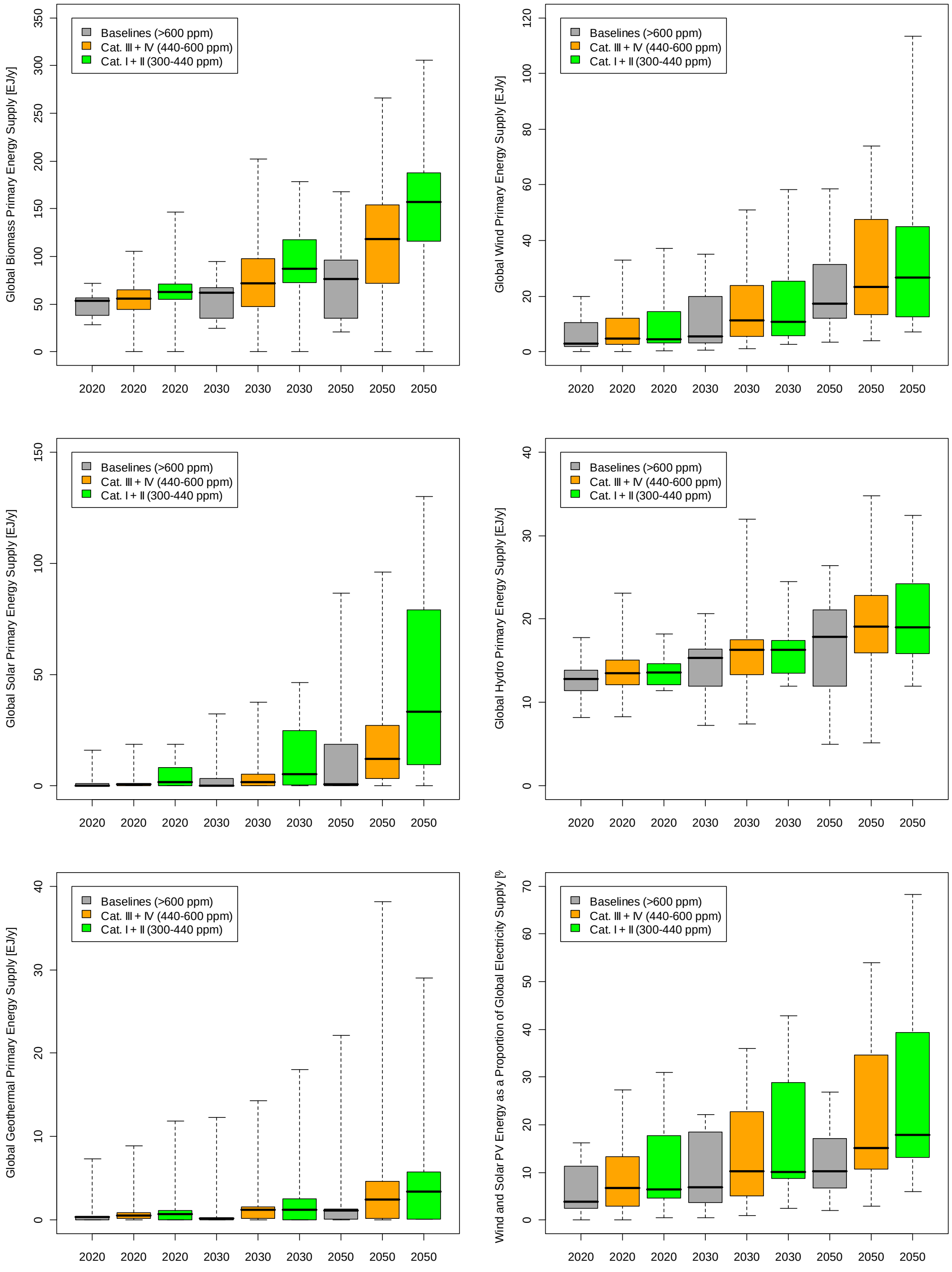

Figure TS 10.2 Global primary energy supply of biomass, wind, solar, hydro, geothermal and share of variable renewables (wind and solar PV) in global electricity generation in the long-term scenarios by 2020, 2030 and 2050, grouped by different categories of atmospheric CO2 concentration level in 2100. [The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios.]

This decrease cannot be compensated by an increase in commercial direct biomass use in the majority of scenarios. In contrast, biomass that is used as a feedstock for liquids production or an input to electricity production – commercial biomass – is increasing over time, reflecting assumptions about growth in the ability to produce bioenergy from advanced feedstocks, such as cellulosic feedstocks.

Third, the deployment of some RE sources in the scenarios is driven mostly by climate policy (e.g. solar, geothermal, commercial biomass) whereas others are deployed irrespective of climate action (e.g. wind, hydro, direct use of bioenergy) (Figure TS 10.2). This is also to a large degree a reflection of assumptions regarding technology maturity. Wind and hydro are already considered largely mature technologies, so the imposition of climate policy would not provide the same increase in competitiveness as it would for emerging technologies such as solar, geothermal, and advanced bioenergy.

Finally, the distribution of RE deployments across countries is highly dependent on the nature of the policy structure. In scenarios that assume a globally efficient regime in which emissions reductions are undertaken where and when they will be most cost-effective, non-Annex 1 countries begin to take on a larger share of RE deployment toward mid-century. This is a direct result of the assumption that these regions will continue to represent an increasingly large share of total global energy demand, along with the assumption that RE supplies are large enough to support this growth. All other things being equal, higher energy demands will require greater deployment of RE sources. This is important in the sense that it highlights that RE sources in climate mitigation is both an Annex 1 and a non-Annex 1 issue.

The notion that deployment in the non-Annex 1 will become increasingly important is robust across scenarios; in the long run, meeting the stricter goals will require fully comprehensive global mitigation. At the same time, a more realistic assumption regarding the near- to mid-term is that mitigation efforts may differ substantially across regions, with some regions taking on larger commitments than others. In this real-world context, the distribution of RE deployments in the near-term would be skewed toward those countries taking the most aggressive action.

Assessment of Representative Mitigation Scenarios for Different Renewable Energy

The regional and global energy scenarios found in the literature show a wide range of RE deployment in the future, as portrayed in the previous section. In this section, a selected part of the global scenarios is reviewed, with a more detailed and near-term-focus, providing a next level of detail for exploring the role of RE in climate change mitigation. Four scenarios integrate the subgroup here reviewed, representing the whole scope of available literature, from a more or less business as usual pathway to a more optimistic deployment scenario path for RE, assuming that the current dynamic in the sector can be maintained. These four scenarios are: the ReMind, EMF 22, IEA World Energy Outlook 2009 and Energy [R]evolution scenarios. Interesting enough, even without having reached their full technological development limits, technical potentials seem not to be the limiting factor to the expansion of RE in all scenarios reviewed.

The total contribution of renewable energy sources to the world global primary energy demand is the summary of the four scenario outcomes for all sectors: power generation, heating/cooling and transport. Figures TS 10.3 and TS 10.4 provide, for the four scenarios here reviewed, summaries of both global RE development projections by technology (Figure TS 10.3), and global RE development projections by source and global renewable primary energy shares by source (Figure TS 10.4) for 2020, 2030 and 2050. Bioenergy has the highest market share all scenarios, followed by solar. This is due to the fact, that bioenergy can be used across all sectors (power, heating & cooling as well as transport), while solar can be used for power generation and heating/cooling. As the residual material potential and available land for bioenergy is limited and competition with nature conservation issues as well as food production must be avoided, the sectoral use for the available bioenergy depends on where it is used most efficiently. Cogeneration power plants use bioenergy most efficiently to a level of up to 90%.

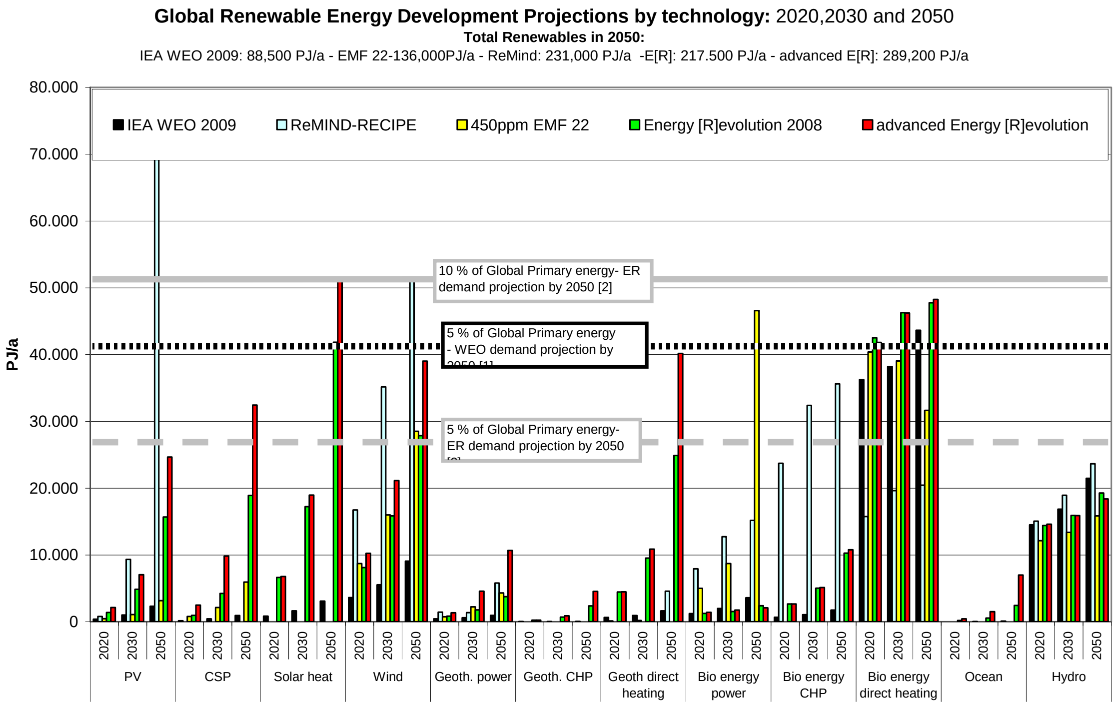

Figure TS 10.3 Global Renewable Energy Development Projections by Technology

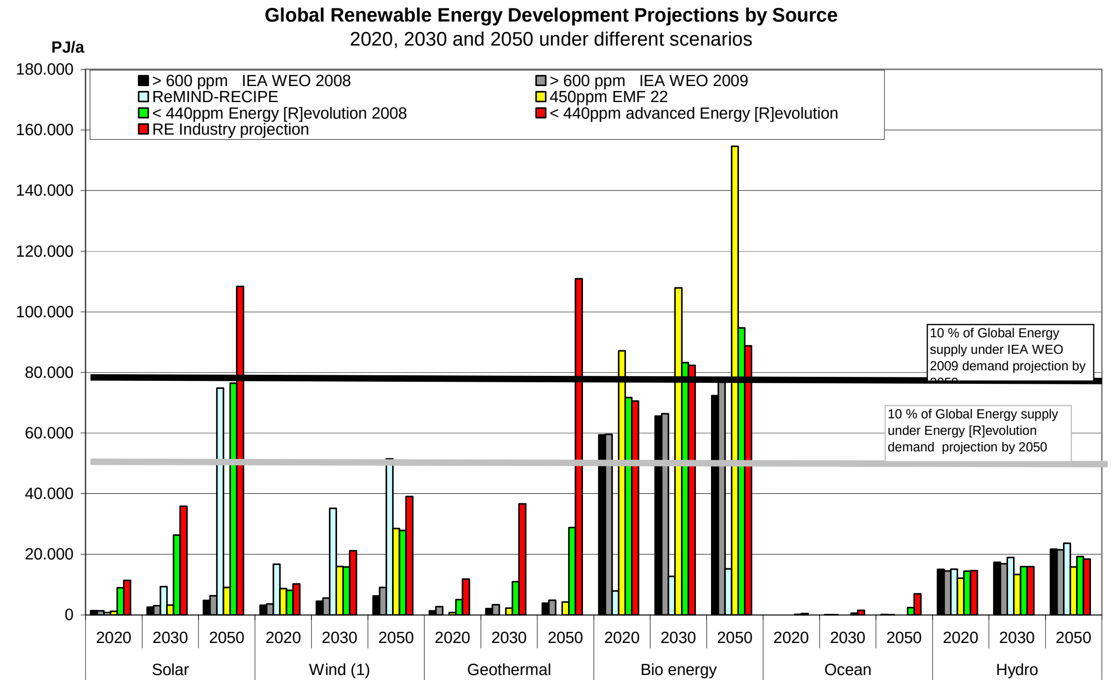

Figure TS 10.4 Global Renewable Energy Development Projections by Source and Global renewable primary energy shares by source

However solar energy can be used for heating/cooling and power generation as well, but solar technology starts from a relatively low level. In the medium case, solar energy ranks third by 2050 followed by hydro and wind energy. The relatively low primary energy share for wind and hydro is due to its exclusive use in the power sector. None of the analysed scenarios looks in to the use of wind in the transport sector, such as advanced wind drives for shipping.

The total renewable energy share by 2050 has a huge variation across all four scenarios. With only 15% by 2050 – about today´s level – the IEA WEO 2009 projects the lowest renewable energy share, while the Energy [R]evolution achieves 56% of the worlds primary energy demand. Both the ReMind and EMF 22 projection are in the range of one quarter renewable energy by 2030 and one third by 2050.

Finally, when it comes to regional scenarios, some scenarios available in the literature also show a wide range of the RE shares in the future. In order to show the different ranges of deployment rates for RE sources by sector and region, Figure TS 10.5 compares a reference scenario (>600ppm), which was developed from the German Space Agency (DLR) on the basis of the IEA World Energy Outlook 2007, with a category II (<440ppm) scenario (Energy [R]evolution 2008 DLR/EREC/GPI). While the reference scenario more or less represents the pathway of a “frozen” energy policy, the ER2008 assumes a wide range of policy measure in favour of renewable energy sources as well as a significant price setting for carbon.

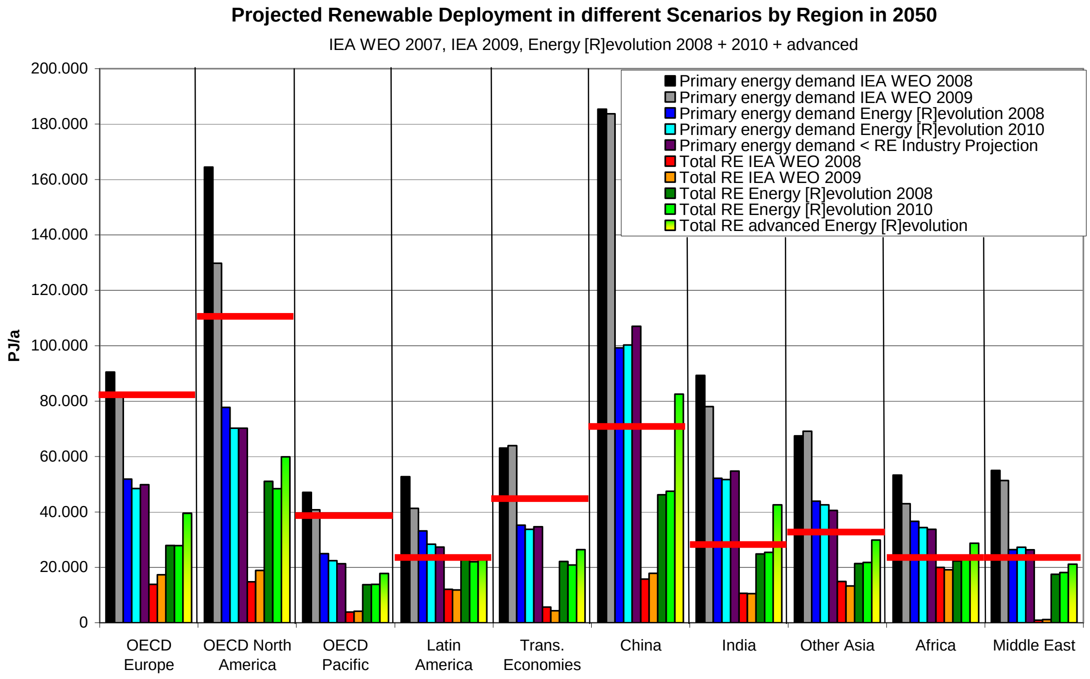

Figure TS 10.5 Regional breakdown from possible renewable energy market potential: Reference (> 600ppm) versus Category II (<440ppm) scenario

Regional Cost Curves for Mitigation with Renewables

Cost curves have already been touched upon in the previous section. While these curves illustrate, from a specific perspective, how scenarios see RE deployment and which technology when and at what cost, additionally the existing literature on regional RE sources supply curves as well as abatement cost curves as they pertain to mitigation using RE are reviewed.

The concept of supply curves of carbon abatement, energy, or conserved energy all rest on the same foundation. They are curves consisting typically of discreet steps, each step relating the marginal cost of the abatement measure/energy generation technology or measure to conserve energy to its marginal cost; and rank these steps according to their cost. As a result, a curve is obtained that can be interpreted similarly to the concept of supply curves in traditional economics.

This concept is very often used approach for mitigation strategy setting and prioritizing abatement options. One of the most important strengths of this method is, of course, that the results can be understood easily and that the outcomes of those methods give, on a first glance, a clear orientation as they rank available options in order of cost-effectiveness.

While abatement curves are very practical and can provide important strategic overviews, it is pertinent to understand that their use for direct and concrete decision-making has also some severe limitations. Most of the concerns are, amongst others, related to simplification issues; difficulties with the interpretation of negative costs; the reflecting of real actor's choice; the uncertainty factors with regard to the discount rate as a crucial assumption for the resulting cost data; the missing dynamic system perspective considering relevant interactions with the overall system behaviour; and the sometimes not very sufficient documentation status. For GHG abatement cost curves, a key input that largely influences the results is the carbon intensity, or emission factor of the country or area to which it is applied, and the uncertainty in projecting this into the future. This may lead to a situation where the option in one locality is a much more attractive mitigation measure as compared to an alternative than in another one simply as a result of the differences in emission factors. As a result, a carbon abatement curve for a future date may say more about expected policies on fossil fuels than about the actual measures analyzed by the curves, and the ranking of the individual measures is also very sensitive to the developments in carbon intensity of energy supply.

The reviews of the existing regional and national literature on RE supply or, more generally, mitigation potential related cost curves , show a very broad range of results (Table TS 10.1). In general, it is very difficult to compare data and findings from different RE supply curves, as there have been very few studies using a comprehensive and consistent approach and detail their methodology, and most studies use different assumptions (technologies reviewed, target year, discount rate, energy prices, deployment dynamics, technology learning, etc.). Therefore, country- or regional findings in need to be compared with caution, and for the same reasons findings for the same country can be very different in different studies. The weakness of many regional or technology studies is that they usually do not account for the competition for land and other resources such as capital among the various energy sources (except for probably the various plant species in the case of biomass). In studies that do take this into account, potentials seriously decline in case of exclusive land use, with solar PV suffering the worst losses both in technical and economic potential.

Regional carbon abatement cost curves related to RE deployment, on the other hand, have a different focus, goal and approach as compared to RE supply curve studies, and are broader in scope, examining RE sources within a wider portfolio of mitigation options (Table TS 10.2). One general trend can be observed based on this limited sample of studies. Abatement curve studies tend to find lower potentials for mitigation through RE sources than those focusing on RE for energy supply. Even for a same country these two approaches may find very different potentials. For instance, the Enviros (2005) study identified a 33% potential by renewable energy as a percentage of 2015 TPES in the UK (see) under the cost of 200 USD/MWh; while CBI (2007) attributed only an 0.93% carbon mitigation potential for renewables for the UK for 2020 under the cost of 200 USD/t CO_2e. The highest figure in carbon mitigation potential share by the deployment of RE sources, as demonstrated by

, is for Australia: 13.43% under 200 USD/t CO_2e by 2030 (in contrast with the much higher shares as a percentage of national TPES reported before) (data from McKinsey and Company 2008a).

One factor contributing to this general trend is that RE supply studies typically examine a broader portfolio of RE technologies, while the carbon mitigation studies reviewed focus on selected resources/technologies to keep models and calculations at reasonable complexity. For instance, remaining with the UK example, the CBI (2007) study does not take into consideration other RE sources presented by Enviros (2005) as low-cost options, such as landfill gas, sewage gas and hydropower.

Table TS 0.2 Summary of regional/national literature on renewable energy supply curves, with the potentials grouped into cost categories

Country/region		Cost ($/MWh)	Total RES (TWh/yr)	% of baseline	Discount rate (%)	Notes	Source
Central and Eastern Europe		<100	3,233	74	N/A	- Biomass only, best scenario with willow being the selected energy crop (highest yield) - Countries: BG, CZ, EST, HU, LV, LT, PL, RO, SK - Baseline data includes Slovenia, however, its share is rather low, therefore resulting distortion is not so high.	RES data: van Dam et al. (2007) Target year: 2030 Baseline data: Solinski (2005)
Czech Republic		<100	101	20	4	- Only biomass production - Best case scenario where future yields equal the level of the Netherlands	RES data: Lewandowski et al. (2006) Target year: 2030 Baseline data: IEA (2005)
Germany		<100	160	24	N/A	- Only Wind and PV are included - PV only enters above 200 USD	RES data: Scholz (2008) Baseline data: McKinsey and Company (2007)
		<200	177	27			
		<300	372	56			
Global (Biomass)		<100	97,200	N/A	10	- Study claims biomass production under this price can exceed present electricity consumption multiple times	Hoogwijk et al. (2003) Target year not specified
Global		< 100	200,000-300,000	>100	10	- Combined potential of Onshore Wind, solar PV and Biomass given land usage constrains and technology scenarios - Sources of uncertainty considered	de Vries et al. (2006), baseline: World Energy Council, 2001 and Hoogwijk, 2004.
Global	Wind	<100	42,000	133	10	- Liquid transport fuel and electricity from biomass, onshore wind, PV - Capacity calculated for the whole world, grid connections, supply-demand relationships etc. not incorporated - Global technical potential for electricity generation - High technology development scenario (A1) with stabilizing world population and fast and widespread yield improvements.	RES data: de Vries et al. (2007) Target year: 2050 Baseline data: IEA (2003)
		<80	39,000	123			
		<60	23,000	72			
		<40	2,000	6			
	Biomass	<60	59,000	187			
	PV	<100	1,850,000	5,868			
		<80	400,000	1,268			
Global		<70	21,000	600-700	10	- Technical potential for onshore wind based on wind strength and land use issues, grid availability, network operation and energy storage issues are ignored - baseline refers to 2001 world electricity consumption	Hoogwijk et al. (2004), Reference year: 2004 baseline IEA 1996
		<100	53,000				
	Former USSR	<70	2,000	160			
		<100	7,000	550			
	USA	<70	3,000	80			
		<100	13,000	350			
	East Asia	<70	0	0			
		<100	50	3			

Western Europe	<70 <100	1,000 2,000	40 80			

Country/region	Cost ($/MWh)	Total RES (TWh/yr)	% of baseline	Discount rate (%)	Notes	Source
Global	<50	121,805	N/A	10	- Biomass energy from short-rotation crops at abandoned cropland and restland - four IPCC CRES land-use scenarios for the year 2050 - land productivity improvement over time, cost reductions due to learning and capital-labour substitution - Present world electricity consumption (20 PWh/yr) may be generated at costs below $45/MWh (A1 B1 scenarios) and 50 $/MWh (A2 B2 scenarios) in 2050	Hoogwijk et al. (2009) Target year: 2050
Former USSR		23,538				
USA		9,444				
East Asia		17,666				
OECD Europe		3,194				
India	<200	450,000	12	10	- wind - Grid availability not expected to be a serious concern - baseline refers to 2005 electricity consumption	Pillai et al. (2009) Target year: 2030
	<100	140,000	6		- small hydro - Grid availability not expected to be a serious concern - baseline refers to 2005 electricity consumption	
Netherlands	<100	22	2.1	N/A	- Included: onshore and offshore wind, PV, biomass and hydro; - Interest rate is not available, however, this option is a scenario where sustainable production is calculated. Therefore they use 5% IRR assuming that there are governmental support; - Baseline is TPES forecast for 2020 by IEA;	RES data: Junginger et al. 2004 Reference year: 2020 Baseline data: IEA (2006)
	<200	23	2.2			
	<300	24	2.3			
UK	<100	815	22	7.9	- Included: "Low-cost technologies" (landfill gas, onshore wind, sewage gas, hydro); - Costs: capital, operating and financing elements; - Baseline is all electricity generated in the UK forecasted for 2015;	RES data: Enviros (2005) Baseline data: UK SSEFRA (2006)
	<200	119	33			
United States	<100	3,421	15	N/A	- Wind energy only	RES data: Milligan (2007) Baseline data: EIA (2009)
United States (WGA)	<100	177	0.77	N/A	- Only the WGA region - CSP, biomass, and geothermal; - Geothermal reaches maximum capacity under 100 $/MWh; - CSP has a large potential, but full range is between 100 and 200 $/MWh	RES data: Mehos and Kearney (2007), Overend and Milbrandt (2007), Vorum and Tester (2007) Baseline data: EIA (2009)
	<200	1,959	8.5			
	<300	1,971	8.6			
United States (AZ 2025)	<100	0.28	N/A	Biomass and PV: 7.5	- State of Arizona, United States - RES: wind, biomass, solar, hydro, geothermal - Interest rates vary between energy sources	RES data: Black & Veatch Corporation (2007)
	<200	10.5	N/A			

	<300	20	N/A	7.5 Rest: 8	Interest rates vary between energy sources	

Table TS 0.3 Summary of carbon abatement cost curves literature (cells including grey literature are coloured in grey)

Country/region	Year	Cost ($/tCO2e)	Mitigation potential (million tonnes CO2)	% of baseline	Discount rate (%)	Notes	Source
Annex I	2020	<100	2,818	20	N/A	- Different abatement allocations analysed depending (equal marginal cost, per capita emission right convergence, equal percentage reduction) - CO2 equivalent emissions six Kyoto GHGs, but exclude LULUCF - Costs in 2005 USD	Elzen et al. (2009) Baseline Scenario: WEO 2009
Australia	2020	<100	74	9.5	N/A		McKinsey and Company (2008a)
Australia	2030	<100	105	13			
Australia (NSW Region)	2014	<100	8.1	1.0	N/A	- New South Wales region - Includes governmental support for RES	Abatement data: Next Energy (2004) Baseline data: McKinsey (2008a)
		<300	8.5	1.1			
China	2030	<100	1,560	11	4		McKinsey and Company (2009a)
China	2030	<50	3,484	30	N/A	- Storylines do not describe all possible development (eg. disaster scenarios, explicit new climate policies) - Main abatement (half of total) is efficiency, the rest is renewable and fuel switch from coal	Van Vuuren et al. (2003) Baseline scenario: IPCC SRES (2000) Baseline Scenario: WEO 2009

China	2030	<100	2,323	20	N/A	- Main factor influencing abatement cost is constraints on the rollout of nuclear power - Baseline seems to be underestimated as 2010 power consumption is 40% below fact.	Chen, 2005 Baseline Scenario: WEO 2009
Country/region	Year	Cost ($/tCO2e)	Mitigation potential (million tonnes CO2)	% of baseline	Discount rate (%)	Notes	Source
Czech Republic	2030	<100	9.3	6.2	N/A	- Scenario with maximum use of renewable energy sources	McKinsey and Company (2008b)
		<200	11.9	8.0			
		<300	16.6	11			
Germany	2020	<100	20	1.9	7	- Societal costs (governmental compensation not included)	McKinsey and Company (2007)
		<200	31	3.0			
		<300	34	3.2			
Global	2030	<100	6,390	9.1	4	- Scenario A (Maximum growth of renewables and nuclear) - Scenario B (50% growth of renewables and nuclear)	McKinsey and Company (2009c)
		<100	4,070	5.8			
Global	2050	<200	46,195	85	N/A	- Key sensitivities: lower potential for wind, hydro or CCS, lower uranium resources raise abatement costs by 2-5%	Syri et al. (2008). Baseline model: global ETSAP/TIAM Baseline Scenario: WEO 2009
Poland	2015	<100	50	11	6	- Only biomass - Best case scenario	Abatement data: Dornburg et al. (2007) Baseline data: EEA (2007)
		<200	55.90	12			
Switzerland	2030	<100	0.9	1.6	2,5	- Base case scenario	McKinsey and Company (2009b)
South Africa	2050	<100	83	5.2	10	- Renewable electricity to 50% scenario	Hughes et al. (2007)
Sweden	2020	<100	1.26	1.9	N/A		McKinsey and Co. (2008c)
United States	2030	<100	380	3.7	7		Creyts et al. (2007)

United Kingdom	2020	<100	4.38	0.46	N/A		CBI (2007)
		<200	8.76	0.93			

Costs of Commercialization and Deployment

This sections reviews current RE technology costs, as well as the expectations on how these costs might evolve into the future resulting in assumptions regarding the cost of commercialization and deployment.

Although some technologies are already competitive (e.g., large hydropower, combustible biomass (under favorable conditions) and larger geothermal projects (>30 MW), IEA, 2007a, page 6), many innovative technologies in this field are still on the way to becoming mature alternatives to fossil fuel technologies (IEA, 2008a). Currently and in the mid-term, the application of these technologies therefore will result in additional (private) costs compared to energy supply from conventional sources if external costs are not considered.

Most technologies applied in the field of renewable energy usage are innovative technologies. As a consequence, huge opportunities exist to improve the energetic efficiency of the technologies, and/or to decrease their production costs. Together with mass market effects, these two effects are expected to decrease the levelized energy generation cost of many renewable energy sourcing technologies substantially in the future.

As a consequence of a growing demand on the market in combination with significant R&D expenditures, many technologies applied in the field of renewable energies showed a significant cost decrease in the past (see Figure TS 10.6). This effect is called technological learning. However, the respective learning rate is not time-independent. Care must be taken if historic experience curves are extrapolated in order to predict future costs. Obviously, the cost reduction cannot go ad infinitum and there might be some unexpected steps in the curve in practice (e.g. caused by technology breakthroughs). In order to avoid implausible results, integrated assessment models that extrapolate experience cost curves in order to assess future costs therefore should constrain the cost reduction by appropriate *floor costs* (cf. Edenhofer et al., 2006).

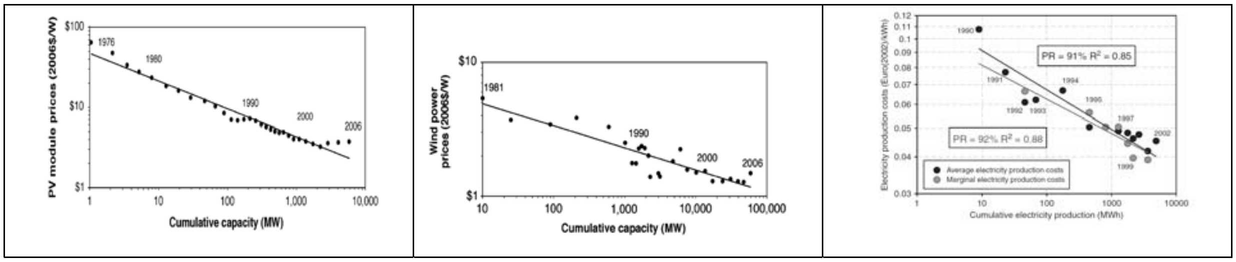

Figure TS 10.6 Illustrative learning curves for a) photovoltaic modules, b) wind turbines and c) Swedish bio-fuelled combined-heat and power plants. Source: Nemet, 2009, Junginger et al. 2006. Due to data gaps learning curves normally have to be based on product prices and not the underlying real costs. Both might differ significantly from each other and deviations can be explained by supply bottlenecks for instance or by typical effects of demand or supply driven markets.

In the beginning of the deployment phase, additional costs are expected to be positive (“expenditures”). Due to technological learning and the possibility of increasing fossil fuel prices, additional costs could be negative after some decades. A least cost approach towards a decarbonized economy therefore should not focus solely on the additional costs that are incurred until the break-even point with conventional technologies has been achieved (learning investments). After the break-even point, the innovative technologies considered are able to supply energy with costs lower than the traditional supply. As these costs savings occur then (after the break-even point) and indefinitely thereafter, their present value might be able to compensate the upfront investments (additional investment needs). Whether this is the case depends on various factors and technology.

From a macro-economic perspective significant upfront investments in innovative renewable energy technologies are often justified if these technologies are promising with respect to their renewable resource potential and their learning capability (Edenhofer et al., 2006). Unfortunately, many of the existing global energy scenarios do not calculate *technology specific* mitigation costs in a comprehensive way. Therefore, there is a severe lack of economic assessments, in general, and additional costs of technology specific mitigation paths and the avoided cost in a longer time period, in particular. The IPCC AR4 highlights the overall GDP losses of different mitigation paths (referring to given scenarios), but does not specify the resulting transition costs of specific renewable energy penetration strategies. In order to fill this gap, the present report focuses at least using illustrative examples on the cumulative and time dependent expenditures that are needed in the deployment phase in order to realize ambitious renewable energy pathways.

In the following Figure TS 10.7, deployment cost estimates indicating how much money will be spent in the sector of renewable energies once these scenarios materialize are shown for different emission mitigation scenarios discussed in Chapter 10.3. The given numbers therefore are important for investors who are interested in the expected market volume.

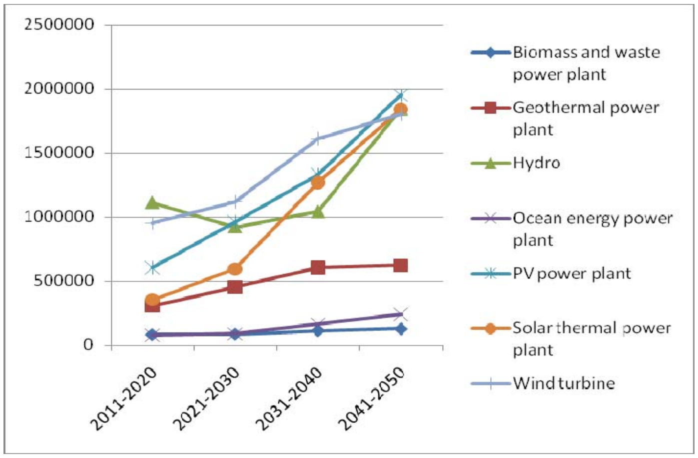

Figure TS 10.7 Illustrative global decadal investment needs (in Mio US $2005) in order to achieve ambitious climate protection goals. Source: Greenpeace, 2007. [Editorial note: In the second order draft, this diagram will be replaced by common assessment of various top-down studies discussed in Chapter 10.2. The corresponding deployment cost ranges will be depicted similar to Fig.8 of Chapter 10.2 that shows the total primary energy supply for different renewable energy sources.]

Although a few scenarios considered in Chapter 10.3 provide technology specific data on the associated (investment) needs no global scenario currently is able to deliver the fossil fuel cost that are avoided by the deployment of the various renewable energy technologies – and to attach the respective share to the considered technology which is a clear knowledge gap. Only for some regions as here (Figure TS 10.8) shown for Germany taking the so called Lead Scenario which was conducted on behalf of the German Ministry for Environment as an illustrative example the upfront investment in renewable energies have been compared with fossil fuel costs that can be avoided in the long-term.

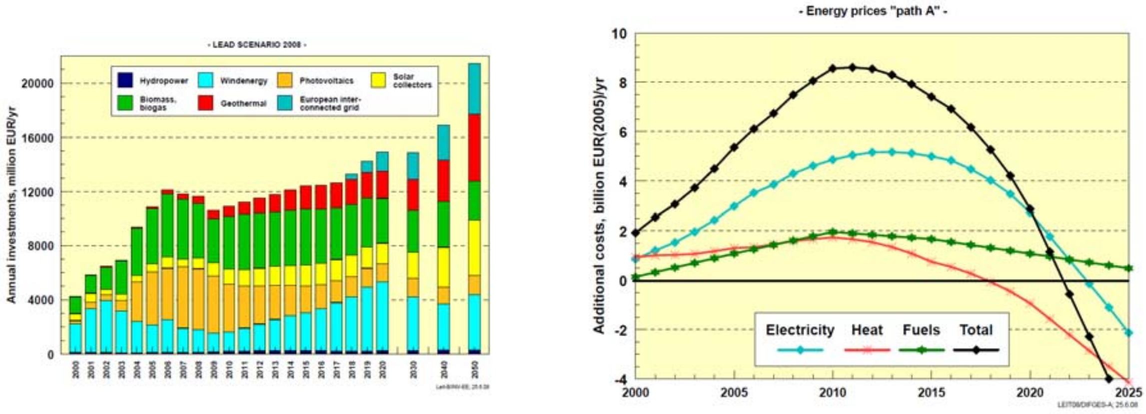

Figure TS 10.8 a) Annual investment volume for renewable installations for electricity and heat supply (including investments for local district heat networks) according to the Lead Scenario 2008. b) Additional costs of renewable energy expansion in all sectors according to the Lead Scenario 2008 (Nitsch, 2008, p. 26 and 28).

Social, Environmental Costs and Benefits

Social, environmental costs and benefits of increased deployment of RE are synthesized in relation to climate change mitigation and sustainable development. The analysis is performed by RE technology and, to a minor extent also by geographical area, as regional information is still mostly very sparse, in the context of sustainable development.

Although social and environmental external costs vary heavily amongst different energy sources and are still connected with a high uncertainty range, they should be considered if the advantages and disadvantages of future paths are being assessed. Typically, the production and use of fossil fuel cause the highest external costs dominated by the costs due to climate change impacts. Most of the time RE sources have clearly lower external costs than non-RE, even when assessed on a life-cycle basis. However, the uncertainty and variability by energy chains is considerable. Some RE production cases can cause considerable external cost relevant impacts as well.

The increase of RE in the energy system typically reduces the overall external costs of the system and can on the other hand produce external benefits. The increase of RE decreases for instance society’s dependency on fluctuating prices and depleting resources of fossil fuels and it can improve the access to energy. It can also have a positive impact on trade balance and employment, e.g. in the case of energy biomass production. So far there are no holistic approaches available to translate these benefits completely into cost figure. However, also negative cost relevant effects can be emerge. According to the results of some economic model studies, a forced increase of RE can raise the price level of energy and slow slightly the growth of the economy as well, in certain situations.

Policy, Financing and Implementation

An Introduction to Policy Options

This chapter sets out the issues surrounding the policies, financing and implementation of RE. It lays out the general RE policy options that are available for rapidly increasing the uptake of RE, examines which policies have been most effective and efficient to date and why, and it looks at both RE specific policies and policies that create an "enabling environment" for RE. Issues concerning individual RE resources and/or technologies are examined in the appropriate technology chapter.

The key findings of this chapter are the following:

- Targeted RE policies accelerate RE development and deployment;
- Multiple success stories exist and it's important to learn from them;
- Economic, social, and environmental benefits are motivating Governments and individuals to adopt RE;
- Multiple barriers exist and impede the development of RE policies to support development and deployment;
- 'Technology push' coupled with 'market pull' creates virtuous cycles of technology development and market deployment;
- Successful policies are well-designed and -implemented, conveying clear and consistent signals;
- Policies that are well-designed and predictable can minimize key risks, encouraging greater levels of private investment and reducing costs;
- Well-designed policies are more likely to emerge and to function most-effectively in an enabling environment;
- The global dimension of climate change and the need for sustainable development call for new international public and private partnerships and cooperative arrangements to deploy RE;
- Structural shifts characterize the transition to economies in which low CO_2 emitting renewable technologies meets the energy service needs of people in both developed and developing countries;
- Better coordinated and deliberate actions accelerate the necessary energy transition for effectively mitigating climate change.

The number of countries with RE policies in place has risen significantly, particularly since the early to mid-2000s.

This trend toward more RE policies in a growing number of countries has played an important role in advancing RE and increasing investment in the RE sector. RE policies have a critical role to play in the transition to an energy future based on low-CO_2 RE. Although there are limited examples of countries that have come to rely primarily on RE without supportive policies (such as Iceland and Norway with geothermal and hydropower, both of which generate more than 80% of their electricity with hydropower, in most cases targeted policies are required to advance RE technology development and use.

The Importance of Tailored Policies and an Enabling Environment

To date, in almost every country that has experienced significant installation of RE capacity, production, and investment in manufacturing and capacity, there have been policies to promote RE. There is now clear evidence of success, on the local, regional and national levels, demonstrating that the right policies have a substantial impact on the uptake of RE and enhanced access to clean energy. A limited number of communities and regions have made quite rapid transitions to or toward 100 percent RE

At the same time, the IEA has found that only a limited number of countries have implemented policies that have effectively accelerated the diffusion of RE technologies in recent years. Simply enacting support mechanisms for RE is not enough.

Tailored policies are required to overcome the numerous barriers to RE that currently limit uptake in investment, in private R&D funding, and in infrastructure investments. Accelerating the take-up of RE requires a combination of policies but also a long-term commitment to renewable advancement, policy design suited to a country's characteristics and needs, and other enabling factors.

Policies are most effective if targeted to reflect the state of the technology and available RE resources, and to respond to local political, economic, social and cultural needs and conditions. Moreover, policies that are clear, long-term, stable and well-designed, and that provide consistent signals generally result in high rates of innovation, policy compliance, and the evolution of efficient solutions. When these factors are brought together, a policy can be said to be well-designed and -tailored.

Policy and regulation, and their design, play a crucial role in improving the economics of RE, and as such can be central to attracting private capital to RE technologies and projects, and influencing longer-term investment flows.

Well-designed policies are more likely to emerge, and to lead to successful implementation, in an enabling environment, described later.

Finally, achieving a sustainable energy system, one in which low-CO_2 RE meets the energy service needs of people around the world, will require a structural shift to a more integrated energy service approach that takes advantage of synergies between RE and energy efficiency. The RE growth seen to date must be accelerated on a global scale for RE to play a major role in mitigating climate change. This is true not only for those RE technologies which have already seen successes related to manufacture and implementation, but also for other RE uses such as renewable heating and cooling, which thus far has experienced limited growth and limited policy support despite its enormous potential.

Political and Financial Trends in Support of RE

The number of RE policies—specific RE policy mechanisms enacted and implemented by governments—and the number of countries with RE policies, is increasing rapidly around the globe. The focus of RE policies is shifting from a concentration almost entirely on electricity to include the heating/cooling and transportation sectors as well. These trends are matched by increasing success in the development of a range of RE technologies and their manufacture and implementation (See Chapters 2-7), as well as by a rapid increase in annual investment in RE and a diversification of financing institutions. This section describes recent and current trends in RE policies and in public and private finance and investment.

Table TS 11.1 lists and defines a range of mechanisms currently used specifically to promote RE, and notes which types of policies have been applied to RE in each of the three end-use sectors of electricity, heating and cooling, and transportation.

Table TS 11.1 Existing RE Policy Mechanisms, Definitions and Use by Sector

Policy	Definition	End-use Sector Electricity	 Heating/ Cooling	 Transport
REGULATORY				
Access Related				
Net metering	Allows a two-way flow of electricity between the electricity distribution grid and customers with their own generation. The meter flows backwards when power is fed into the grid.	X		
Priority Access to network	Provides RE supplies with unhindered access to established energy networks.	X	X	
Priority Dispatch	Ensures that RE supplies are integrated into energy systems before supplies from other sources.	X	X	
Quota Driven				
Renewable Portfolio Standard/ Renewable Obligations or Mandates	Obligates designated parties (generators, suppliers, consumers) to meet minimum RE targets, generally expressed as percentages of total supplies or as an amount of RE capacity. Includes mandates for blending biofuels into total transportation fuel in percent or specific quantity. Also RE heating purchase mandates and/or building codes requiring installation of RE heat or power technologies.	X	X	X
Tendering/ Bidding	Public authorities organize tenders for given quota of RE supplies or supply capacities, and remunerate winning bids at prices mostly above standard market levels.	X		
Tradable Certificates	Provide a tool for trading and meeting RE obligations among consumers and/or producers. Mandated RE supplies quota are expressed in numbers of tradable certificates which allow parties to meet RE obligations in a flexible way (buying shortfalls or selling surplus).	X	X	

Price Driven				
Feed-in tariff (FIT)	Guarantees RE supplies with priority access and dispatch, and sets a fixed price per unit delivered during a specified number of years.	X	X	X
Premium payment	Guarantees RE supplies an additional payment on top of their energy market price or end-use value.	X	X	
Quality Driven				
Green energy purchasing	Regulates the option of voluntary RE purchases by consumers, beyond existing RE obligations.	X	X	
Green labeling	Government-sponsored labeling (there are also some private sector labels) that guarantees that energy products meet certain sustainability criteria to facilitate voluntary green energy purchasing. Some governments require labeling on consumer bills, with full disclosure of the energy mix (or share of RE).	X	X	X
Guarantee of origin (GO)	A (electronic) document providing proof that a given quantity of energy was produced from renewable sources. Important for RE trade across jurisdictions and for green labeling of energy sold to end-users.	X		
FISCAL				
Accelerated depreciation	Allows for reduction in income tax burden in first years of operation of renewable energy equipment. Generally applies to commercial entities.	X	X	X
Investment grants, subsidies or rebates	One-time direct payments from the government to a private party to cover a percentage of the capital cost of an investment in exchange for implementing a practice the government wishes to encourage.	X	X	X
Energy production payments	Direct payment from the government per unit of renewable energy produced.	X	X	

Production/ investment tax credits	Provides the investor or owner of qualifying property with an annual income tax credit based on the amount of money invested in that facility or the amount of electricity that it generates during the relevant year. Allows investments in RE to be fully or partially deducted from tax obligations or income.	X	X	X
Reductions in sales, VAT, energy or other taxes	Reduction in taxes applicable to the purchase (or production) of renewable energy or technologies.	X	X	X
PUBLIC FINANCE				
Grants	Grants and rebates that help reduce system capital costs associated with preparation, purchase or construction of renewable energy equipment or related infrastructure. In some cases grants are used to create concessional financing instruments (e.g., allowing banks to offer low interest loans for RE systems).	X	X	X
Equity investments	Financing provided in return for an ownership interest in an RE company or project. Usually delivered as a government managed fund that directly invests equity in projects and companies, or as a funder of privately managed funds (*fund of funds*).	X	X	X
Loans	Financing provided to an RE company or project in return for a debt (i.e., repayment) obligation. Provided by development banks or investment authorities usually on concessional terms (eg lower interest rates or with lower security requirements).	X	X	X
Guarantees	Risk sharing mechanism aimed at mobilizing domestic lending from commercial banks for RE companies and projects that have high perceived credit (i.e., repayment) risk. Typically guarantees are partial, that is they cover a portion of the outstanding loan principal with 50%-80% being common.	X	X	X
OTHER				
Public Procurement	Public entities preferentially purchase renewable energy and RE equipment.	X	X	X

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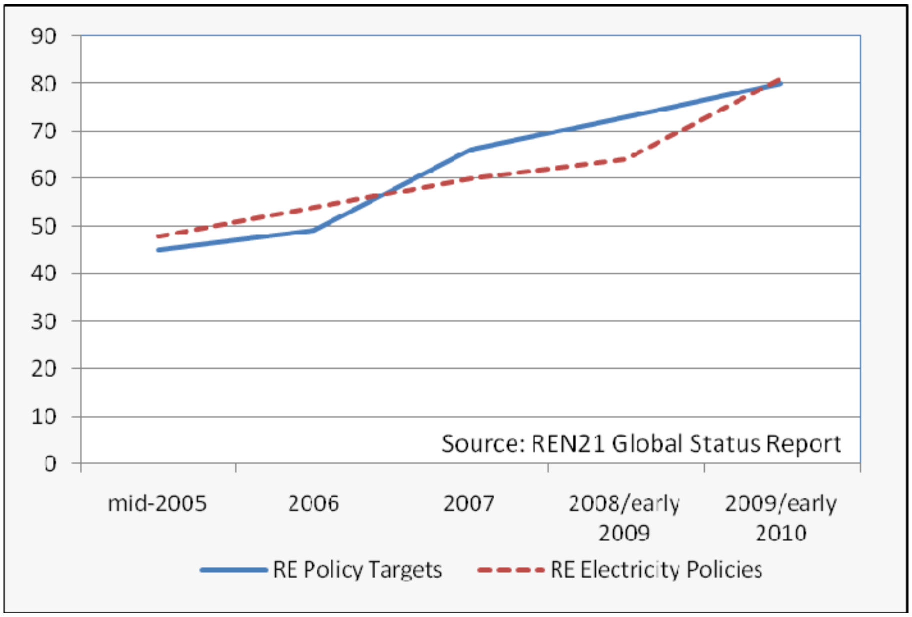
Trends in RE Policies

While several factors are driving rapid growth in RE markets, government policies have played a crucial role in accelerating the deployment of RE technologies to date.

Until the early 1990s, few countries had enacted policies to promote RE. Since then, and particularly since the early- to mid-2000s, policies have begun to emerge in an increasing number of countries at the national, provincial/state, regional, and municipal levels. Initially, most policies adopted were in developed countries, but an increasing number of developing countries have enacted policy frameworks to promote RE since the late 1990s and early 2000s.

According to the Renewable Energy Network for the 21st Century (REN21)[5], the only source that currently tracks RE policies annually on a global basis, the number of countries with some kind of national RE target and/or RE deployment policy in place almost doubled from an estimated 55 in early 2005 to more than 100 in early 2010. At least 80 countries had adopted policy targets for RE by early 2010, up from 45 (43 at the national level and two additional countries with state/provincial level policies) in mid-2005. (See Figure TS 11.1) Many of these countries aimed to generate a specific share of their electricity from RE sources by a specific date (with most target years between 2010 and 2020), while many (with some overlap) had targets for share of primary or final energy from RE. There were also a large number of countries with specific RE capacity targets by early 2010. In addition, many existing policies and targets have been strengthened over time and several countries have more than one RE-specific policy in place.



Source: REN21 Global Status Report

Figure TS 11.1 Number of Countries with RE Targets or Electricity Policies, 2005-early 20106 [To be updated.]

RE policies are directed to all end-use sectors – electricity, heating and cooling, transportation. However, most RE had focused on the electricity sector. At least 81 countries had adopted some

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[5] REN21 is a global policy network that is open to a range of stakeholders and connects governments, international institutions, non-governmental organisations, industry associations, and other partnerships and initiatives. Its goal is to advance policy development for the rapid expansion of RE in developed and developing and economies.

[6] Note that all numbers are minimum estimates. Not all national renewable energy targets are legally binding. Overall RE targets and electricity promotion policies are national policies or targets, with the exception of the United States and Canada, which cover state and provincial targets but not national. 2006 statistic for number of countries with RE promotion policies is not available, so figure shows the average of 2005 and 2007 data.

sort of policy to promote RE power generation by early 2010, up from an estimated 64 in early 2009, and at least 48 in mid-2005. (Figure 11.1) These included regulations such as feed-in tariffs (FITs), quotas, net metering, and building standards; fiscal policies including investment subsidies and tax credits; and government financing such as low-interest loans. Of those countries with RE electricity policies, approximately half were developing countries from every region of the world.

Despite the increasing number of countries, states and municipalities with RE policies, the vast majority of capacity or generation for most non-hydropower RE technologies is still in a relatively small number of countries. By early 2010, five countries—the United States, Germany, Spain, China and India—accounted for more than 85% of global wind energy capacity. Three countries—Germany, Spain and Japan—represented approximately 82% percent of the world's solar photovoltaic (PV) capacity, while a handful of countries led in the production and use of biofuels.

Financing Trends

In response to the increasingly supportive policy environment, the overall RE sector globally has seen a significant rise in the level of investment since 2004-2005 These global figures are aggregated for all types of finance, with the possible exception of public R&D. Figure TS 11.2 shows that $117 billion of new financial investment went into the RE sector in 2008, up from 15.5 billion USD$_{2005}$ in 2004[7].

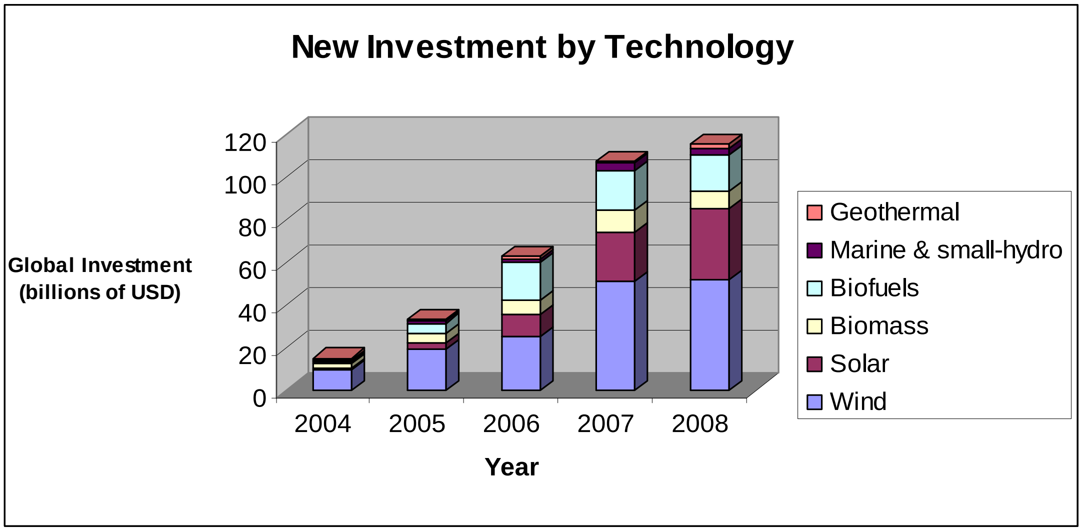

Figure TS 11.2 Global Investment in RE, 2004 – 2008 [TSU: reference missing]

Financing has been increasing along the continuum into the five areas of i) R&D; ii) technology development and commercialization; iii) equipment manufacture and sales; iv) project construction; and v) the refinancing and sale of companies, largely through mergers and acquisitions. The trends in financing along the continuum represent successive steps in the innovation process and provide indicators of the RE sector's current and expected growth

Financing Technology R&D

Figures collected by the International Energy Agency are a good guide to public RE R&D spending in OECD countries up till the middle of this decade. (IEA, 2008b) provides supplementary information on spending by large non-OECD economies, while data for spending on some forms of

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[7] Derived by stripping out the energy efficiency investment figures from United Nations Environment Programme and New Energy Finance (2009): Global Trends in Sustainable Energy Investment 2009: Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency, Paris. (Will update with 2009 data.)

RE technology in non-IEA European countries is provided in (Wiesenthal, Leduc et al., 2009). The IEA data suggest the heyday of public funding in RE R&D occurred three decades ago. Spending on renewables peaked at 2.03 billion USD_{2005} in 1981. As oil prices dropped, spending fell by over two thirds, hitting a low in 1989. It has crept up since then, to about 727 M USD_{2005} a year in 2006.

The relationship between spending on RE R&D and movements in the oil price illustrate the significant role that the 'security of supply' consideration has on government decisions to fund research into alternative sources of energy. By this logic, governments would choose to focus their attention on technologies that have greatest potential to harness natural resources that are present on their territories. Indeed, this is argued by (International Energy Agency (IEA), 2008), noting that New Zealand and Turkey have spent 55 percent and 38 percent, respectively, of their RE R&D budgets on developing geothermal energy. Non-IEA countries also justify focusing on a particular energy resource by pointing to its relative local abundance, like solar energy in India and Singapore. But there are important exceptions to the rule. Germany, for instance, spends more on photovoltaic R&D than any other country in Europe, but does so with a view to growing a competitive export industry.

Photovoltaics and bioenergy are each now the beneficiaries of a third of all government R&D on RE. The proportion spent on wind has remained stable since 1974 and declined for geothermal, concentrating solar and solar for heating and cooling applications. Ocean energy and other RE technologies have also received support but at a much lower level. An overview of the kind of research being funded around the world in these areas can be found in (European Commission, 2006).

It is perhaps most instructive to look at R&D spending patterns in recent years when policy support for renewables has been growing quickly. Spending on wind, bioenergy, PV and concentrating solar thermal power averaged 536 M USD annually in the EU Member States over the 2002-2006 period, compared to 226 M USD_{2005} in the United States and 95.7 M USD_{2005} in Japan during the same years. The International Energy Agency notes that averaging figures over this period hides some steep increases in spending, which have occurred in UK, France, Hungary and China. By 2006 Chinese spending on solar and wind R&D was up in the 37 and 42 M USD_{2005} range, roughly equivalent to that of Spain.

Financing technology development and commercialization

While governments fund most of the basic R&D and large corporations fund applied or 'lab-bench' R&D, venture capitalists begin to play a role once technologies are ready to move from the lab-bench to the early market deployment phase. According to Moore and Wüstenhagen, venture capitalists have initially been slow to pick up on the emerging opportunities in the energy technology sector, with Renewable Energies accounting for only 1-3 percent of venture capital investment in most countries in the early 2000s. However since 2002 venture capital investment in RE technology firms has increased markedly. Venture capital into RE companies grew from $188 million USD_{2005} to $3.81 billion USD_{2005}[8], representing a compound annual growth rate of 60%. This growth trend in technology investment now appears to be a leading indicator that the finance community expects continued significant growth in the RE sector. Downturns such as that experienced in 2008/2009 may slow or reverse the trend in the short term, but in the longer term an increasing engagement of financial investors is foreseen in RE technology development.

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[8] Derived by stripping out energy efficiency investment from venture capital figures in United Nations Environment Programme and New Energy Finance (2009): Global Trends in Sustainable Energy Investment 2009: Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency, Paris.

Drivers and Barriers to RE Implementation

Deployment of RE has been driven in great part by government policies, and policies for the deployment of RE are, in turn, driven by several environmental, economic, social and security goals. Drivers are factors that are pushing for the deployment of RE policy (for example climate change and the need to reduce fossil fuel emissions from the energy sector). Drivers are not necessarily objective but reflect the perception of policy makers about RE. Drivers can also take the form of opportunities which, for example, lead a country to invest in RE with the explicit goal of developing a new domestic or export industry. Certain benefits of RE, like for instance reduced emissions, improved health and more jobs may also drive promotion policies. The distinctions among these factors are necessarily close and overlapping. In this section we use the term “driver” to describe drivers in its narrower sense as well as opportunities and benefits. Examples from selected countries are included hear for illustrative reasons.[9]

The relative importance of the drivers, opportunities or benefits varies from country to country and may vary over time, as changing circumstances affect economies, attitudes and public perceptions. RE technologies offer governments the potential to realize multiple policy goals, sometimes simultaneously, that cannot be obtained to the same extent or quality through the development and use of conventional energies.

Key drivers for policies to advance RE are:

- Mitigating climate change
- Enhancing access to energy
- Improving security of energy supply and use
- Decreasing environmental impacts of energy supply
- Decreasing health impacts associated with energy production and use and, a key issue which is both a driver and an opportunity: fostering economic development and job creation..

Barriers to RE Implementation

A barrier may be defined as ‘any obstacle to developing and deploying a RE potential that can be overcome or attenuated by a policy, programme or measure’. Barriers are factors, or attributes of factors, that operate in between the actual development and deployment of RE and the, often much higher, potential of RE supply. Policies address the failures and barriers which cause this gap between actual deployment and potential.Chapter 1 offers an overview of barriers to RE development and implementation and it categorises them as barriers as: information and awareness; socio-cultural; technical and structural; economic and institutional and this section follows the same categories. Barriers to putting a RE policy in place related to

A Lack of Information and Awareness includes a limited consensus on how the transitions of the various energy systems in the world would best proceed. This means that many policy-makers lack the required knowledge to, and experience of, pro-actively integrating RE supplies with other low-carbon options (like energy efficiency); Furthermore, RE technological development is uncertain, dynamic, systemic, and cumulative. Staying informed about the best technical options for local conditions requires time and links to the practitioner and scientific communities.

Socio-Cultural Changing energy behaviour is not a simple, nor a mechanical process. While prices, information, education and technological availabilities contribute to changing people’s ways of producing and consuming energy, energy behaviours are not dictated by context variables in a mechanical way. This is especially the case for what is called “active” behaviour – the fact of

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[9] For a comprehensive review of features of RE compared to other energy carriers refer to Chapter 9.

actually changing "ways of doing" with energy, such as adopting a distributed RE technology or switching to a RE electricity supply – as opposed to "passive" behaviours – the fact of subscribing to a campaigning NGO, or supporting a policy to increase the share of RE in the supply mix. This translates into a slow build-up of support for RE, followed by pressure to have RE policies; and then a complex active-passive interaction with the outcomes of those policies.

- Behaviour relates in a complex way to individual values, attitudes, personal norms, social norms and current ways of living. This makes it sometimes difficult to find ways of sustaining a shift from "passive" to "active" behaviours.
- There often remains a gulf between the high levels of "passive" support for RE found in opinion polls and the lesser extent of active support for distributed generation and renewable energy.

Technical and Structural Energy use and supply is a complex, global technical-socio-economic activity. Most energy systems worldwide are still fossil fuel based. The existing energy system exerts a strong momentum for its own continuation, which Locks-in and Locks-out new technologies and ways of doing things.

Economic Discourse and action in the energy world is still based on the concept of "cheap fossil fuels" and "affordable nuclear risks". The external costs and risks of non-sustainable options continue to be insufficiently recognized, identified , quantified and incorporated. This means that energy markets continue to favour fossil fuels and nuclear power more than they should.

Institutional The building blocks, or enabling environment, of a successful RE policy may not be in place, and it may not be clear to policy-makers of all levels, whether international through to local, what institutions are required to get a policy going. In addition, RE project developers face a number of administrative barriers. There can be many authorities involved in deploying RE and a lack of co-ordination between them. A different acceptance of RE benefits between national and local authorities or disagreements on spatial planning rules for accommodating RE installations may lead to a long process for obtaining the necessary permits.

RE Financing barriers

In terms of scale, capacity, energy resource characteristics, points of sale for output, status of technology, and a number of other factors, RE technologies are usually markedly different from conventional energy systems. The differences are not lost on financiers, as financing a RE plant is different from financing conventional fossil-fuelled power plants and requires new thinking, new risk-management approaches, and new forms of capital.

To become more effective at placing capital in RE markets, financiers must travel up a learning or experience curve. Market failures impede this learning process and create barriers to entry into the market. To operate effectively, markets rely on timely, appropriate, and truthful information. In perfect markets this information is assumed to be available, but the reality is that energy markets are far from perfect, particularly those like the RE market in technological and structural transition. As a result of insufficient information, underlying project risk tends to be overrated and transaction costs can increase.

Compounding this lack of information are the issues of financial structure and scale. RE projects typically have higher capital costs and lower operational costs than conventional fossil-fuel technologies. The external financing requirement is therefore high and must be amortised over the life of the project. This makes exposure to risk a long-term challenge.

Since RE projects are typically smaller, the transaction costs are disproportionately high compared with those of conventional infrastructure projects. Any investment requires initial feasibility and due-diligence work and the costs for this work do not vary significantly with project size. As a result, pre-investment costs, including legal and engineering fees, consultants, and permitting costs have a proportionately higher impact on the transaction costs of RE projects. These costs apply as well to the CDM where, according to Willis and Wilder, the transaction costs of developing smaller scale RE projects as CDM projects may be prohibitively high compared to the volume of CERs expected to be generated. Furthermore, the generally smaller nature of RE projects results in lower gross returns, even though the rate of return may be well within market standards of what is considered an attractive investment.

Developers of RE projects are often under-financed and have limited track records. Financiers therefore perceive them as being high risk and are reluctant to provide non- recourse project finance. Lenders wish to see experienced construction contractors, suppliers with proven equipment, and experienced operators. Additional development costs imposed by financiers on under-capitalised developers during due diligence can significantly jeopardise a project.

Laying out the Policy Options

Chapter 11 has set out policies in Table TS 11.1 as regulatory, fiscal, public finance (including R&D) and other mechanisms, such as Government (or any other) procurement.

- The regulatory policies are described as access based (meaning they are either related to payment for RE once it has accessed the distribution grid, beyond self-generation; or related to rules of connection access to a grid or rules for taking RE generation before other sorts of generation); Quota driven (such as obligations or mandates; Tendering/Bidding, Mandating, Tradable Green Certificates (TGC)); Price driven (Feed-in tariffs, premium or bonus payments); and Quality driven (such as green energy purchasing, green labeling and guarantees of origin).
- The Fiscal policies related to accelerated depreciation, investment grants, subsidies and rebates, energy production payments, production or investment tax credits; reductions in taxes (for example sales tax, VAT and so on)
- Public finance policies relate to grants; equity investments, loans and guarantees; and
- Other policies include public procurement.

Those policies can also be differentiated between those which provide technology push support, which tend to occur at the start of their development, and demand pull policies, which are implemented as the technology becomes nearer competitiveness. An appropriate balance between technology push and demand pull policies for any given technology can lead to a virtuous cycle of reducing costs, increasing investment and increasing demand and deployment (Figure TS 11.3). Technology push policies can improve technologies and reduce their costs, attracting investment which can, along with demand pull policies, help introduce them to the market cycle and lead to greater deployment. The demand pull also helps to reduce their costs which in turns makes them more attractive in the market, which increases deployment which allows technology learning to occur, thereby improving the technology. In this virtuous cycle, investors have confidence in the technology, as a result of the earlier R&D, and capital becomes easier to access, leading new companies to enter the market and to increased competition for market shares through additional R&D investment for technological improvement. Designing a series of policies which together enables this virtuous cycle will lead to effective and efficient technology development and deployment.

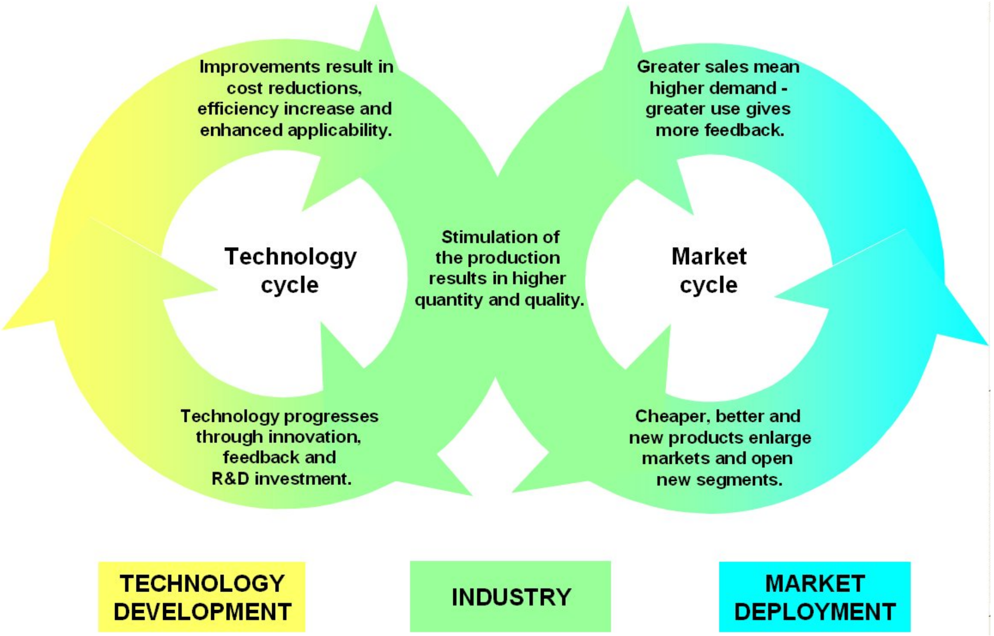

Figure TS 11.3 The mutually-reinforcing "virtuous cycle" of technology development and market deployment drives technology costs down.

Policies for Different Targets

RE policies can provide support from the R&D technology area through to payments for installed or available production capacity (heat or power), or generated electricity or produced heat (kWh). Both capacity and generation supplies can be qualified by RE source (type, location, flow or stock character, variability, density), by technology (type, vintage, maturity, scale of the projects), by ownership (households, co-operatives, independent companies, electric utilities), and other attributes that are in some way measurable which allows the amount of support to be made contingent upon it. RE may be weighed by additional qualifiers such as time and reliability of delivery (availability) and other metrics related to RE's integration into networks.

The link between policy and finance

Policies, and their design, play an important role in improving the economics of renewable energy systems, and as such can be central to attracting private finance and influencing longer-term investment flows. Private sector investment decisions are underpinned by an assessment of risk and return. A policy framework to induce investment will need to be designed to reduce risks and enable attractive returns, and be stable over a timeframe relevant to the investment. To be fully effective, or 'investment grade', policy needs to cover all of the factors (see Box TS11.1) relevant to a particular investment or project.

Box TS 11.1 Investment Grade Policies

General features of investment grade policies include:

- Clearly set objectives: financiers may want to anticipate a policy review or change should progress not be on track. Policy design to achieve the objective may also differ: for example achieving a simple volume increase of renewable energy and seeking a diversity of renewable technologies within the energy mix are likely to require different incentive design.

- Stability across project-relevant time horizon: project finance may cover a 15 year period or greater. The legal or mandatory nature of goals and support mechanisms can foster greater confidence in policy and regulatory stability, together with a clear enforcement or penalty regime.
- Simplicity: complex market systems can increase risk and uncertainty, compared to more straightforward ones.

For a specific project, relevant policy areas include:

- Planning or licensing approval: clarity over average timeframe to move through the planning process and costs involved are directly relevant. Financiers will want to know if experience indicates a long planning period with a track record of objections, or multiple approvals from different agencies, that could delay project start-up (and revenue generation), this could prove unattractive
- Support mechanisms/incentives : a crucial part of making returns attractive; the design of mechanisms including feed-in tariffs will be important, with one international bank describing the design features as 'transparency, longevity and certainty' review provisions will also be closely scrutinised.
- Policy coherence across any relevant national or international supply chain, e.g. policies that might impact access to biomass feedstock; sustainability, water etc.
- Grid or infrastructure availability, access and costs: projects are unlikely to get financed if there is uncertainty over the availability of underlying infrastructure e.g. for offshore grid for offshore wind projects. The ability to sign a long-term power purchase agreement from a creditworthy off-taker may also be a key part of the financing equation. Infrastructure has implications for sequencing of planning and policy, as well as anticipating new regulatory needs.

A regional policy perspective, beyond national boundaries, may be increasingly relevant for larger scale penetration of renewable energy, with respect to anticipating medium-term rising levels of interconnection, particularly electricity, which could have implications for energy trading, energy pricing and so on.

Policies for Tech. Development

The costs of the transition to a low carbon economy are so large, that Governments are aiming to leverage their funding as far as possible with private collaboration and investment across the technology development spectrum.

Policy measures in the RD&D sphere are becoming more collaborative and innovative as they seek new means of tapping into potential financiers, investors and innovators

The amount of funding is not the only important factor – achieving an appropriate balance between R&D and deployment funding can accelerate 'learning' as can supporting efforts for 'bricolage' (or the steady progression of small scale learning which sum up to large scale innovation) rather than 'breakthrough' (ie focusing on large scale innovation)

Specific policies in support of renewable energy are required from the early stages of technology development through to when they become commercially mature. An important Government role is to fill in the 'gaps' in this continuum where support for technology development is lacking, while at the same time encouraging input (ie financial /in-kind support) from other sectors where possible.

Developing Country Off-grid and Rural Issues

Many of the issues related to RE development are the same for developed and developing countries. There are several challenges for investors in RE in developing countries – just as there are in developed countries – and these are discussed in more detail in 11.5.4, 11.5.5 and 11.5.6. There have been several reviews of the importance of RE policies for developing countries, for example from the World Bank; their successes and difficulties. These reviews reinforce the central role that national policy plays. There is no 'one size fits all'. The overall policy environment needs to provide enough confidence for investors.

RE policy for off-grid and rural issues – given the specific differences of requirements in developing countries from developed countries are very important. Access to energy is of paramount importance as it increases living standards of rural populations, providing essential goods and services. RE enhances access to reliable, affordable clean energy to meet basic needs, especially through small scale decentralized systems renewable, and it allows for industries, production and transport to leapfrog and avoid dependence on fossil fuels.

There are some success stories, for example in Nepal by 2009, more than 200,000 rural families were using domestic biogas technology for cooking. By early 2009, in India, a cumulative total of 4250 villages and 1160 hamlets had been electrified using RE. Contrary to that Nepal has managed to install more than 150, 000 domestic biogas plants from *ad-hoc* support mechanisms before a national rural (renewable) energy policy promulgated in 2006. In Bangladesh to more than 100,000 solar home systems were promoted before a national level renewable energy policy was promulgated in 2008.

For many low income developing countries, simply channelling a subsidy to rural areas is not enough. This is due to immature markets and a lack of capacity, and a weak and fragmented supply chain Developing countries have multiple tasks of development, so more integrated renewable policies emphasising on energy access, rural and regional development, betterment of health and education sector and promoting better environment, employment and industrial sector development should be promulgated

Policies for Deployment – Electricity

Feed-in Tariff (FIT)

The most prevalent national policy for promoting renewable electricity is the FIT, also known as Feed Laws, Standard Offer Contracts, Minimum Price Payments, Renewable Energy Payments, and Advanced Renewable Tariffs, and is an over-arching term for price driven support. FITs can be divided between those where the Government sets a fixed price which is independent of electricity market prices and those that are linked to electricity market prices but paid a fixed premium price, also set by the Government. All FITs have different impacts on investor certainty and payment, ratepayer payments, the speed of deployment, and transparency and complexity of the system.

Like all mechanisms, their success comes down to details but the most successful FIT designs have included most or all of the following elements:

- Priority dispatch and access
- Establish tariffs based on cost of generation and differentiated by technology type and project size;
- Ensure regular adjustment of tariffs, with incremental adjustments built into law, to reflect changes in technologies and the marketplace
- Provide tariffs for all potential generators, including utilities

- Guarantee tariffs for long enough time period to ensure adequate rate of return
- Ensure that costs are integrated into the rate base and shared equally across country or region
- Provide clear connection standards and procedures to allocate costs for transmission and distribution
- Streamline administrative and application processes.

Quota Obligations

After FITs, the most common policy mechanism in use is a quota obligation, also known as Renewable Portfolio or Electricity Standards (RPS or RES) in the United States and India, Renewables Obligations (RO) in the United Kingdom, Mandatory Renewable Energy Target in Australia. By the end of 2008, quotas were in place in at least 9 countries at the national level and by at least 40 states or provinces, including more than half of U.S. states.

Under quota systems, governments typically mandate a minimum share of capacity or generation to come from renewable sources. Any additional costs of RE are generally bourne by electricity consumers. With the most common form of quota system, generators comply with the quota by installing capacity which an actor purchases. In the case, of the UK this is the electricity supplier who is responsible for all contractual arrangments. Elsewhere, for example Texas, renewable electricity may by bought through a bidding process. .

As with FITs, the success or failure of quota mechanisms comes down to the details. The most successful mechanisms have included most if not all of the following elements, particularly those that minimize risk:

- System should apply to large segment of the market
- Include specific purchase obligations and end-dates; and not allow time gaps between one quota and the next
- Establish adequate penalties for non-compliance, and provide adequate enforcement
- Provide long-term targets, of at least 10 years
- Establish minimum certificate prices
- Liquid market to ensure that certificates are tradable

Policies for Deployment – Heating and Cooling

Heating and cooling processes account for 40-50 percent of global energy demand with consequent implications for emissions from fossil fuels. Historically, renewable energy policy has tended to have a greater focus on renewable electricity, with increasing activity in support of biofuels for transportation over the last decade. However, renewable energy sources of heat (RES-H) have gained support in recent years as awareness of their potential has been increasingly recognized. Many nations have some form of district heating. As well as heat delivery infrastructure this tends to imply some pricing and regulatory oversight. Waste heat from fossil fuel and nuclear generation is commonly used in systems across Eastern Europe, former soviet states and Scandinavia. RE for cooling (RES-C) has even fewer mechanisms of support than RE for Heating. As a result, experience of what works and what doesn't is far less than that for RE electricity or fuels.

Bonus Mechanisms and Quotas

The bonus (or tariff) mechanism and the quota or renewable portfolio standard (RPS) are the two key variations in providing support to RES-H. The bonus mechanism (roughly, the equivalent to the RES-E FIT) has been characterised as a "purchase/remuneration obligation with fixed reimbursement rates". It legislates a fixed payment for each unit of heat generated, with potential for setting different levels of payment according to technology. Payments can be capped either for a fixed period, or for a fixed output, and can be designed to vary with technology and building size to complement energy conservation efforts. Digression may be applied to reduce the level of the bonus payment annually to allow the capture of cost reductions for the public purse. Digression has been cited as 'best practice' in the consultation document for the adoption of a renewable heating tariff in the UK, based on experience with RES-E tariffs in Europe.

Currently, no RES-H/C centred quota mechanism has been applied in practice nor are any planned. Efforts to legislate a RES-H quota mechanism in the UK in 2005 were unsuccessful and the UK has now adopted legislation for a RES-H bonus mechanism with a projected April 2011 adoption largely on the grounds of the greater projected cost associated in a comparison of quota ad tariff mechanisms. Germany also favoured a bonus mechanism for RES-H, but finally adopted mandatory installation of RES-H in new buildings.

Other regulated policies are Mandating Connection Technologies, 'Use' Obligation and Standards and Building Regulations

Policies for Deployment – Transportation

A range of policies have been implemented to support the deployment of biofuels in countries and regions around the world. Robust biofuels industries exist only in countries where government supports have enabled them to compete in markets dominated by fossil fuels. An example of this is Brazil. There are many countries where basic regulations for the production, sale, and use of biofuels do not yet exist. Some countries, like Mexico and India, have implemented national biofuels strategies in recent years. The most widely used policies include volumetric targets or blending mandates, tax incentives or penalties, preferential government purchasing, and local business incentives for biofuel companies.

Renewable Fuel Mandates and Targets

National targets are key drivers in the development and growth of most modern biofuels industries. Blend mandates have been enacted or are under consideration in at least 27 countries and 40 countries have some form of biofuels promotion legislation. Among the G8 +5 Countries, Russia is the only one that has not created a transport biofuel target. Voluntary blending targets have been common in a number of countries. However blending mandates enforceable via legal mechanisms are becoming increasingly utilized and with greater effect.

Governments do not need to provide direct funding for blending mandates since the costs are paid by the industry and consumers. Mandates have been quite effective in stimulating biofuels production, but they are very blunt instruments and should be used in concert with other policies, such as sustainability requirements, in order to prevent unintended consequences.

Sustainability Standards

Although environmental quality is regulated in most countries, comprehensive sustainability laws for biofuels are in place only in Europe where individual government efforts (especially in the Netherlands, the United Kingdom, and Germany) led to an EU-wide mandatory sustainability requirements for biofuels that was put into law in 2009. These include biodiversity, climate, land use and other safeguards.

Taxes

Taxes are one of the most widely used and most powerful policy support instruments for biofuels because they change the cost competitiveness of biofuels compared to fossil fuel substitutes in the marketplace. In recent years, the European countries and several of the other G8 +5 countries have begun gradually abolishing tax breaks for biofuels, and are moving to obligatory blending.

Other Direct Government Support for Biofuels

Most countries that are encouraging biofuels development are using some form or forms of direct loan or grant supports, generally paid for directly by Government.

Indirect Policy

Policies, other than those that are focused on renewable energy, can also be supportive for renewable transport fuels. These can be agricultural policies (discussed further in Chapter 2); storage policies (discussed further in Chapter 8); and on non-RE specific transport policies (for example, urban transport policies, also discussed in Chapter 8); and low carbon fuel standards.

Infrastructure Policies

Alternative fuels, including electricity, hydrogen and biofuels all require new infrastructures and capital investment to supply transport users with propellants. The dynamics underlying competition between fuels are crucial. Conventional fuels and power trains represent sunk investments, and with experience and economics of scale they have developed down their respective technological learning curves for 100 years; alternative fuels and technologies are naturally disadvantaged. Hence, policies addressing infrastructure investments are needed to overcome fossile fuel dependence. The degree of these investments, however, varies among alternative fuels.

Enabling Environment and Regional Issues

Energy systems are complex. They are made up of interrelated components. The process of developing and deploying new energy technologies follows systemic innovation “pathways”: innovation most often occurs in concert with several other associated or overlapping innovations. This pathway has been described as a succession of phases from R&D to full market deployment, but these phases are not linear.

The scale of technology development is conditioned by an “enabling environment”, which interlinks with RE policies (i.e. enables targeted RE policies to be more effective and efficient). The enabling environment includes institutions, regulations, the business and finance communities, civil society, material infrastructures for accessing RE resources and markets, and international agreements for facing the challenge of climate change or developing technology transfer (Figure TS 11.4).

> The Enabling Environment is defined as:
>
> “A network of institutions, social norms, infrastructure, education, technical capacities, financial and market conditions, laws, regulations and development practices that in concert provide favorable conditions to create a rapid and sustainable increase in the role of renewable energies in local, national and global energy systems”

Policies can be successful on their own in certain context. For instance, British Columbia and Norway provide examples of countries or jurisdiction with large endowments of renewable energy resource, that RE policies have brought on the way to high penetration of renewable energies (see Box 11.7).

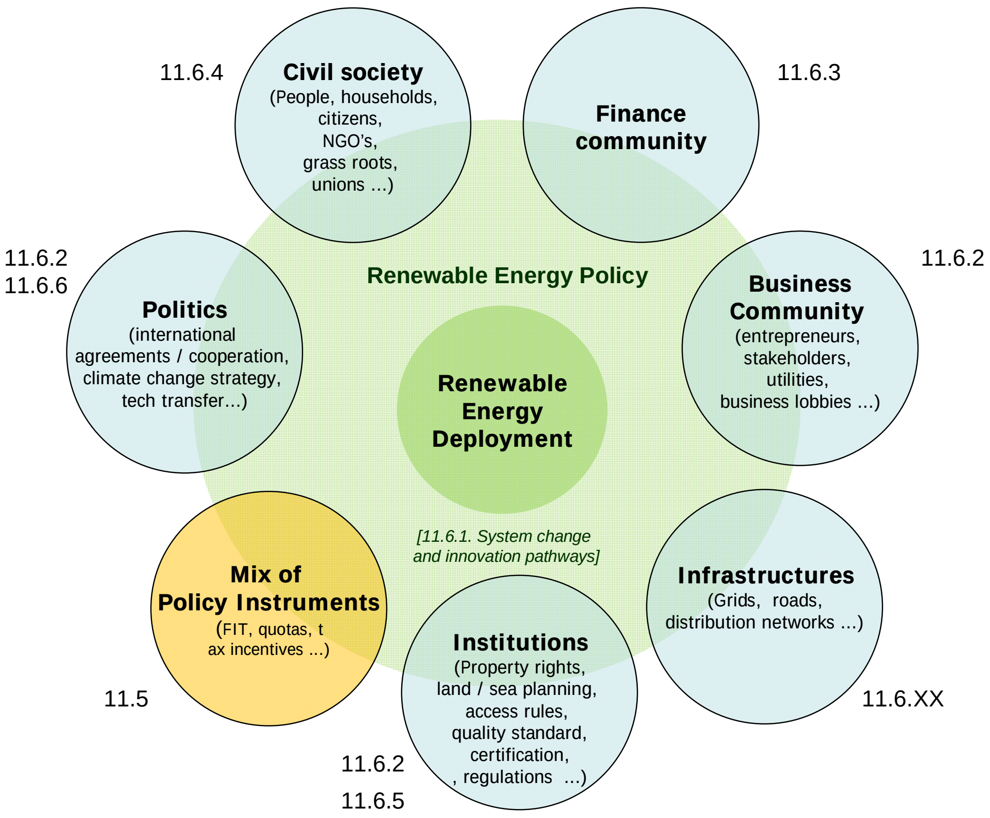

Figure TS 11.4 RE technology is embedded in an enabling environment, RE policy is one decisive dimension of this environment, but not the only one [TSU: reference?]

However, as renewable energy deployment increases, the enabling environment – whether gaining planning permission, gaining access to financing or to the grid – can make renewable energy deployment easier. On the whole, the barriers set out in various parts of the SSREN Report relate to one or several aspects of an enabling environment. If that enabling environment is in place then its related barriers should be overcome or reduced.

So, while RE policies can start very simply, with a mix of the various policy instruments discussed in section 11.5, successful experiences also suggest that developing such an enabling environment contributes to the emergence of well-designed policies and to their success, which in turn contributes to an increasing flow of private investment.

An enabling environment is therefore characterised by the readiness of society and stakeholders, including decision-makers to create an environment in which RE development and deployment can prosper. The intertwined requirements to increase the rate of deployment needed is a systemic and evolutionary process.The coordination among policies and the sub-components of the enabling environment – whether technological, social, cultural, institutional, legal, economic, financial– is essential

A Structural Shift

Transitions from one energy source to another have characterized human development. A shift from the current energy system to one that includes a high proportion of RE also implies a number of structural changes.

Movements from one energy source to another have occurred as each new source of energy provided a new and desired service which displaced and augmented the services available from the previous ‘standard’ energy source. The timescales of these energy transitions and their linked infrastructure replacements or developments varied by countries but occurred over several decades. A transition to a low carbon economy using low carbon emitting RE is different from past transitions because the time period available is restricted, and relatively short compared to the timescales of previous transitions. Further RE is trying to integrate into a system (including policies, regulations and infrastructure) that was built to suit fossil fuels (which have a number of continuing useful qualities such as energy density and portability) and nuclear power. While RE provides different benefits, services are similar. Because of this movement towards the transition has to be deliberate.

A few towns, local authorities, or communities have moved considerably toward sourcing 100% of their energy from RE (see Case Study 11.17). The key lesson of whether, and how, these city’s and communities were able to do this ultimately depended on the *spatial, environmental, social and economic capacities to implement RE* – and this would only be possible if the concerns of the three main actors – state, market and civil society - are addressed together. This is the practical representation of the arguments for structural change set out in 11.7.2 – an alignment has to occur between the State; the social mindset and institutions.

Key Choices and Implications

This section has illuminated the key requirements and choices that policy makers face and which have significant implications for society. Governments are required to orchestrate the deliberate move from fossil fuels to RE use. As is argued in the IEA’s Deploying Renewables (2008), success in delivery occurs where countries have got rid of non-economic barriers and where policies are in place at the required level to reduce risk to enable sufficient financing and investment. In addition, this section has set out that

- RE Policies, the enabling environment and more structural shfts are all on a continuum towards a transition to an energy system with more and more RE.
- A ‘breakthrough’ or a ‘bricolage’ policy approach to technology develeopment and system change is a key choice
- Another key choice is the the policy priority of whether to support a technology optimistic pathway ; a behaviour optimistic pathway or one that combines both
- the degree to which policies are devolved down from national to local governments, and open to individual choice
- the degree to which the State, the market and civil society are brought together to address, and create, sufficient spatial, environmental, social and economic capacities to enable a move to a low carbon economy

The choices will affect the actors described above so that societal activities, practices, institutions and norms can be expected to change. Thus, choice of policies is central to the success of policies.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Chapter 1

Renewable Energy and Climate Change

Chapter:	1	
Title:	Overview of climate change and renewable energy	
(Sub)Section:	All	
Author(s):	CLAs:	William Moomaw, Francis Yamba
	LAs:	Masayuki Kamimoto, Lourdes Quintana Maurice, John Nyboer, Kevin Urama,Tony Weir
	CAs:	Arnulf Jaeger-Waldau, Volker Krey, Ralph Sims, Jan Steckel, Michael Sterner Aviel Verbruggen
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COMMENTS ON TEXT BY TSU TO REVIEWER

Yellow highlighted – original chapter text to which comments are referenced

Turquoise highlighted – inserted comment text from Authors or TSU i.e. [AUTHOR/TSU: ….]

Chapter 1 has been allocated a maximum of 34 (with a mean of 27) pages in the SRREN. The actual chapter length (excluding references & cover page) is 43 pages: a total of 9 pages over the maximum (16 over the mean, respectively).

Expert reviewers are kindly asked to indicate where the Chapter could be shortened by 10-17 pages in terms of text and/or figures and tables to reach the mean length.

Pending final approval by the IPCC Plenary section 1.6 on methodology (foreseen by the original outline) has been moved to the back of the whole report as Appendix II.

All monetary values provided in this document are adjusted for inflation/deflation and converted to USD for the base year 2005 or will be if not yet done so.

Errors in formatting, spelling etc. will be corrected in the publication phase of the report

Chapter 1: Overview of climate change and renewable energy

CONTENTS

EXECUTIVE SUMMARY

The IPCC Fourth Assessment Report showed that climate change due to human activity (emissions of greenhouse gases especially carbon dioxide from the use of fossil fuels) is accelerating and that global warming in this century may be significantly greater and the consequences more severe than previously realized. Many governments now advocate that to avoid the most dangerous climate change it will be necessary to hold temperature rises to less than about 2°C above pre-industrial values. The Assessment Report indicates that to achieve this goal will require global greenhouse gas emissions to be 50% to 80% lower in 2050 than in 2000, and to begin declining by 2015. Renewable energy (RE) in combination with major changes in the end use of energy, including increasing efficiency and changing consumption patterns, is one of the solutions that enable reducing CO_2 output while maintaining energy services and economic growth. This Special Report on Renewable Energy (SRREN) explores the potential for renewable energy sources to meet goals for reduction of greenhouse gas emissions. It includes assessments of resources, technologies, integration requirements, future energy scenarios, costs and benefits, barriers and policy options.

The theoretical potential for renewable energy exceeds current and projected global energy demand by far, but the challenge is to capture and utilize it to provide the desired energy services in a cost effective manner. Various forms of RE are universally available, and can readily be introduced in both developed and developing countries. The technical potential exceeds the estimated ‘business as usual’ demand by a factor of 50 by 2050. Hence, there is no shortage of renewable energy supply to meet the demand, even when the only gains in end-use efficiency are endogenous ones rather than being policy driven. Substantial efficiency gains in the amount of heat, electricity and mechanical energy required to provide energy services benefit all forms of energy, but are especially important in matching the sometimes low and distributed energy density of renewable energy to end use energy services.

In 2008 the investment in new installations of RE systems by the electric power sector globally and in both the EU and the USA exceeded their investment in new coal and gas energy systems. RE is growing rapidly and in 2007 contributed about 18% of global energy use. Traditional use of biomass (firewood, dung and agricultural waste), much of which is both inefficient and ecologically unsustainable, accounts for 10% of global energy end-use and hydroelectricity (the most established RE technology) for 2.3%. (Note: these figures depend on the accounting conventions used for energy statistics, in ways discussed in this report.) Use of wind power and solar energy (PV) for electricity are both increasing rapidly from a low base.

The scenarios analyzed in this report indicates that with a combination of high market development for RE and a successfully implemented strategy for delivering energy services with higher efficiency, CO_2 could eventually be stabilized at 450 ppm by 2100. To be on this trajectory, RE would need to approximately double its current (2007) amount of primary energy, increasing from 64 EJ to about 133 EJ by 2030, and total primary energy would need to rise only slightly from 441 EJ in 2007 to 472 EJ (Chapter 10). The analysis also points to large uncertainties in such projections, including growth projections, development and deployment of higher efficiency technologies, the ability of RE technologies to overcome initial cost barriers, preferences, environmental considerations and other barriers. In this context it is important to consider the multi-step process whereby primary energy is converted into an energy carrier (heat, electricity or mechanical work), and then into an energy service. Doing so can help to identify the most cost effective, most energy efficient or least environmentally damaging strategy for meeting a particular energy service such as cooking, transportation, building heating, cooling or lighting or an industrial process.

To achieve the very large potential energy supply from RE requires a shift in development strategy in both developed and developing countries by systematically implementing policies on a wide scale that can overcome the economic, technical, institutional, and social barriers, which have limited the adoption of RE to date. Many of these policies are known and have already been attempted, but only on a limited economic or geographical scale.

Apart from climate change mitigation, renewable energy can play a significant role in meeting sustainable development goals in both developed and developing countries, not least by enhancing energy security and creating employment. In particular, use of modern energy services from renewable energy in developing counties can contribute to meeting Millennium Development Goals, e.g. by reducing smoke-related diseases especially for women and children, improving agriculture productivity, and developing micro-industries.

1.1 Background

1.1.1 Climate Change

The IPCC Fourth Assessment Report (AR4) expressed very high confidence (>90%) that the release of heat trapping greenhouse gases (GHGs) from human activities since 1750 has resulted in global warming. The global average temperature has been measured to increase by 0.76°C (± 0.2°C) between 1850-1899 and 2001-2005, and the warming trend has increased significantly over the last 50 years ((IPCC, 2007)). Although other GHGs contribute to this warming, CO_2 from fossil fuels accounts for some 60% of the radiative forcing from GHGs. By 2010 concentrations had increased from preindustrial levels of 280 ppm to 390 ppm and continue to increase ((NOAA, 2010)). Moreover, even if GHG concentrations were to be stabilised, warming due to human activity and the associated sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks **(**(IPCC, 2001)). Burning of fossil fuels is not the only source of GHGs. Notably, $CO_2$and some methane (another significant GHG) are released from coal mining, oil and gas production and natural gas transmission and distribution leaks. While this report focuses on the energy sector, forest clearing and burning and land use change as well as the release of non-CO_2 gases from industry, commerce and agriculture also contribute to global warming ((IPCC-WG1, 2007)).

IPCC (AR4, 2007) projected that global average temperature will rise over this century by between 1.1 and 6.4° C depending on socio-economic scenarios ((Nakicenovic & Swart, 2000)). The adverse impacts of such climate change (and the associated sea level rise) on water supply, ecosystems, food security, human health and coastal settlements were assessed by IPCC (AR4, 2007). The severity of the consequences of reaching irreversible tipping points in the climate system has led many governments to advocate limiting temperature rises to no more than 2°C, as is noted by the Copenhagen Accord of COP-15 in 2009.

It is the total concentration of GHGs in the atmosphere that directly affects the global temperature. Carbon dioxide concentrations are increasing in the atmosphere because emission rates from fossil fuels currently exceed the ability of natural sinks to absorb them (see Figure 1-1). Therefore the concentration of CO_2 in the atmosphere will continue to increase unless and until emissions decrease to less than the rate that they can be removed from the atmosphere by the natural sinks of the ocean and the terrestrial biosphere. Other GHGs such as nitrous oxide and industrial fluorinated gases are also rising. Methane concentrations are now more than double those of preindustrial levels, but their rise has slowed substantially in recent decades.

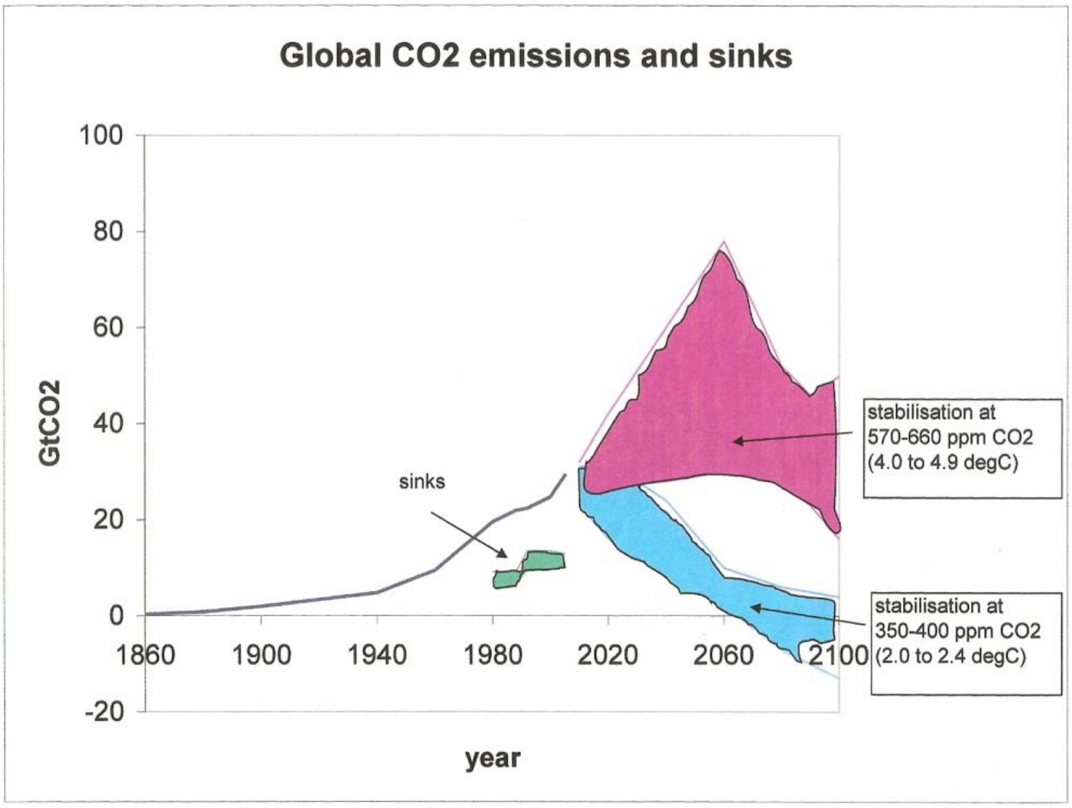

Figure 1.1. Global CO_2 emissions and sinks. Historical data is gross emissions from fossil fuels and cement from 1860 to 2000. 'Sinks' is measured difference between gross emissions and increase in tonnage of CO_2 in atmosphere; it includes both land and ocean components, is moderately uncertain (as indicated by the band) and may change over time, in response to the atmospheric CO_2 concentration and changes in climate. Projected emission bands to 2100 correspond to stabilisation of CO_2 *concentrations* at 570-660 ppm (upper band) and at 350-400 ppm (lower band). Width of bands reflects spread of modelled results in AR4. These bands correspond to 710-885 ppm CO_2-eq and 445-490 ppm CO_2-eq respectively, and to equilibrium global average temperature increases of 4.0-4.9°C and 2.0-2.4°C above preindustrial, assuming AR4 best estimate of 'climate sensitivity'. Using the 'likely' range of climate sensitivity, the corresponding temperature ranges would be wider: 2.7-7.2°C and 1.3-3.6°C respectively. Note that approaching equilibrium can take several centuries, especially for scenarios with higher levels of concentrations. Diagram adapted from IPCC- Synthesis (2007) Figure SPM-11, using sinks data from IPCC AR4 WG1 Table TS-1 and historical emissions from the (GCP, 2009) and (Boden, Marland, & Andres, 2009).

If global emissions continue at their current or higher levels until 2100 (upper band of Figure 1.1), then global average temperature is projected to increase by 4 to 4.9°C. To limit the average temperature increase to less than 2.4°C above preindustrial levels requires emissions to decrease sufficiently to stabilise CO_2 concentration below 400 ppm (lower band of Figure 1). This in turn implies that global emissions will have to decrease by at least 50-80% below current levels by 2050 and begin to decrease (instead of their current increase) before year 2015. ((IPCC-Synthesis, 2007), Table SPM-6).

Analysis of the economic cost of damages from climate change and of the costs of mitigation to avoid those damages (notably by (Stern, 2006) and (IPCC-WG3, 2007)) has also influenced thinking concerning potential mitigation options. Chapter 10 of this report indicates some of the many issues in any analysis of mitigation costs. These include debates over appropriate discount rates and whether one utilizes a top down (usually more costly) or bottom up (usually less costly) analysis.

1.1.2 Factors increasing CO_2 emissions

Bioenergy (except for basic cooking, lighting and heating in developing countries) and other forms of early fortms of RE (except hydropower) were largely replaced by abundant coal, petroleum and natural gas during the 20th century. The rapid rise in fossil fuels has produced a corresponding rapid growth in CO_2. See Figures 1.1 and 1.2.

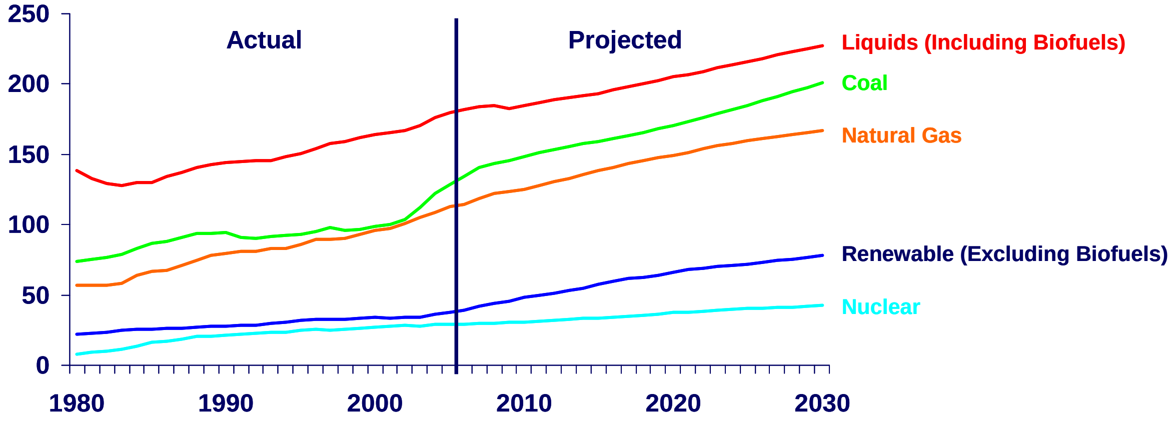

Figure 1.2 – Global Historical and Projected Marketed Energy Use by Fuel Type (EJ) 1980 to 2006. Projected marketed energy use by fuel from 2007-2030. ((IEA, 2009d)).

In developing strategies for reducing CO_2 emissions it is useful to use the Kaya identity that decomposes energy related CO_2 emissions into four factors: 1) Population, 2) GDP per capita, 3) energy intensity (i.e. total primary energy supply (TPES) per GDP) and 4) carbon intensity (i.e. CO_2 emissions per TPES) ((Ehrlich & Holdren, 1971); (Kaya, 1990)).

CO_2 = Population x (GDP/population) x (TPES/GDP) x (CO_2/TPES)

This is sometimes referred to as

CO_2 = Population x Affluence x Energy intensity x Carbon intensity

The absolute (a) and percentage (b) changes of global CO_2 emissions decomposed into the Kaya factors are shown in Figure 1.3, ((Edenhofer, Knopf, & al., 2010)).

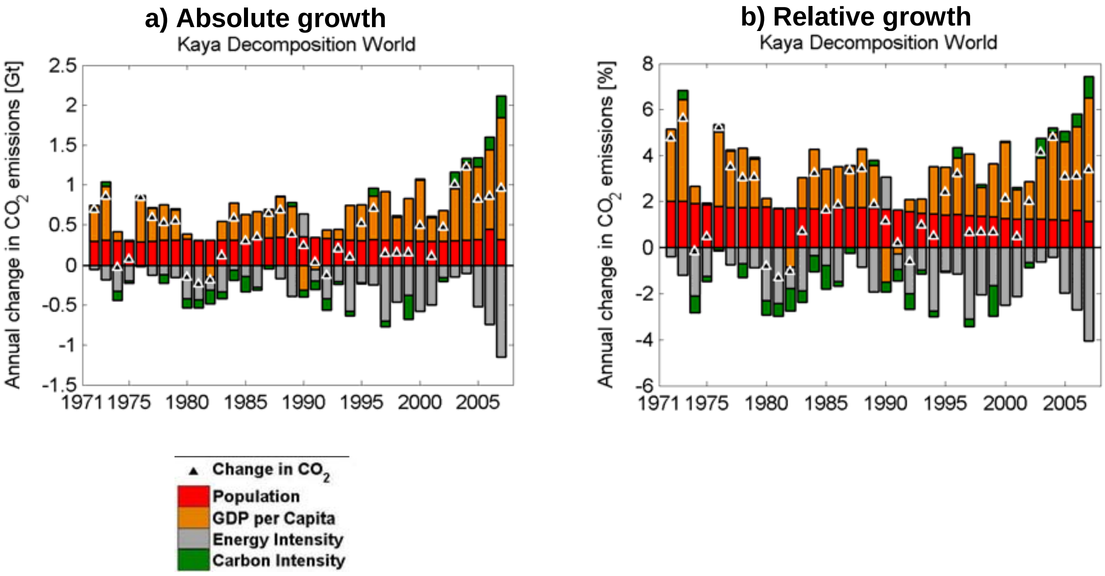

Figure 1.3: Kaya decomposition of global energy related CO2 emissions by population (red), GDP per capita (orange), energy intensity (grey) and carbon intensity (green) from 1971 to 2007. Total annual changes are indicated by a black triangle. Part (a) Absolute changes; Part (b) percentage changes. Data source: (IEA, 2009d)

While GDP per capita and population growth had the largest effect on emissions growth in earlier decades, decreasing energy intensity significantly slowed emissions growth in the period from 1971 to 2007. In the past, expansion of nuclear energy in the 1970s and 1980s, particularly driven by Annex I countries, caused carbon intensity to fall. In recent years (2000 – 2007), increases in carbon intensity have mainly been driven by the expansion of coal use by both developed and developing countries, although coal and petroleum use have fallen slightly since 2007. Since the early 2000s the energy supply has become more carbon intense, thereby amplifying the increase resulting from growth in GDP/capita.

In Figure 1.4 absolute emissions growth is examined on terms of different countries and country groups between 1971 and 2007. Historically developed countries have contributed the most to global emissions, but developing country annual emissions have risen to more than half of the total, and China surpassed the U.S. on annual emissions ((Edenhofer, et al., 2010)). Developed countries still have the highest total historical emissions and largest emissions per capita.

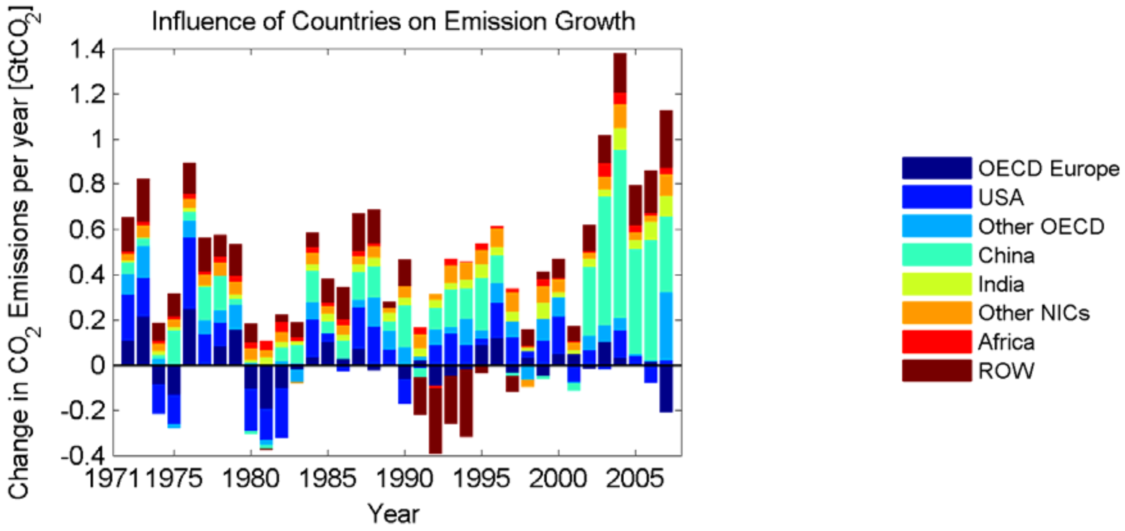

Figure 1.4: Emission growth decomposed by different countries/country groups. 'Other Newly Industrializing Countries' (NIC) includes Brazil, Indonesia, Mexico, South Africa and South Korea. Data source: (IEA, 2009c).

Shifting from carbon intensive fossil fuels to alternative low carbon sources can help to lower CO_2 emissions and avoid severe climate change. It will be essential for all countries, beginning with the most intensive energy users, to find ways to meet energy service needs with less energy and less carbon-intensive energy sources. This report explores the potential for low carbon RE sources in combination with increased energy efficiency to meet the GHG reduction goals set by policy makers to reduce the extent of future climate change.

1.1.3 What is Renewable Energy and what is its role in addressing climate change?

Renewable energy (RE) is any form of energy from geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. As long as the rate of extraction of this energy does not exceed the natural energy flow rate, then the resource can be utilized for the indefinite future, and may be considered as "inexhaustible." Not all energy classified as 'renewable' is necessarily inexhaustible; e.g. it is possible to utilize biomass at a greater rate than it can grow, or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. By contrast, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the earth.

Most forms of RE produce little or no CO_2emissions, which makes them useful tools for addressing climate change. It is important to assess the entire life-cycle of each energy source to ensure that all of the dimensions of sustainability are met. For a RE resource to be *sustainable*, it must be inexhaustible and not damage the delivery of environmental goods and services including the climate system. For example, to be sustainable, biofuel production should not increase net CO_2emissions, should not adversely affect food security, or require excessive use of water and chemicals or threaten biodiversity To be sustainable, energy must also be economically affordable over the long term, it must meet societal needs and be compatible with social norms now and in the future. Indeed, as use of renewable energy technologies accelerates, a balance will have to be struck among the several dimensions of sustainable development.

Each RE technology has a specific set of associated environmental impacts, and the resource may be affected by climate change. These aspects are discussed in the 'technology' chapters of this report. The RE sources examined in this report are categorised as bioenergy (ch.2), direct solar energy (ch.3), geothermal (ch.4), hydropower (ch.5), ocean energy (ch.6) and wind energy (ch.7).

1.1.4 Why a special report on renewable energy

The IPCC Scoping Meeting on Renewable Energy Sources held in January 2008 in Lübeck, Germany, was convened to determine whether a special report was necessary, and what such a report might cover. The participants concluded that a Special Report would be appropriate for a number of reasons ((Hohmeyer, 2008)). First, RE technology is already being depolyed at a rapidly growing rate, and in combination with energy efficiency, is likely to contribute substantially to climate change mitigation by 2030 and has the potential to contribute a major portion of energy supply by 2100. Second, since the publication of the AR4, various stakeholders from governments, civil society and the private sector have asked for more information and more extensive coverage of renewable energy sources, particularly in regions where specific information was lacking. Consequently, this Special Report on Renewable Energy provides information for policy makers, the private sector and civil society on:

1. Identification of RE resource and available technologies by region and impacts of climate change on these resources;
2. Mitigation potential of RE sources;
3. Linkages between RE growth and co-benefits in achieving sustainable development by region;
4. Impacts on global, regional and national energy security;
5. Technology and market status, future developments and projected rates of deployment;
6. Options and constraints for integration into the energy supply system and other markets, including energy storage options;
7. Economic and environmental costs, benefits, risks and impacts of deployment;
8. Capacity building, technology transfer and financing in different regions;
9. Policy options, outcomes and conditions for effectiveness; and
10. Scenarios that demonstrate how accelerated deployment might be achieved in a sustainable manner.

1.1.5 Options for mitigation

Many studies suggest a strong correlation between economic growth and energy use, and since nearly 85% of global primary energy comes from fossil fuels, that economic growth is correlated with CO2 emissions as well. This has lead many to conclude that emissions are essential to development. There are however, a number of developed countries with very low emissions such as Norway that rely heavily on RE to supply energy services. Near term energy supply appears adequate to supply most energy services in most of the developed countries ((IEA, 2009d)).

In most developing countries, on the other hand, many people lack even basic energy services and especially those that are supplied by electricity. Since it is energy services and not energy that people need, it is possible to meet those needs in an efficient manner that requires less primary energy consumption with low carbon technologies that minimise CO2 emissions ((Haas, et al., 2008)).The long-term energy scenarios analysed in chapter 10 expect high growth rates of energy consumption in developing countries, so that energy supply with low energy and carbon intensities is indispensable to reducing CO2 emissions.

There are multiple means for lowering the heat trapping emissions from energy sources, while still providing energy services. RE and demand side energy efficiency work synergistically to lower the energy required to provide each end use energy service by lowering power density demands to match those of RE supply ((Pacala & Socolow, 2004); (IPCC, 2007)).

The following mitigation options related to energy supply are relevant:

- Shift to zero carbon primary RE sources such as solar, geothermal, hydropower, oceans and wind.
- Shift from coal, petroleum or natural gas to solid, liquid or gaseous biomass energy that is produced in a low-carbon emitting manner.
- Utilize combined heat and power technologies for thermal production of electric power from both fossil fuels and renewable energy sources.
- Switch from fossil fuels with high specific CO_2 emissions (especially coal) to fossil fuels with lower specific CO_2 emissions (especially natural gas) or to nuclear power.
- Utilize carbon capture and storage (CCS) technology to prevent fossil fuel combustion products from entering the atmosphere. CCS has the potential to remove carbon dioxide from the atmosphere when biofuels are burned.
- Reduce the release of black carbon particulates from diesel engines and other combustion sources and from the burning of biomass fuels.

The main mitigation options related to energy demand are as follows:

- Provide the same energy service with less energy. Energy savings of 50 to 80% have been identified for providing specific services in buildings, industrial processes and transportation throughout all economies (Weizsäcker, Club of Rome., & Natural Edge Project., 2009).
- Change consumer behaviours to use fewer carbon and energy-intensive products and services.

Alternative means of reducing GHGs include

- Utilize forests, soils and grassland sinks to absorb carbon dioxide from the atmosphere
- Reduce non-CO_2 heat trapping greenhouse gases (CH_4, N_2O, HFC, SF_6)

Geoengineer solutions

- Address other aspects of the heat balance of the earth such as increasing surface albedo, atmospheric light scattering or ocean fertilization to increase CO_2 absorption from the atmosphere.

The geo-engineering ‘solutions’ that are sometimes suggested to moderate climate change may address global warming, but leave untouched the unsustainable use of energy resources or the GHG emissions which are causing that problem. These efforts may also cause unanticipated biogeophysical and social problems. For example, deliberately releasing large quantities of sulphate aerosols into the atmosphere to reduce the amount of solar radiation reaching the Earth’s surface will not address the increasing acidification of the oceans by CO_2 or the growing air pollution and ozone in cities by the increasing number of motor cars on the road ((Robock, Marquardt, Kravitz, & Stenchikov, 2009); (RoyalSociety, 2009)).

This report focuses on substitution of low carbon, RE supply to reduce heat trapping carbon dioxide, and will examining the synergies between RE and energy end -use efficiency.

1.1.6 Role of renewable energy in addressing co-issues of climate change (energy security, employment, MDGs and sustainability goals)

Three major concerns about energy use motivate the consideration of RE: price, environmental impacts, development and energy security.

Despite the worldwide economic recession of 2008-2009, oil prices will likely continue to rise over the medium to long term with economic recovery in the absence of other market drivers ((IEA, 2009d)). Price volatility of petroleum and natural gas has created economic problems for most countries, and price spikes have been especially hard on poorer nations that must import their transportation fuels. Liquid biofuels and renewably generated electricity offer promise as potential alternatives for the transportation sector, and as a variety of RE sources are found throughout the world, countries can utilize locally available resources. A diversified and expanded supply of energy may act to lower the long-run price of all fuels and reduce price volatility benefitting all energy users ((Bartis, Camm, & Ortiz, 2008)). These benefits could accrue nationally even if one sector were to continue using fuels derived from conventional petroleum because of the displacement of other users of petroleum derived energy.

There are generally increased public and government expectations in all parts of the world for better environmental performance. The contribution to global GHG reductions as RE replaces non-sustainable energy sources is valued for this reason, but so too may be a reduction in local environmental impacts. Producing electricity with wind and PV solar require very little water compared to thermal conversion technologies. In addition, wind, PV, ocean and hydro technologies produce very little waste heat. Water demand for cooling thermal power generation is becoming a significant limitation for siting new thermal power stations including coal, biomass, gas, nuclear, solar concentrating power and geothermal, There have been necessary power reductions during drought conditions in the United States and France in recent years. Most renewable technologies produce lower conventional air and water pollutants than fossil fuels, but hydropower and biofuels require large amounts of land and water. See Figure 1.5. Chapter 9 of this report elaborates on many of the ways in which RE can contribute to sustainable development, in addition to mitigating climate change.

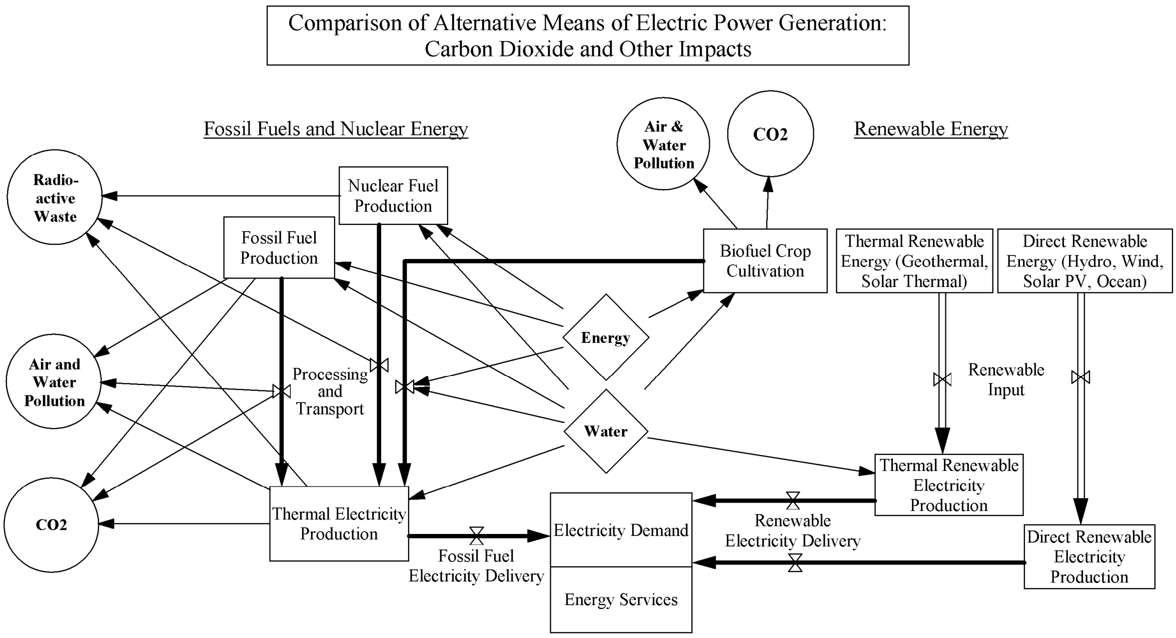

Figure 1.5. Comparison of co-benefits, water use and CO2 emissions associated with primary energy sources for electricity power generation. Not included are land impacts from surface mining of coal, land clearance for bioenergy and hydro reservoirs or methane leakage from coal natural gas and petroleum production and use, or damage from oil spills and coal ash storage. [TSU: Source? Legend?]

In developing countries, increasing the availability of energy services is central to sustainable development and poverty reduction efforts. It affects all aspects of development -- social, economic, and environmental -- including livelihoods, access to water, agricultural productivity, health, population levels, education, and gender-related issues. None of the *Millennium Development Goals* (MDGs) can be met without major improvement in the quality and quantity of energy services in developing countries. RE sources represent an important opportunity for developing countries, since access to energy is a key factor in combating poverty ((Cherian, 2007)). A large proportion of the population in these countries live in rural areas. The lack of transmission grids makes conventional energy supply challenging in such locations. The decentralised nature of some RE options offers the opportunity to provide a basic energy supplies through an off grid system ((BMU, 2008)). In this way, RE could provide access to modern energy services, particularly electricity, for a large number of people, which in turn improves living conditions and opportunities for economic development. For example, modern energy services can support MDG goal 1 of eradicating extreme poverty and hunger by freeing up household time from gathering firewood. This time can be reallocated to tending agricultural tasks, improving agriculture productivity and developing micro-industries to build assets, increase income, and financial well being of rural communities ((UNDP, 2006)). Production and utilisation of RE can also spur rural and economic development, providing opportunities for farmers and entrepreneurs to produce feedstocks for RE production and participate as owners of production facilities across all types of RE. Agriculture remains one of the most significant economic activities for large portions of the world. Hence renewable provides many rural economic development opportunities, ranging from improved energy access to industrial development, i.e., through wind power and biomass manufacturing and production facilities being located primarily in rural areas ((WIREC, 2008)). The opportunities culminate in improved income, job creation, and improved education, health care, distributive computing, telecommunications and public services. International energy assistance may provide a low-cost, effective opportunity to reduce future growth in greenhouse gas emissions and oil consumption before current development patterns become increasingly locked in throughout the developing world ((Hassell, et al., 2009)) Developing, installing and servicing RE resources and technologies is an effective creator of new employment in developed countries as well ((Wei, Patadia, & Kammen, 2010); (AIA, 2009); (BMU, 2009) **).**

National security concerns about the geopolitical availability of fuels has also been a major driver for many countries to consider RE. For example in the U.S, the military has led the effort to expand and diversify fuel supplies for aviation and cites improved energy supply security as the major driving force for sustainable alternative fuels ((Secretary of the Airforce, 2009 #71); (Hileman, et al., 2009); (USDoD, 2010)). Chapter 9 further expands upon the benefits of RE beyond climate impact mitigation and its role in sustainable development.

1.1.7 Trends in International Policy for RE

The international community’s discussions of RE go back three decades to the fuel crises of the 1970s, when many countries began exploring alternative energy sources. Since then, various attempts have been made to ensure RE featured prominently in the United Nations agenda on environment and development through various initiatives and actions (WIREC, 2008), including:

1. 1981 UN Conference on New and Renewable Sources of Energy, which adopted the Nairobi Programme of Action; the 1992
2. UN Conference on Environment and Development (UNCED), Rio de Janeiro, Brazil, and Action Plan for implementing Sustainable development that addressed sustainable energy and protection of the atmosphere;
3. 2001 session of the UN commission on Sustainable Development through its decision “Energy for Sustainable Development”, which highlighted the importance of RE;
4. 2002 World Summit on Sustainable Development (WSSD) in Johannesburg-South Africa, when several RE Partnerships were signed;
5. Bonn RE Conference 2004, which addressed best practices, research and policy development, energy services, and MDGs;
6. Beijing RE Conference (BIREC) 2005;
7. Washington RE Conference (WIREC) 2008.

These meetings all agreed on an evolving holistic view of energy for sustainable development which has three major pillars, as highlighted in Chapters 1, 9 and 11 of this report, namely the need for: (1) more efficient use of energy, in industrial applications, transportation, buildings and especially in the delivery of energy services at the point of end-use, (2) increased utilization of RE and low-carbon energy can reduce pollution and anthropogenic climate change in the short and long-term while having additional co-benefits of lower air and water pollution, and (3) accelerated research, development and deployment of new and more efficient energy technologies that offer

enhanced delivery of energy services can accelerate the introduction of energy efficient technologies and practices, RE and other low carbon emitting energy systems.
The International Energy Agency (IEA) has provided a forum for discussing energy issues among OECD industrialised countries. A new international organisation has also been established especially for RE in 2009 that currently has 143 member countries and the EU: the International RE Agency (IRENA).

1.2 Summary of RE resources

1.2.1 Resource advantages of RE

1.2.1.1 Wide distribution and low recurrent cost

Various forms of RE resources are far more uniformly distributed among all nations than are fossil fuels and uranium. Thus, from an energy security perspective, they are more available to more countries than other energy resources.

Primary energy for wind, solar, hydro, geothermal and ocean is free and it is delivered at no cost to the energy conversion technology. Furthermore, the capital costs for building the technology to extract and convert primary energy to a useful secondary form are known at the time of construction. Hence the price of delivered energy in the form of electricity, heat or mechanical energy is known with considerable certainty for the life of the project. Land based large-scale wind, hydro, geothermal and solar electric projects may require considerable investment in transmission infrastructure similar to that required for large central fossil and uranium fuelled power stations. Because population density is high along coastlines, offshore wind projects are relatively close to the demand, and require less extensive transmission systems. Distributed technologies such as rooftop solar PV deliver the electricity where it is made eliminating the need for transmission even when grid connected. For the world’s poor who utilize wood, dung and crop residues for cooking and heating biofuels are available locally and can be gathered with their own labour with no market cost.

1.2.1.2 Scalability of RE technology

Some analyses conclude that only very large facilities such as nuclear power, large scale hydro or large coal plants with carbon capture and storage can be scaled up rapidly enough to meet CO_2 reduction goals ((MIT, 2003, 2007, 2009)). However, the rapid introduction of natural gas fired turbines during the past 20 years in North America and Europe demonstrates that modular scaling to produce sufficient modestly sized energy units can meet a large scale energy demand. This has important implications for RE.

Many renewable technologies such a solar PV, solar thermal, wind turbines and wave devices are modular in nature and can be readily and rapidly produced in conventional manufacturing facilities. This has the advantage of introducing additional production capacity in incremental amounts that more closely approximate the growth in demand rather than having to wait for the completion of very large, single power generation facilities. This lowers borrowing costs that have proven to be a major contribution to the costs of nuclear power plants. At current rates of production, it appears that wind, solar and biomass have all demonstrated that they can be manufactured at a rate that can meet growing demand. Wind and solar capacity production is currently doubling in three years or less, and the U.S. bioethanol program has achieved significant growth in three years to pass Brazil as the largest producer ((REN21, 2009a)).

1.2.2 Resource disadvantages of RE

Chapter 8 of this report discussses two issues in utilising RE for electric power:

- available for dispatch when needed. On the other hand, some RE resources are matched to Some renewable resources such as wind and solar are variable and may not always be demand such as solar electricity and air conditioning, and some energy services such as water pumping, purification or desalination can be provided whenever the energy source is available. Linked hybrid systems of multiple renewable sources significantly increase the capacity factor for the entire system, and this can be augmented with electric and thermal storage.
- The energy density of many renewable sources is relatively low, so that their power levels may be insufficient on their own for some purposes such as very large-scale industrial facilities. This is why providing end use energy services more efficiently is often a major factor in the utility of some renewable technologies. See chapter 8 for further discussion

1.2.3 Resource potential

The theoretical potential for RE is much greater than all of the energy that is used by all the economies on earth. The challenge is to capture it and utilize it to provide desired energy services in a cost effective manner. Estimated fluxes of RE and a comparison with fossil fuel reserves and 2007 annual comsuption of approximately 500 Exajoules/year are provided in Table 1.1.

Table 1.1: RE fluxes compared to annual energy use.

Renewable source	**Annual flux**	**Ratio** **Annual energy flux/ annual demand**	**Total reserve**
Solar	3,900,000 EJ/y*	8,700	- - -
Wind	6,000 EJ/y*	13	- - -
Hydro	149 EJ/y*	0.33	- - -
Bioenergy	2,900 EJ/y*	6.5	- - -
Ocean	7,400 EJ/y*	17	- - -
Geothermal	140,000,000 EJ/y*	31,000	- - -
Annual Primary energy source	**Annual Use**	**Lifetime of Proven Reserve**	**Total Reserve**
Total energy fossil fuel used/y	411 EJ/y**	111 years	46,700 EJ
Total Uranium used/y	10 EJ/y**	100 – 350 years	1,000- 3,500 EJ
Total RE used/y	61 EJ/y	- - -	- - -
Current Global Energy Use/y	482 EJ/y (2007)**	1	- - -

Sources: *IEA, World Energy Outlook 2000 and 2004, **IEA, 2009 converted to direct equivalent method (Appendix II), *** IEA, 2006.

The literature related to the technical potential supply of these RE types varies considerably (technology chapters contain details and references). Among other things, this variation exists in due to differences in calculation method, variant definitions of technical potential and variation due to differences between reviewers on how technologies and resource capture techniques may change over time. Table 1.2 provides an abbreviated list of the major resource types, associated technologies, the status of their development and the typical or primary distribution method (centralized network / grid required or decentralized, local standalone supply). Further details related to these technologies and types are provided in their respective chapters.

Table 1.2: Overview of Renewable Energy technologies and applications

Renewable Energy Source	**Select Renewable Energy Technologies**	**Energy Sector (Electricity, Thermal, Transport, Mechanical)**	**Technology Maturity***				**Primary Distribution Method****	
			R & D	**Demo & Pilot Proj**	**Early-Stage Com'l**	**Later-Stage Com'l**	**Centralized**	**Decentralized**
Bioenergy	Non-Commercial Use of Fuelwood/Charcoal	Thermal				X		X
	Cookstoves (Primitive and Advanced)	Thermal				X		X
	Domestic Heating Systems (pellet based)	Thermal				X		X
	Small- and Large-Scale Boilers	Thermal				X	X	X
	Digestion	Electricity/Thermal				X	X	X
	Combined Heat and Power (CHP)	Electricity/Thermal				X	X	X
	Co-firing in Fossil-Fuel Power Plant	Electricity				X	X	
	Combustion-based Power Plant	Electricity				X	X	X
	Gasification-based Power Plant	Electricity			X		X	X
	Sugar-Cane Ethanol Production	Transport				X	X	
	Corn Ethanol Production	Transport				X	X	
	Wheat Ethanol Production	Transport				X	X	
	Rapeseed Biodiesel Production	Transport				X	X	
	Palm Oil Biodiesel Production	Transport				X	X	
	Soy Biodiesel Production	Transport				X	X	
	Jathropha Biodiesel Production	Transport				X	X	
	Lignocellulose Ethanol Production	Transport			X		X	
	Lignocelluose Synfuel Production	Transport			X		X	
	Algae Fuel Production	Transport	X				X	
Direct Solar	Photovoltaic (PV)	Electricity				X	X	X
	Concentrating PV (CPV)	Electricity		X			X	
	Concentrating Solar Thermal (CSP)	Electricity			X		X	
	Low Temperature Solar Thermal	Thermal				X		X
	Solar Cooling	Thermal		X				X
	Passive Solar Architecture	Thermal				X		X
	Solar Cooking	Thermal			X			X
	Solar Fuels	Transport	X				X	X
Geothermal	Hydrothermal, Condensing Flash	Electricity				X	X	
	Hydrothermal, Binary Cycle	Electricity				X	X	
	Engineered Geothermal Systems (EGS)	Electricity		X			X	
	Submarine Geothermal	Electricity	X				X	
	Direct Use Applications	Thermal				X		X
	Geothermal Heat Pumps (GHP)	Thermal				X		X
Hydropower	Run-of-River	Electricity/Mechanical				X	X	X
	Reservoirs	Electricity				X	X	
	Pumped Storage	Electricity				X	X	
	Hydrokinetic Turbines	Electricity/Mechanical		X			X	X
Ocean Energy	Swell/Wave	Electricity		X			X	
	Tidal Rise and Fall	Electricity				X	X	
	Tidal Currents	Electricity		X			X	
	Ocean Currents	Electricity		X			X	
	Ocean Thermal Energy Conversion	Electricity/Thermal		X			X	
	Osmotic Power	Electricity		X			X	
	Marine Biomass Farming	Transport	X				X	
Wind Energy	On-shore, Large Turbines	Electricity				X	X	
	Off-shore, Large Turbines	Electricity			X		X	
	Distributed, Small Turbines	Electricity				X		X
	Turbines for Water Pumping / Other Mechanical	Mechanical				X		X
	Wind Kites and Sails	Transport		X				X
	Higher-Altitude Wind Generators	Electricity	X				X	

* The highest level of maturity within each technology category is identified in the table; less mature technologies exist within some technology categories.

** Centralized refers to energy supply that is distributed to end users through a network; decentralized refers to energy supply that is created onsite. Categorization is based on 'primary' distribution method, recognizing that virtually all technologies can, in some circumstances, be used in both a centralized and decentralised fashion.

[TSU: Source?]

We define technical potential as the *amount of RE output obtainable by full implementation of demonstrated and likely to develop technologies or practices.*[1] A recent publication, released by

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[1] The glossary provides a more comprehensive definition of this term.

the German Federal Ministry of the Environment (Krewitt, Nienhaus, Klessmann, Capone, & al., 2009) has surveyed many of the relevant articles and provided a consistent set of tables on the technical potential summarized in Table 1.3 below.[2] The range of technical potential, not defined in Table 1.3, is addressed both in (Krewitt, et al., 2009) and in each of the related chapters in this document. The table contains details on the sources for the higher and lower estimates.

Table 1.3: Technical potential for renewable energy (EJ/y).

	Energy	Technical Resource Potential (EJ/y)					*Sources for Range of Estimates*[2]
		Krewitt et al. (2009)[1]			Range of Estimates		
		2020	*2030*	*2050*	*Low*	*High*	
Electric Power (EJ/y)	Solar PV[3]	1,126	1,351	1,689	1,338	14,766	(Krewitt, et al., 2009); Chapter 3 reports total range of solar electric potential (PV and CSP) of 1440 to 50,400 EJ/y
	Solar CSP[3]	5,156	6,187	8,043	248	10,603	(Krewitt, et al., 2009); Chapter 3 reports total range of solar electric potential (PV and CSP) of 1440 to 50,400 EJ/y
	Geothermal	5	18	45	1	144	(Krewitt, et al., 2009)
	Hydropower	48	49	50	45	52	(Krewitt, et al., 2009)
	Ocean	66	166	331	330	331	(Krewitt, et al., 2009)
	Wind On-shore	362	369	379	70	1,000	Chapter 7: low estimate from (WEC, 1994), high estimate from (WBGU, 2004) and includes off-shore
	Wind Off-shore	26	36	57	15	130	Chapter 7: low estimate from (Fellows, 2000), high estimate from (Leutz, Ackermann, Suziki, Akisawa, & Kashiwagi, 2001)
Heat (EJ/y)	Solar	113	117	123	na	na	(Krewitt, et al., 2009)
	Geothermal	104	312	1,040	4	12,590	(Krewitt, et al., 2009)
Primary Energy (EJ/y)[4]	Biomass Energy Crops[5]	43	61	96	49	260	Chapter 2 (higher quality lands): large number of studies and several recent assessments, e.g., (Dornburg, van Vuuren, van de Ven, Leangeveld, & al., 2010)
					10	70	Chapter 2 (marginal/degraded lands): large number of studies and several recent assessments, e.g., (Dornburg, et al., 2010)
	Biomass Residues	59	68	88	100	200	Chapter 2: large number of studies and several recent assessments, e.g., (Dornburg, et al., 2010)
IEA Forecast (EJ/y)[6]	BAU Primary Energy	605	703	868[7]			
	450ppm Scenario	586	601				

1. Technical potential estimates for 2020, 2030, and 2050 are based on a review of studies in (Krewitt, et al., 2009); data presented in Chapters 2-7 may disagree with these figures due to differing methodologies.
2. Range of estimates comes from studies reviewed by (Krewitt, et al., 2009)as revised based on data presented in Chapters 2-7.
3. Estimates for PV and CSP from (Krewitt, et al., 2009) for 2020, 2030, and 2050 are based on different data and methodologies, which tend to significantly understate the technical potential for PV relative to CSP.

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[2] The definition of technical potential in Krewitt, *et al.* (2009), p. 75 is similar to the definition here in that it is bounded by local / geographical availability and technological limitations associated with conversion efficiencies and the capture and transfer of the energy.

4. Primary energy from biomass could be used to meet electricity, thermal, or transportation needs, all with a conversion loss from primary energy ranging from roughly 20% to 80%.
5. Even the high-end estimates presented here take into account key limitations with respect to food demand, water availability, biodiversity and land quality.
6. IEA (2009)
7. DLR (2008)

The table provides a perspective for the reader to understand the relative sizes of the RE resources in the context of demand for energy in the future. Both the technical potentials and future demand are highly uncertain; further refinement of the values adds little to the discussion. Issues related to technology evolution, sustainability, resource availability, land use and other factors that relate to this potential are explored in the various chapters. Analysis related to the technical potentials as defined in Table 1.3 and their impact on climate change are addressed in chapter 10.

Note also that one cannot necessarily add the various types of energy together to estimate a total. For example, one cannot assume that the total electric power available is the sum of those represented in the "Electric Power" section because each type was estimated independently of the others and, as such, there may be overlap or double counting (i.e., the assessment did not take into account land use allocation; one cannot have both PV and CSP occupying the same space even though a particular site was suitable for either of them).

While the resource is obviously large and could theoretically supply all energy needs long into the future, cost issues place further constraints on the exploitation of these resources. Table 1.4 provides data related to costs associated with the various technologies. Cost data were gathered from a variety of sources in the available literature; details can be found in respective chapters and a data table defining costs can be found in appendix III. All costs were assessed using standard discounting analysis at 3%, 7% and 10% as described in the appendix on methodology. The following default assumptions were made to define the Levelized Cost of Energy (LCOE) if data were unavailable:

- time of construction - one year, no production during that year
- O&M costs - constant over lifetime
- production - start after commissioning at (nameplate capacity x Capacity Factor)
- lifetime - excludes years of construction
- retrofit or other major costs during regular lifetime -assumed to be included as annuity in O&M costs, i.e., constant costs after construction
- decommissioning - costs not included in LCOE
- Lower bound = lower bound of capital and O&M cost, higher bound of capacity factor (CF) and lifetime
- Higher bound = higher bound of capital and O&M cost, lower bound of CF and lifetime

Table 1.4: Levelized Cost of Energy (2005 US$/kWh)

Source	RE technology	LCOE at 3%		LCOE at 7%		LCOE at 10%		Learning Rate (%)	
		lower bound	*higher bound*	*lower bound*	*higher bound*	*lower bound*	*higher bound*	*lower bound*	*higher bound*
Direct Solar Energy	**PV, res roof**	0.20	0.50	0.31	0.69	0.40	0.85	11	19
	PV, com roof	0.17	0.46	0.26	0.64	0.34	0.79	11	19
	PV, fixed tilt	0.11	0.25	0.17	0.34	0.22	0.42	11	19
	PV, 1-axis	0.10	0.28	0.15	0.38	0.19	0.47	11	19

	CSP	0.11	0.19	0.16	0.25	0.20	0.31	2	15
Geothermal Energy	**Condensing-flash**	0.03	0.08	0.04	0.11	0.04	0.13		
	Binary-cycle	0.03	0.11	0.04	0.14	0.05	0.17		
	Enhanced Geo Sys								
Hydro		0.01	0.06	0.02	0.08	0.02	0.11		
Ocean Energy	**Wave Energy**								
	Tidal Current								
	OTEC								
	Salinity Gradient								
Wind Energy	**On-shore, Large**	0.04	0.09	0.04	0.13	0.05	0.15	10	17
	Off-shore, Large	0.07	0.12	0.10	0.16	0.12	0.20		

Source: Various chapters provide cost details and a summary is provided in appendix III. Biomass is excluded due to high variation in costs; for details, see Chapter 2.

These costs are based on the most recent information available in the literature; some documentation exists for the rate at which the costs might come down in the future based on a doubling of the production of the technology. The final columns in Table 1.4 provide this Learning Rate for the technologies where such information was available.

Data on biomass sourced energy show great variation in costs based on local conditions, biomass supply and other factors. That said, there are significant uncertainties surrounding the costs in Table 1.4 and, as with technical potential, the data are meant to provide context for comparison. In viewing the table, one needs also to consider other factors that have an impact on the final cost of the electricity to the consumer: typical capacities, dispatchability, socio-economic conditions, grid requirements, capacity factor variations, etc. These too are addressed in the various chapters.

1.3 Current Status of RE in Meeting Energy Service Needs

1.3.1 Energy Flows and Metrics

1.3.1.1 Energy pathways from source to end-use

In a typical energy system, consumers (the demand side) wish to receive specific services provided by the energy delivered to them by producers (supply side). Energy sources typically require transformation into secondary energy carriers, which then deliver energy to the point of end use. Energy is then transformed by appropriate technologies to provide the service demanded. RE sources can serve as a primary energy supply.

To meet a requirement for an energy service (e.g., lighting) a primary [renewable] energy source (e.g., geothermal energy) is transformed into a secondary energy carrier (e.g., electricity) that can be transformed again into a form (e.g., light) that performs the desired service. Such an end-use is often attributed to one of the four end-use sectors (buildings, transportation, industry, agriculture).

Economies are driven by energy. Over 80% of primary energy comes from the combustion of fossil fuels, which are the source of 60% of GHGs ((IPCC, 2007)). Hydropower, nuclear energy and a portfolio of renewable sources provide the remainder of non-CO_2 emitting energy. To maintain both a sustainable economy that is capable of providing essential goods and services to the citizens of both developed and developing countries, and to maintain a supportive global climate system requires a major shift in how energy is supplied and utilized. There is a multi-step process whereby primary energy is converted into an energy carrier (heat, electricity or mechanical work), and then into an energy service. This is illustrated in Figure 1.6.

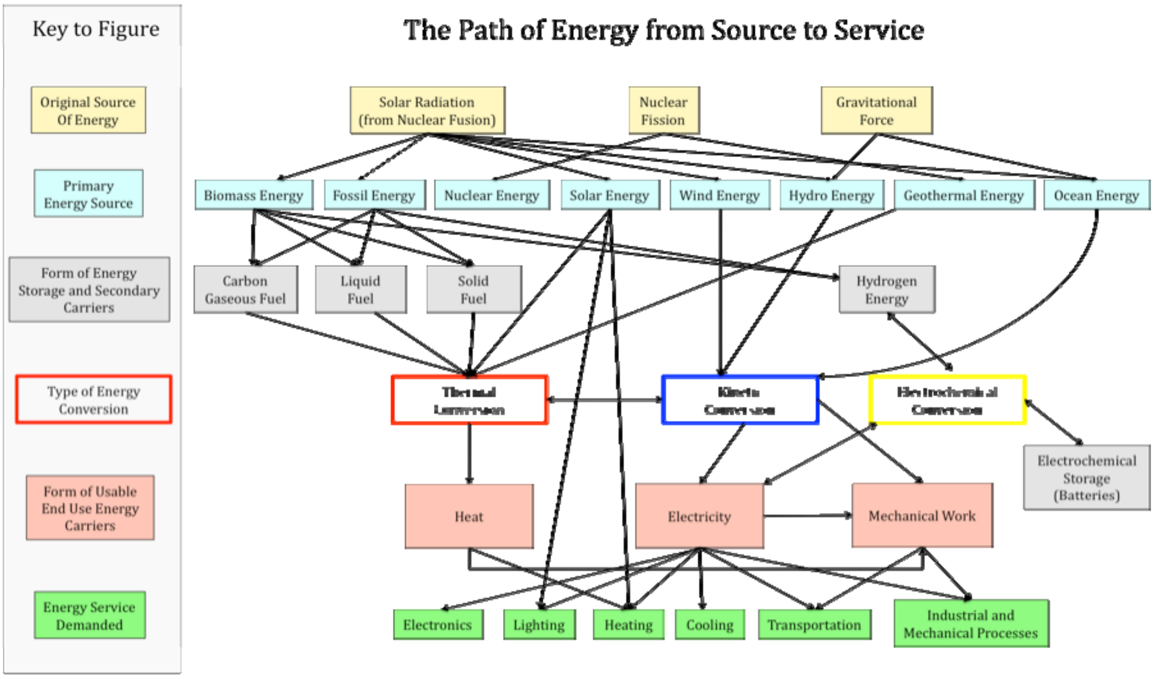

Figure 1.6. The Path of Energy from Source to Service. The Energy services delivered to the users can be provided with differing amounts of end use energy. This in turn can be provided with more or less primary energy from different sources, and with differing emissions of CO2 and other environmental impacts. [TSU: Source?]

Thermal conversion processes to produce electricity (including from biomass and geothermal) suffer losses of approximately 50-90% and losses of around 80% to supply the mechanical energy needed for transport. These conversion losses raise the share of primary energy from fossil fuels, and the wasted heat from fossil fuel combustion is the primary source of CO_2 ((LLNL, 2009); (Sterner, 2009)). Direct energy conversions from solar, hydro, ocean and wind energy to electricity do not suffer these thermal losses. Hence primary energy requirements are much smaller for these forms of RE than for fossil fuel, biomass combustion or for nuclear power. Stored solar heat in the ground, water and air may be efficiently captured utilizing heat pumps, which will not produce CO_2 emissions if powered by a RE source such as wind or solar. Solar direct heating and day lighting are also direct energy transfers without conversion losses, and direct heating from geothermal, biomass and solar thermal systems can also be highly efficient processes. By comparison, CCS requires substantial energy inputs, which would increase the demand for primary energy to supply the same amount of end use energy for energy services. It is important to recognize this when accounting for primary energy using different methodologies (Section 1.3.1.2)

Figure 1.6 can be used as an organizing tool for conducting a life cycle assessment (LCA) of specific energy options to meet alternative energy service needs in different end use sectors. It can help to identify where energy transformation losses and environmental impacts including GHG emissions occur. Similarly, Life Cycle Assessment can become the basis of a systemic analysis of costs, highlighting where economic savings might be achieved. Utilizing this approach can help to identify the most cost effective, most energy efficient and least environmentally damaging strategy for meeting a particular energy service such as lighting, cooking or an industrial process. It is especially helpful in identifying energy savings through reduction of energy transformation losses, and reduction in end use demand ((Huber & Mills, 2005)).

1.3.1.2 Methodology and Units Used in this report

In this report Joules are used (usually ExaJoules = 10^{18} Joules) when discussing and comparing different forms of energy, and Watthours may be used for electricity (Usually TeraWatt hours = 10^{12} Watthours). See the glossary for definitions of terms.

Different energy analyses use a variety of accounting methods that lead to different quantitative outcomes for both reporting of current primary energy use and energy use in scenarios that explore future energy transitions. Energy accounting systems are utilized in the literature often without a clear statement as to which system is being used ((Lightfoot, 2007), (E. Martinot, Dienst, Weiliang, & Qimin, 2007)). A comprehensive overview of differences in primary energy accounting from different statistics has been described ((Macknick, 2009)) and the implications of applying different accounting systems in long-term scenario analysis were illustrated by Nakicenovic *et al.*, ((Nakicenovic, Grubler, & McDonald, 1998).

Three alternative methods are predominantly used to report primary energy. While the accounting of combustible sources, including all fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e. nuclear energy and all RE sources except biomass. These methods are:

- *the physical energy content method* adopted, for example, by the OECD, the International Energy Agency (IEA) and Eurostat, (IEA/OECD/Eurostat, 2005).
- *the substitution method* which is used in slightly different variants by BP (2009) (Finley, 2009) and the US Energy Information Administration, each of which publish international energy statistics, and
- *the direct equivalent method* that is used by UN Statistics (2010) and in multiple IPCC reports that deal with long-term energy and emission scenarios (Nakicenovic & Swart, 2000); (Morita, et al., 2001); (Fisher, Nakicenovic, & al., 2007).

For non-combustible energy sources, the *physical energy content method* adopts the principle that the primary energy form should be the first energy form used down-stream in the production process for which multiple energy uses are practical (IEA/OECD/Eurostat, 2005). This leads to the choice of the following *primary* energy forms:

- heat for nuclear, geothermal and solar thermal; and
- electricity for hydro, wind, tide/wave/ocean and solar PV.

The *direct equivalent method* counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy. This method is mostly used in the long-term scenarios literature, including multiple IPCC reports ((Watson, Zinyowera, & Moss, 1996); (Nakicenovic & Swart, 2000); (Morita, et al., 2001); (Fisher, et al., 2007)), because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources.

In this Special Report, IEA data are utilized, but energy supply is reported using the *direct equivalent method*. The major difference between this and the *physical energy content method* will appear in the amount of energy reported for electricity produced by geothermal heat, concentrating solar thermal, ocean temperature gradients or nuclear energy.

Table 1.5 compares the amounts of primary energy by source and percentages using the *physical energy content*, *the direct equivalent* and a variant of the *substitution method* for the year 2007 based on IEA data (IEA, 2009d).

Table 1.5 Comparison of global total primary energy supply in 2007 using different primary energy accounting methods (data from IEA (2009a)).

	Physical content method		Direct equivalent method		Substitution method[3]	
	EJ	%	EJ	%	EJ	%
Fossil fuels	411.09	81.62	411.09	85.27	411.09	79.41
Nuclear	29.69	5.90	9.81	2.04	25.79	4.98
Renewables	62.47	12.40	60.81	12.61	80.40	15.53
Bioenergy	48.31	9.59	48.31	10.02	48.31	9.33
Solar	0.40	0.08	0.40	0.08	0.49	0.10
Geothermal	2.05	0.41	0.39	0.08	0.78	0.15
Hydro	11.08	2.20	11.08	2.30	29.17	5.63
Ocean	0.00	0.00	0.00	0.00	0.01	0.00
Wind	0.62	0.12	0.62	0.13	1.64	0.32
Other	0.39	0.08	0.39	0.08	0.39	0.08
Total	503.64	100.00	482.10	100.00	517.67	100.00

IEA, 2009: Energy Balances of Non-OECD Countries International Energy Agency, 2009 edition.

For the purpose of this report, the direct equivalent method is chosen for the following reasons:

All non-combustible sources are treated in an identical way by using the amount of secondary energy they provide. This allows the comparison of all non-CO_2 emitting RE and nuclear energy sources on a common basis. Primary energy of fossil fuels and biomass combines both the secondary energy and the thermal energy losses from the conversion process. When fossil fuels or biofuels are replaced by nuclear systems or other renewable technologies, the total of reported primary energy decreases substantially (Jacobson, 2009). Energy and emissions scenario literature that deals with fundamental transitions of the energy system to avoid dangerous anthropogenic interference with the climate system over the long-term (50-100 years), has used the direct-equivalent method most frequently ((Nakicenovic & Swart, 2000); (Fisher, et al., 2007)).

Figure 1.7 shows the differences in the three methods when projected to 2050 for a particular scenario that might achieve a stabilization of CO_2 at 550ppm. A more complete discussion of the different methodologies is provided in Appendix II.

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[3] For the substitution method conversion efficiencies of 38% for electricity and 85% for heat from non-combustible sources were used. BP uses the value of 38% for electricity generated from hydro and nuclear. BP does not report solar, wind and geothermal in its statistics for which, here, also 0.38 is used for electricity and 85% for heat.

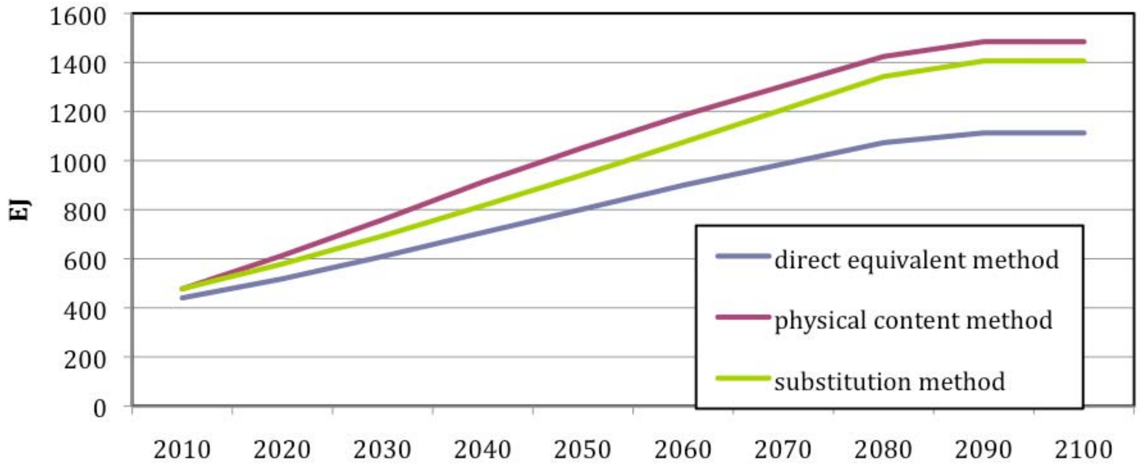

Figure 1.7 Comparison of global total primary energy supply between 2010 and 2100 using different primary energy accounting methods based on a 550 ppm CO2-equivalent stabilization scenario ((Loulou, Labriet, & Kanudia, 2009)). See Chapter 10 and Appendix II for additional information.

1.3.2 Importance of energy end-use efficiency

Often the lowest cost option is to reduce end use energy demand through efficiency measures, which include new technologies and more efficient practices. For example, compact fluorescent or light emitting diode lamps use only about one-fourth to one-sixth as much electricity to produce a lumen of light as does a traditional incandescent lamp. Properly sized variable speed electric motors and improved efficiency compressors for refrigerators, air conditioners and heat pumps can lower primary energy use in many applications (Weizsäcker et al, 2009). Efficient houses and small commercial buildings such as the Passivhaus design from Germany are so air tight and well insulated that they require only about one-tenth the energy of more conventional dwellings ((Passivhaus, 2010). Avoiding international style glass box construction of high-rise buildings in tropical countries could dramatically reduce emissions at a substantial cost saving for cooling.

RE installations (with zero or low GHG emissions) are often more feasible once end use demand has been lowered. For example, if electricity demand is high, the size of the required rooftop solar system might be larger than the roof but, by lowering demand, the size and cost of the distributed solar system may be manageable.

The transportation sector could reduce emissions significantly by shifting to appropriately produced biofuels or by utilizing engineering improvements in traditional internal combustion engines to reduce fuel consumption rather than to enhance acceleration and performance. Biofuels become more feasible for aircraft as efficiency improves. Significant efficiency gains and substantial CO_2 emission reductions have also been achieved through the use of hybrid electric systems, battery electric systems and fuel cells (see sec. 8.3.1). Two additional approaches to energy efficiency are combined heat and power systems ((Casten, 2008)), and recovery of otherwise wasted thermal or mechanical energy (about 19% of US electricity equivalent with no increase in CO_2 emissions and at a few cents/kWh) ((Bailey & Worrell, 2005)). Combined heat and power can significantly reduce emissions by avoiding burning additional fuel for commercial and industrial heat. A residential scale unit that operates on natural gas is also available in Japan and North America.

These principles are also applicable to enhancing the overall delivery of energy from RE such as capturing and utilizing the heat from PV or biomass-electricity systems, which is done frequently in the forest products industry.

Technological improvements can and will continue to make progress reducing GHGs through efficiency. However, technology alone can only take us so far. The forecasted growth in population and the projected demand for energy could well outpace the pace of technological innovation, and emissions will continue to grow without some behavioural changes especially in the richer countries.

1.3.3 Current status of RE

1.3.3.1 Global primary energy consumption and electricity production

Since 1990, global energy consumption almost doubled, rising to around 504 EJ in 2007, with RE's share at approximately 13.0% (12.6%) ((IEA, 2009d)**)** See Figure 1.8.

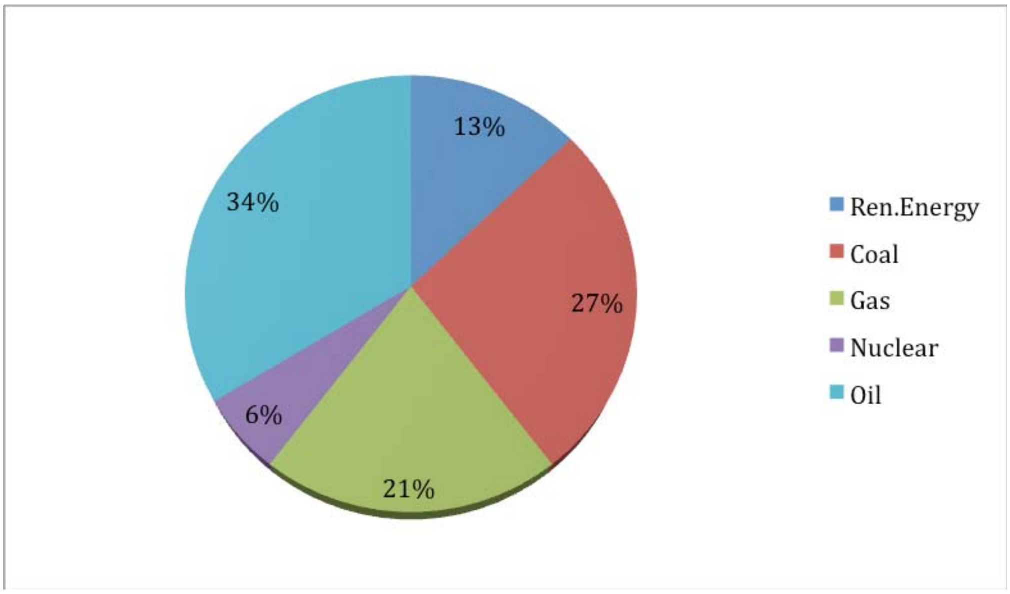

Figure 1.8 Global primary energy consumption 2007 ((IEA, 2009b)).

The 12.6% RE is distributed as solid biomass (9.5%), large hydroelectric power (2.2%), geothermal (0.4%), liquid biomass (0.3%), and new renewables embracing wind solar and marine energy (0.2%). At the global level, on average, renewables have increased by 1.8% per annum between 1990-2007 **(**(IEA, 2009d)**)** only just managing to keep pace with growth in total primary energy consumption (1.9%). Wind energy registered the highest average growth rate of 29.0%, and grid-tied solar PV 70 percent. The capacity of utility-scale solar PV plants 200 kilowatts) tripled during 2008, to 3 GW. Solar hot water grew by 15 percent, and annual ethanol biodiesel production both grew by 34 percent. Heat and power from biomass and geothermal sources continued to grow, and small hydro increased by about 8 percent ((REN21, 2009a)).

Globally, around 55% of RE has been used to supply heat in private households and in the public and services sector. Essentially, this refers to wood and charcoal, widely used in developing countries for cooking. Electricity production stands at 24.0% ((IEA, 2009d)). RE's contribution to electricity generation is summarized in Table1.6.

Table 1.6. RE share of world electricity production 2007

	Electricity TWh	Share of RE supply
Renewable total	3578	1
Biomass	259	0.073

Hydro	3078	0.860
Geothermal	62	0.017
Solar PV	4	0.001
Concetrating Solar Power	1	0.000
Wind	173	0.048
Tide & wave	1	0.000

Source: IEA WEO 2009 ((IEA, 2009d))

1.3.3.2 Regional aspects of RE

As regards biomass as a share of regional primary energy consumption. Africa is particularly high with a share of 47.0%, followed by India 20%, Asia excluding China 16%, and China 10% (Figure 1.9)

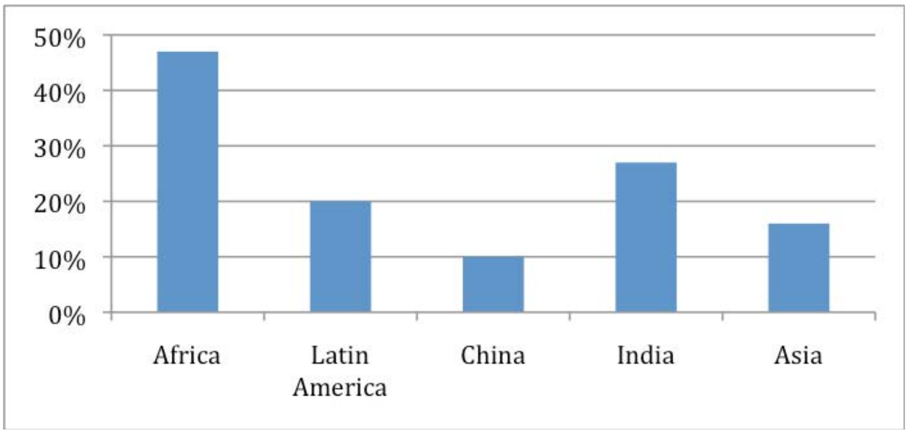

Figure 1.9 Biomass as a share of regional Primary Energy Consumption ((IEA, 2009d)).

UNEP finds that global investment in RE rose 5% and exceeded that for coal and natural gas by $140 billion to $110 billion in 2008 [TSU: needs to be converted into 2005US$] despite a decline in overall energy investments. UNEP estimates that an additional $15 billion [TSU: needs to be converted into 2005US$] was invested in energy efficiency during that year. Much of this investment was in the United States, China and Europe ((UNEP, 2009); (REN21, 2009b)).

In China, growing energy needs for solar cooking and hot water production have promoted their development. China is now the leading producer, user and exporter of solar thermal panels for hot water production, and has been rapidly expanding its production of solar PV, most of which is exported, and has recently become the leading global producer. In terms of capacity, in 2008, China was the largest investor in thermal water heating, second in wind power additions and third in bioethanol production. In terms of renewable power capacity, China now leads the world followed by the U.S., Germany, Spain and India ((REN21, 2009a)). China has been doubling its wind turbine installations every year for the past five years, and could overtake Germany and the U.S. by 2010. India has become a major producer of wind turbines and now is among the top five countries in terms of installation, and has become a major international turbine manufacturer.

These developments suggest the possibility that RE could play a much more prominent role in both developed and developing countries over the coming decades. New policies in the U. S., China and the EU are supporting this effort. European leaders signed up in March 2007 to a binding EU-wide target to source 20% of their energy needs from renewables, including biomass, hydro, wind and solar power, by 2020.

As noted above, RE is more evenly distributed than fossil fuels, there are countries or regions rich in specific RE resources. The share of geothermal energy in the national electricity production is above 15% in four countries: El Salvador (22%), Kenya (19.8%), Philippines (19%) and Iceland (17%). More than 70% of energy is supplied by hydropower and geothermal energy in Iceland. In some years depending on level of precipitation, Norway produces more hydropower electricity than it needs and exports its surplus to the rest of Europe. New Zealand and Canada have also a high share of hydropower electricity to the total electricity: 65% and 60 %, respectively. Brazil is the second largest producer of bio-ethanol, which it produces from sugarcane.

1.3.3.3 Global energy flows of primary RE

Global energy flows from primary energy through carriers to end-uses and losses in 2004 are shown in Figure 4.4 of IPCC AR4 WG3. Figure 1.10, shown here, reflects primary RE only, utilizing the data for 2007 ((IEA, 2009d)). 'RE' here includes combustible biomass, forest and crop residues and municipal solid waste as well as the other types of RE considered in this report: wind, hydropower, geothermal energy and solar energy.

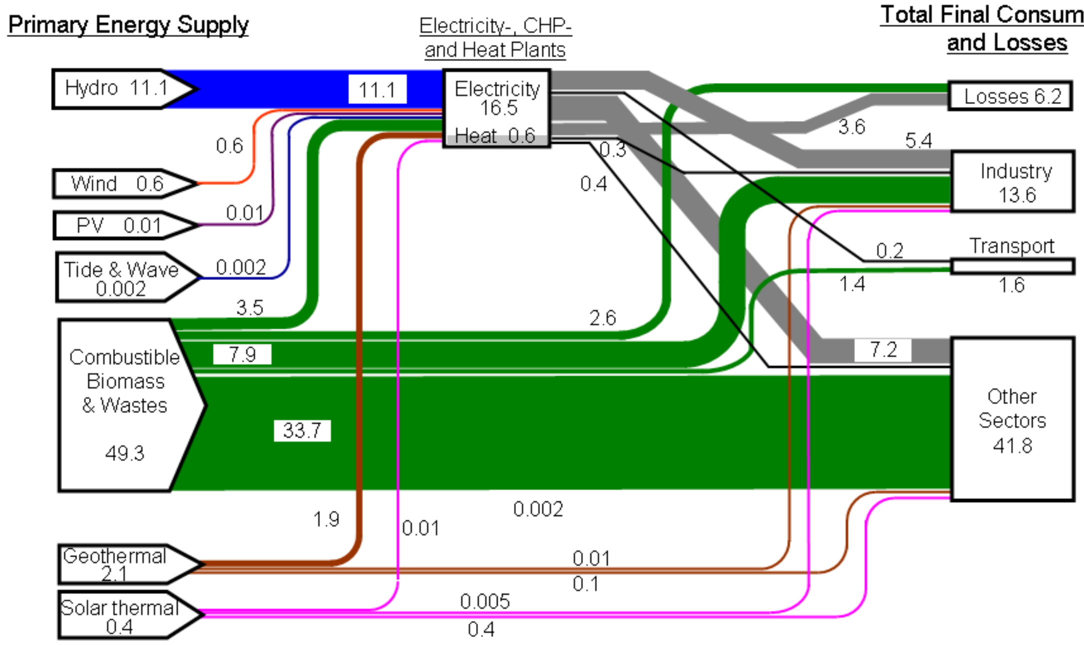

Figure 1.10 Global energy flows (EJ in 2007) from primary RE through carriers to end-uses and losses (based on IEA data). 'Other sectors' include agriculture, commercial and residential buildings, public services and non-specified other sectors. 'Transport sector' includes international aviation and international marine bunkers. **[TSU: Source?]**

In 2007, renewable sources generated 18% of global electricity (19,756 TWh), which consisted of 13% of primary energy (including traditional sources) and 18% of end use energy ((REN21, 2008); (REN21, 2009a)). The flow of biomass, which includes traditional uses, dominates this figure, but there is significant investment in modern RE technologies as noted above and accompanying rapid growth. Approximate technology shares of 2008 investment were wind power at 42%, solar PV 32 %, biofuels 13%, biomass and geothermal power and heat 6%, solar hot water 6% and small hydropower at 5%). An additional $40–45 billion [TSU: needs to be converted into 2005US$] was invested in large hydropower ((REN21, 2009a)). Between 2003 and 2008, solar installations grew at an average annual rate of 56%, biofuels and wind at 25% and hydro by 4%. Germany in 2008 produced 15% of its electricity and 10% of its total energy from renewable sources ((BMU, 2009)).

To integrate large fractions of RE into electric power systems requires improved transmission, distribution and storage technology and greater use of information technology in what is referred to as a smart grid as described in Chapter 8. Fully integrated energy planning for power production, heating, cooling and transportation will require both management of supply and demand, improved end use efficiency and utilizing RE in ways that match its availability and appropriateness to specific tasks.

1.3.4 Current status of RE as function of development

1.3.4.1 Energy consumption and access to electricity

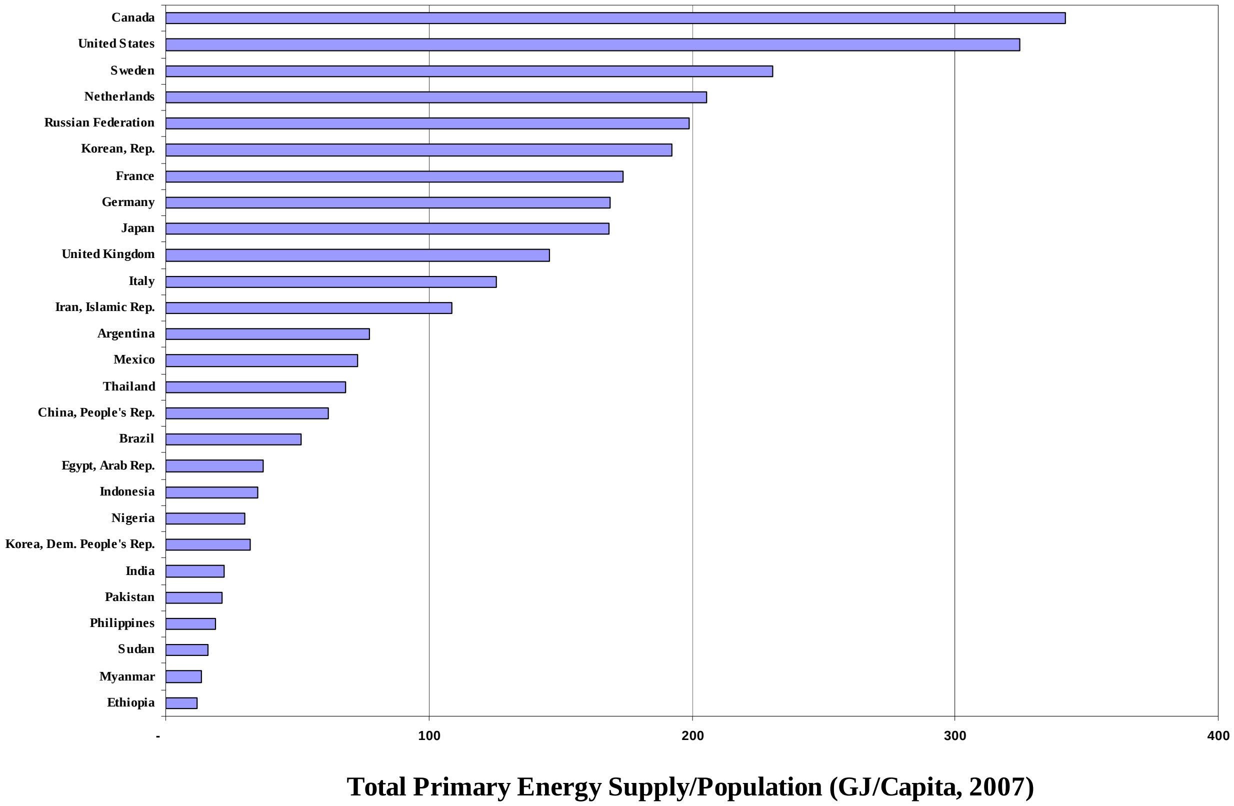

Figure 1.11. Total primary energy supply per person in various countries: > 300 TJ/capita for U.S. and Canada, 100 - 200 TJ/capita for Japan, Korea, Germany, and other European countries, <50 toe/capita most developing countries (adapted from (IEA, 2009b).

Access to electricity in developed countries is high and is still increasing but 1.4 billion people in developing countries still do not have access to electricity. The electrification rate is also different from region to region: North Africa 86%, China and East Asia 82.0%, and Latin America 60%, South Asia 32.0%, Sub-Sahara Africa (SSA) less than 10% (IEA, 2004). Without more electricity supply, people cannot get energy services for activities such as electronics, lighting and productivity enhancing mechanical work such as sewing, carpentry and water pumping or purification. That said, in some developing countries ((E. Martinot, Chaurey, & al, 2002);(Johansson, McCormick-Brennan, & al., 2004) various kinds of RE have been introduced to meet the energy service demands as shown in 1.3.5.

1.3.4.2 Utilization of RE

Biomass is a major source of energy in developing countries. Table 1.7 indicates how inefficient the traditional biomass utilization in rural area is. Although consumption of commercial energy and electricity per capita in urban areas is more than double of that in rural areas (agricultural districts), the total energy consumption, including non-commercial energy, is much higher in rural areas.

Traditional biomass is typically used in inefficient devices, is often accompanied by health issues and is a major source of black carbon, which contributes to global warming. Finding improved energy sources in developing countries would improve health, enhance productivity and decrease climate change.

Table 1.7. Energy consumption of households in urban and rural areas of China. Non-commercial energy includes combustible RE such as methane, rice straw, and firewood. (ChinaStats, 2007)

	Energy consumption GJ/y per capita	Electricity consumption kWh/y per capita
Urban (commercial energy)	7.52	305
Rural (commercial energy)	3.57	149
Rural (non-commercial energy)	10.51	

While blackouts are common in many cities in developing countries, they occur in developed countries as well. Urban centres have become totally reliant on electricity, and cannot function without it. Integration of very large amount of variable RE supply to the power grids raises some technical (systems) issues discussed in chapter 8.

Heat pump systems that extract stored solar energy from the air, ground or water have penetrated the market in developed countries sometimes in combination with renewable technologies such as PV and wind. Heat pump technology is discussed in chapter 4.

Sun-belt areas such as deserts and the Mediterranean littoral are abundant in clear sky solar energy and suitable for concentrated solar thermal power plants. The potential to export solar and wind energy from the countries rich in resources could become important in the future (Desertec, 2010); see case study in chapter 8).

1.3.5 Climbing the Energy Ladder

RE plays an important role in the movement from more traditional to more modern forms of energy supplied to consumers simply because it is typically available locally and can, with the right technologies, advance consumers up the energy ladder. RE based on off-grid energy systems can contribute to poverty alleviation and assist in achieving MDGs by providing unmet energy services, as indicated in section 1.1.5.

In developing countries, energy infrastructures are underdeveloped, but it’s not clear that they should follow a western-style energy system with extensive and costly networks. More evenly distributed underdeveloped (and largely unmapped) RE sources are available in developing countries. Regions and communities without electricity and other modern sources of energy suffer from extreme poverty, limited freedom of opportunities, insufficient health care, etc. Although the energy system will be different from that of developed countries, to raise the electrification rate is indispensible for developing countries. About two thirds of the global hydropower potential is located in the developing countries. In favourable areas, wind energy has become cost competitive with conventional energies, the more so if external costs are taken into account. It has shown rapid development and cost reductions (see chapter 7) . Solar PV is likewise developing rapidly (see Chapter 3). The potential of these modern RE technologies in the developing countries is considerable.

Biomass is the dominant energy source in many developing countries and is increasingly being harvested in an environmentally unsustainable way. To avoid the inefficient traditional biomass utilization for cooking and heating, solar thermal energy utilization is practically useful as well as modern biofuel production. For example, as discussed in chapter 2, improved biomass stoves save 10% to 50% of biomass consumption for the same cooking services and can dramatically improve indoor air quality, as well as reduce black carbon and GHG emissions (Clancy, 2002). Solar water heating is an established technology that can be manufactured in developing countries (China is already the world's largest producer). Many developing countries in desert regions may be suitable locations for solar concentrating power technology (chapter 3).

Progress is being made in developing countries on improving the energy ladder from use of traditional biomass in the form of firewood, cow dung and agriculture residues to more environmentally benign devices/fuels including improved biomass stoves, biogas and, to some extent, solar cookers. Similar progress is being made for provision of modern energy services for productive use of heat and electricity. The energy ladder for household fuel transition is depicted in Figure 1.12.

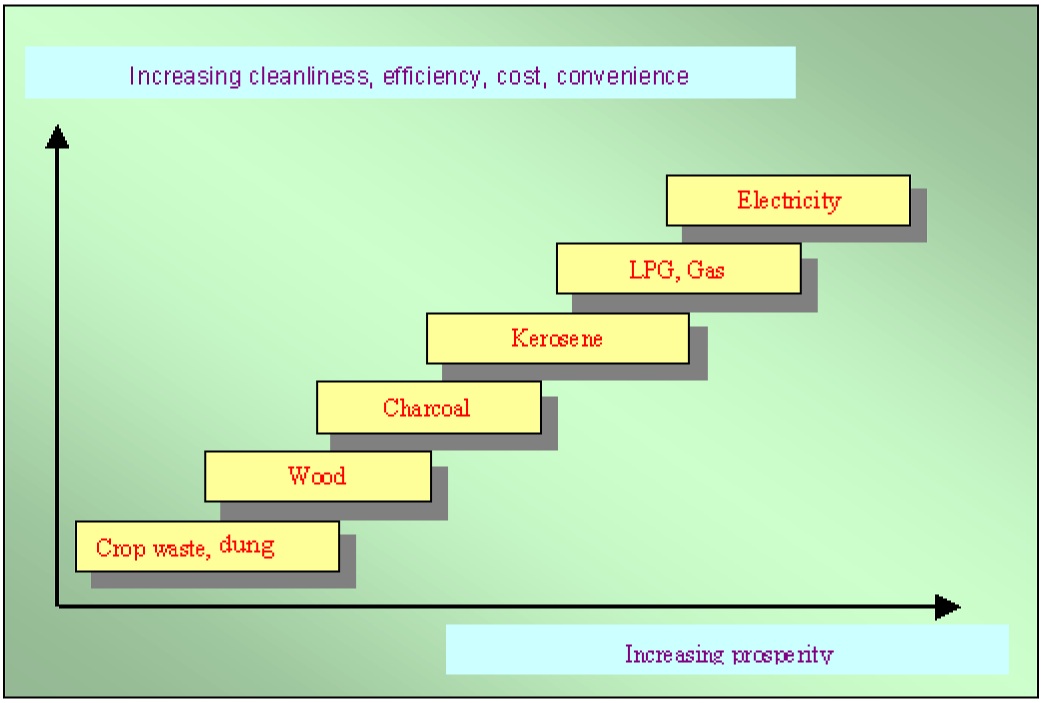

Figure 1.12. Energy Ladder: Household Fuel Transition.
(Source: www.sparknet.info/goto.php/view/1/theme.htm) [TSU: Institution/website & year; link in footnote or reference list]

With development, there is generally a transition up the 'energy-ladder' to fuels that are progressively more efficient, cleaner, convenient and expensive, such as natural gas, LPG and electricity. Commercial energy sources also permit the use of modern technologies that transform the entire production process at the factory level, in agriculture and within the home.

Electricity allows tasks previously performed by hand or animal power to be done much more quickly with electric powered machines. Electric lighting allows individuals to extend the length of time spent on production and hence on income producing activities. It also allows children time to read or do homework and access to television, computer and internet, which opens rural residents to new information that can instil the idea of change and the potential for self -improvement. Of interest in the energy ladder transition is the opportunity to use RE rather than diesel generators for either off or on-grid applications.

Commercial energy sources (in particular modern RE) permit the use of modern technologies that transform the entire production process at the factory level, in agriculture and within the home. Modern liquid fuels (including biofuels) permit modern modes of transportation that cut the cost, both monetary and in time, of travel to nearby towns for trade, education and healthcare. Table 1.8

summarizes the progress that has been made in introducing RE technologies in a number of developing countries that has greatly improved the delivery of energy services by moving up the energy ladder and the scale-up of off grid RE.

Table 1.8. Progress on Energy ladder and of grid RE application

Energy services/ technologies	**Progress**	**Comments**
Improved biomass cookstoves	I. 220 million improved biomass stoves now in use in the world	Increase due to a variety of public programmes over the last two decades. The number can be compared with almost 570 million households world wide that depend on traditional biomass as primary energy
	II. China with 180 million household representing 95% of such households	
	III. India with 34 million representing 25% of such households	
	IV. Africa has 8.0 million with Kenya having the largest number of 3.0 million	
Cooking and lighting	I. About 25 million households worldwide receive energy for lighting and cooking from household scale bio digesters	In addition to providing energy, biogas has improved livelihood of rural household-for example-reduced household time spent on firewood collection
	II. 20 million households in China	
	III. 3 million households in India	
	IV. 150,000 households in Nepal	
Small scale biomass gasification	I. Total capacity of gasifiers in India estimated up to 35MW	Gasifiers used for provision of electricity and heat for productive use e.g. textile and silk production, drying of rubber and bricks before firing
	II. More gasifiers have been demonstrated in the Philippines, Indonesia, Sri-Lanka and Thailand	
Village scale mini grids/ hybrid combinations	I. Tens of thousands of mini grids in China based on small hydro	Mainly from solar PV, wind and biomass, other in hybrid combinations
	II. Thousands in China, Nepal, Vietnam and Sri-Lanka	
	III. Use of wind and solar PV in mini grids and hybrid systems still in order of thousands in China	
Water pumping from wind and solar PV	I. About 1 million mechanical wind pumps in Argentina	Solar PV and wind power (both for irrigation and water pumping) gaining widespread acceptance
	II. Large numbers in Africa: South Africa (300,000), Namibia(30,000), Cape Verde(800), Zimbabwe(650)	
	III. 50,000 solar PV-pumps world wide. India (4000), West Africa (1000)	
	IV. The rest in Argentina, Brazil Indonesia, Namibia, Niger, Philippines, Zimbabwe	

Source: REN21, 2008 and Ren21/GTZ/BMZ 2008 ((REN21, 2008)).

1.3.6 Present status and future potential for RE

1.3.6.1 Meeting demands of developing countries through RE leapfrogging

Table 1.8 shows that technological options exist for providing cleaner cooking fuels and expanding rural electrification delivery –using mainly off-grid power generation. It is clear that successful technological leapfrogging examples are concentrated in Asia and in Brazil, the second largest consumer, and the major exporter of ethanol, which generates income within the country and improves energy security ((Brew-Hammond, Darkwah, & al., 2008)).

However, technological development cannot alone contribute to improved energy access in developing countries. Innovative policies, including financing, are required (see sec 1.4.6.2 and chapter 11).

1.3.6.2 Global Scenarios for RE deployment in the future

Chapter 10 includes a comprehensive analysis of over 100 scenarios of energy supply and demand to assess the costs and benefits of RE options to reduce GHG emissions and thereby mitigate climate change. Even without a push for climate change mitigation, the increasing demand for energy services is expected to drive growth of RE to levels exceeding today's energy usage. There are large uncertainties in projections, including economic and population growth, development and deployment of higher efficiency technologies, the ability of RE technologies to overcome initial cost barriers, preferences, environmental considerations and other barriers.

1.4 Barriers, Opportunities and Issues

Almost everywhere in the world, one can find a RE resource of one kind or other – e.g., solar radiation, wind, falling water, waves, tides and stored ocean heat or heat from the earth - and there are technologies available to harness all of these forms of energy. The opportunities seem great. Then, why is RE not in universal use?

Firstly, there are *barriers*. A barrier was defined in the AR4 as 'any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy programme or measure' ((IPCC, 2007); (Verbruggen, et al., 2010)). For example, the technology as currently available may not suit the desired scale of application. This barrier can be attenuated in principle by a program of technology development (Research &Development).

Secondly, other *issues*, not so amenable to policies and programs, can also impede the uptake of RE. An obvious example is that the resource may be too small to be useful at a particular place: e.g., the wind speed may be consistently too low to turn a turbine or the topography too flat for hydropower.

This section describes some of the main barriers and issues to using RE for climate change mitigation, adaptation and sustainable development. *As throughout this introductory chapter, the examples are illustrative and not comprehensive*. Section 1.5 (briefly) and Chapter 11 [section 11.4] of this report (in more detail) look at policies and financing mechanisms that may overcome them. When a barrier is particularly pertinent to a specific technology, it is examined in the appropriate 'technology' chapters of this report (i.e., chapters 2 to 7).

For convenience of exposition, the various barriers are categorised here as informational, socio-cultural, technical and structural, economic, or institutional (see Table 1.9). This categorization is somewhat arbitrary since, in many cases, barriers extend across several categories. More importantly, for a particular project or set of circumstances it will usually be difficult to single out one particular barrier. They are interrelated and need to be dealt with in a comprehensive manner.

More positively, RE can open opportunities for co-benefits, not least for adaptation to climate change. Some such opportunities are outlined in subsection 1.4.7.

Table 1.9. A categorisation of barriers to RE deployment

Subsection	Type of barrier	Some relevant policy instruments (see chapter 11)
1.4.1	Market failures	Carbon taxes, emission trading schemes, public support for R&D on RE)
1.4.2	Information and awareness barriers	Energy standards, information campaigns
1.4.3	Socio-cultural issues	Improved processes for land use planning
1.4.4	Technical and structural barriers	Enabling environment for innovation, revised technical regulations, international support for technology transfer (e.g. under UNFCCC)
1.4.5	Economic barriers	economic climate that supports investment, carbon taxes, emission trading schemes
1.4.6	Institutional barriers	Microfinance, technical training, liberalisation of energy industries

[TSU: Source?]

1.4.1 Market failures

Many, but not all, barriers are described by economists as *market failures*. With reference to the theoretical ideal market conditions ((Debreu, 1959), (Becker, 1971)), all real-life markets fail to some degree ((Bator, 1958);(Meade, 1971); (Williamson, 1985)), evidenced by losses in welfare. Three major market failures (imperfections) are undersupply of public goods, oversupply of negative externalities and rent appropriation by monopolistic entities. In case of RE deployment, they may appear as:

- Underinvestment in invention and innovation in RE technologies because initiators cannot benefit from exclusive property rights on their efforts ((Margolis & Kammen, 1999); (Foxon & Pearson, 2008)).
- Un-priced environmental impacts and risks of energy use when economic agents have no obligation to internalize the full costs of their actions ((Beck, 1995), (Baumol & Oates, 1998)). GHG emissions and climate change are prevalent examples ((Stern, 2006); (Halsnaes, Shukla, & Garg, 2008), p.135; see also sec.1.4.5.1), but also impacts and risks of some RE projects and of other low-carbon technologies (nuclear, CCS) remain unpaid.
- The occurrence of monopoly or monopsony powers in energy markets limit competition among suppliers or demanders, free market entry and exit (see sec. 1.4.4.2). Monopoly and oligopoly power can be factual by deliberate concentration, control and collusion. Interconnected network industries (for example: electric, gas and heat transmission grids) within a given area, are natural monopolies because network services are least-cost when provided by a single operator ((Baumol, Panzar, & al., 1982)).

Characterizing these imperfections as market failures, with high likelihoods of significant welfare losses and of the impotence of market forces in clearing the imperfections, provides strong economic arguments for public policy intervention repairing the failures ((Coase, 1960); (Bromley, 1986)). On top of imperfections classified as market failures, various factors apart from market prices and budgets affect the behaviour of market agents, and are categorised here as other types of barriers.

1.4.2 Informational and awareness barriers

1.4.2.1 Deficient data about natural resources

RE is widely distributed (e.g. the sun shines everywhere) but is site-specific in a way that ‘conventional’ fossil-fuel systems are not. For example, the output of a wind turbine depends strongly on the wind regime at that place, unlike the output of a diesel generator. While broad-scale data on wind is reasonably well available from meteorological records, it takes little account of local topography, which may mean that the output of a particular turbine could be 10-50 % higher on top of a local hill than in the valley a few hundred metres away ((Petersen, Mortensen, Landberg, H¯jstrup, & Frank, 1998)). To obtain such site-specific data requires on-site measurement for at least a year and/or detailed modelling. Similar data deficiencies apply to many other RE resources, but can be attenuated by specific programs to better measure those resources.

1.4.2.2 Skilled human resources (capacity)

To develop RE resources takes skills in mechanical, chemical and electrical engineering, business management and social science, as with other energy sources. But the required skill set differs in detail for different technologies and people require specific training. Developing the skills to operate and maintain the RE “hardware” is exceedingly important for a successful RE project. It is also important that the user of RE technology understand the specific operational aspects and availability of the RE source. One case where this is important is in the rural areas of developing countries (see Section 1.4.6.2). More generally, in some developing countries, the lack of an ancillary industry of RE, (such as specialized consulting, engineering and procurement, maintenance, etc) implies higher costs for project development and is an additional barrier to deployment.

1.4.2.3 Public and institutional awareness

The oil price peaks of 1973, 1980, 1991 and 2008 made the consumer in both industrialised and developing counties search for alternative sources of energy. These events brought broad enthusiasm for RE, especially solar, wind and biomass, but detailed understanding remains more limited about the technical and financial issues of implementation. For instance, opinion polls in Australia (e.g., (ANU, 2008)) indicate strong public support for greater use of RE (and more generally to mitigate climate change). On the technical aspects, many supporters of single household PV energy systems are initially unaware that to be viable such systems require appliances with much greater end-use efficiency than conventional ones. Even professionals often lack awareness of RE possibilities, e.g. architects who specify ‘conventional’ heating systems instead of renewable ones.

To be fully successful, a program to implement RE technologies requires that there be awareness and support from not only the public, but the government, utilities and industries. Thus, stakeholder consultation is necessary for successful implementation. However, in only a few countries have there been a major effort to educate all parts of society about the nature of RE relative to traditional fossil fuels.

1.4.3 Socio-cultural issues

1.4.3.1 Social acceptance

Social acceptance for RE is generally increasing; having domestic solar energy PV or domestic hot water systems on one’s roof has become a mark of the owner’s environmental commitment (Bruce, Watt, & Passey, 2009). By contrast, many wind farms have had to battle the ‘not in my backyard’ (NIMBY) attitude before they could be established, as have nuclear power stations (Pasqualetti, Gipe, & Righter, 2002); (Klick & Smith, 2010); (Webler & Tuler, 2010). See chapters 7 and 11 of this report for more discussion of how such local planning issues impact the uptake of RE. Chapter 11 also includes a wider discussion of the enabling social and institutional environment required for the transition to RE systems.

1.4.3.2 Land use

Farmers on whose land wind farms are built rarely object; in fact they usually see them as a welcome extra source of income either as owners (Denmark) or as leasers of their land (U.S.), as they can continue to carry on agricultural and grazing activities beneath the turbines ((Milborrow, 2001)) Other forms of RE preclude multiple uses of the land; e.g. a dam for hydropower. Land use can be just as contentious in some developing countries. In Papua New Guinea, for example, villagers may insist on being paid for the use of their land for (e.g.) a mini-hydro system of which they are the sole beneficiaries. ((Johnston & Vos, 2005), p.66) Unintended consequences, such as displacement of rain forests to grow crops for biofuels also need to be avoided.

1.4.4 Technical and structural barriers

1.4.4.1 Resource issues

RE draws on natural environmental flows of energy, most of which by their nature are variable and almost always of lower intensity [W per m^2] than the petrol consumption of a motor car or the core of a nuclear reactor (Twidell & Weir, 2006). These characteristics imply that the engineering techniques needed to harness RE cost-effectively differ from those used for fossil or nuclear energy. In particular, to manage energy supply systems for variable supply as well as variable demand requires a systems approach, which will require the use of information technology. For example, to use solar energy to heat a house in winter is best done by architectural design rather than by converting it to electricity and then installing electric heaters around the building (See Chapter 3 of this report).

1.4.4.2 Existing infrastructure and energy market regulation

The dispersed, relatively low energy-density, nature of most forms of RE implies that the most effective utilization may be though distributed applications, rather than through large centralized power systems such as are required by systems based on coal and nuclear energy. Unfortunately much of the existing energy infrastructure is built on the centralized model. When a planned RE application is of a centralized nature, such as the proposed solar concentrating power system in North Africa intended to supply Europe, the energy source is not usually near existing supply systems. This requires that transmission infrastructure has to be constructed, which adds to the financial costs. This is not a new problem in that harnessing remote hydropower has been accomplished and the electricity generated has been transported over very large distances.

Technical regulations and standards have evolved to make the current energy infrastructure fairly safe and reliable. These standards and regulations generally assume that systems are of high power density and/or high voltage and may therefore be unnecessarily restrictive for RE systems of low power density. Most of the rules governing sea lanes and coastal areas were written long before offshore wind power and ocean energy systems were being developed and do not consider the possibility of multiple uses that include such systems (See Chapter 6 of this report).

The regulations governing energy businesses in many countries are still designed around monopoly or near-monopoly providers (especially for electricity). These standards and regulations were ‘liberalised’ in several countries in the 1990s, to allow ‘independent power producers’ to operate, although scales required often exclude many smaller proposed RE projects. There are current regulations that protect the current centralized production, transmission and distribution system and make the introduction of alternative technologies including many renewables difficult. An examination and modification of existing laws and regulations is a first step in the introduction of RE technologies especially into the electric power system (See chapters 8 and 11 of this report).

1.4.4.3 Intellectual property issues

Technological development of RE has been rapid in recent years, particularly in photovoltaics and wind power. Patents protect many of these new developments. Concerns have been raised that this may unduly restrict low-cost access to these new technologies by developing countries, as has happened with many new pharmaceuticals ((Barton, 2007)).

1.4.5 Economic barriers

Chapter 10 of this report includes a detailed discussion of the current and projected costs of RE systems. A few pertinent general features of the economics of RE are highlighted here.

1.4.5.1 Cost issues

Twidell &Weir (2006) point to some key questions that affect an assessment of the economic costs and benefits of an energy system (Twidell & Weir, 2006):

(a) Whose financial costs and benefits are to be assessed: the owners, the end-users, or those of the nation or the world as a whole? The costs of climate change to a nation or the world or even to a local community have in the past been treated as external to the costs of an energy project, as seen by its owners, operators and bankers. The averted costs of climate-related disasters were thus seen as a benefit to the nation but not directly to the project proponents. However such ‘external costs’ can be made internal to a project’s finances by government policies, such as carbon taxes or emission trading schemes, as discussed in Section 10.6 and Chapter 11 of this report.

(b) Which parameters or systems should be assessed: the primary energy sources or the end-use services? The practical importance of this distinction was raised in section 1.3.1.

(c) Where does the assessment apply? The cost of RE at a particular site strongly depends on the resource available. Similarly, adding a PV system near the end of a long power line from a central power station can boost the voltage there much more cheaply than replacing the whole power line by one with lower power losses. Its site-specific value to the grid operator is thus much greater than its financial cost.

(d) When are the costs and benefits to be assessed: at the start of a project or levelized over its working life? In marked contrast to fossil fuel systems, the fuel cost of RE systems is zero (bioenergy excepted). Instead the main cost is the up-front capital cost.

This capital cost may be considerably higher than for a conventional energy system, but it is not subject to the fluctuations of fossil energy prices - compare the oil price that has varied recently from $11 to 145 USD [TSU: needs to be converted into 2005US$]0020per barrel. Such variation makes it very difficult to assess, at the outset of a project, what will be its levelized cost of energy production. In contrast, the capital cost, and hence the levelized cost, of an RE project is known at the outset, or at worst is subject only to the relatively small variation in interest rates over the life of the project. In either case the revenue stream is usually also uncertain (See Appendix II) (Gross, Blyth, & Heptonstall); (Bazilian & Roques, 2008).

1.4.5.2 Availability of capital and financial risk

All power projects carry financial risk because of uncertainty in future electricity prices, regardless of its source, making it difficult for a private or public investor to anticipate future financial returns on investment. Moreover, the financial viability of an RE system strongly depends on the availability of capital and its cost (interest rates) because the initial capital cost comprises most of the economic cost of an RE system. While the predictability of such costs is a relative advantage of RE systems, bankers are still often reluctant to lend for almost any purpose (e.g. in the financial crisis of 2008-09) **(**(Wright, van der Heijden, Burt, Bradfield, & Cairns, 2008)).

An example of financial risk from an RE system outside the power sector is the development of biofuels for aviation. In 2009 neither the potential bio-jet refiners nor the airlines fully understood how to structure a transaction that is credit worthy and as a result might get financed if there were financial institutions interested in these types of transactions ((Slade, Panoutsou, & Bauen, 2009)).

A socially important case where capital availability can be a barrier to modern energy services is in the rural areas of developing countries (see section 1.4.6.2).

1.4.5.3 Allocation of government financial support

Since the 1940s, governments in industrialized countries have spent considerable amounts of public money on energy-related research development and demonstration (RD&D). However, by far the greatest proportion of this has been on nuclear energy systems. Usually, only in times of ‘energy crisis’ has there been appreciable spending on RE technologies (IEA, 2008). See also section 10.5 of this report). However, following the financial crisis of 2008-09, some governments used part of their ‘stimulus packages’ to encourage RE or energy efficiency. Tax write-offs for private spending have been similarly biased towards non-RE sources (e.g., in favour of oil exploration or new coal-burning systems), notwithstanding some recent tax incentives for RE (GAO, 2007). The policy rationale for government support for developing new energy systems is discussed in section 1.5 and chapter 11 of this report.

1.4.5.4 Trade barriers

There are tariff barriers (import levies) in some countries that render uneconomic some trade in bioenergy that might otherwise be of mutual benefit (see chapter 2 of this report, sec. 2.4.7).

1.4.6 Institutional barriers

1.4.6.1 Industry structure

The energy industry in most countries is based on a small number of companies (sometimes only one in a particular segment such as electricity or gas supply) operating a highly centralized infrastructure. The institutional and personal skills and the mindset that this structure encourages do not fit well with the model of multiple dispersed supplies that characterizes many forms of RE. And even the more centralised forms of RE will usually entail transmission lines from new locations. In this situation, changes to the laws and regulations governing energy supply may be needed to allow RE concerns to operate at all, let alone to compete on a fair basis. Chapter 8 deals with this and other ‘integration’ issues.

Energy businesses are among the largest in any country, industrialised or developing. They have billions of dollars tied up in the existing infrastructure. Although some big businesses in Brazil and

Norway have already embraced RE, and others elsewhere are starting to do so, some incumbent energy suppliers have lobbied against RE for decades. Hamilton (2007) graphically describes such efforts in Australia (Hamilton, 2007). The World Business Council for Sustainable Development presents the more positive view of some other large energy businesses (e.g., (WBCSD, 2008)).

1.4.6.2 Technical and financial support (especially for scattered users)

Technical support for dispersed RE, such as photovoltaic systems in the rural areas of developing countries, requires many people with basic technical skill rather than a few with high technical skill as tends to be the case with conventional energy systems. Training such people and ensuring that they have ready access to spare parts requires new infrastructure to be set up.

Because the cost of such systems is largely up-front, it would be unaffordable to most potential customers, especially in developing countries, unless a financial mechanism is established to allow them to pay for the RE energy service month by month as they do for kerosene. Even if the initial equipment is donated by an overseas agency, such a financial mechanism is still needed to pay for the technical support, spare parts and eventual replacement of the system. The developing world is filled with examples of systems abandoned for lack of such follow-through mechanisms. Failure to have these institutional factors properly set up has been a major inhibitor to the use of RE in the Pacific Islands, where small-scale PV systems would appear to be a natural fit to the scattered tropical island communities (Johnston & Vos, 2005).

1.4.7 Opportunities opened by RE, including for adaptation

Section 1.1.4 has pointed out that the wider use of RE brings benefits not only for climate mitigation but co-benefits in energy security, economic development that is both more sustainable and more potentially more equitable than current patterns. In particular, RE with its dispersed resource and scalable technologies can assist development in the rural areas of developing countries and thereby lessen the urban drift of population with its attendant social problems ((Gupta, 2003); (Cherni & Hill, 2009)). And in both developed and developing countries, some types of RE systems create considerably more new jobs than do ‘conventional’ fossil-based or nuclear-based systems, which tend to be much more centralised and mechanised (Wei, et al., 2010). Chapter 9 of this report elaborates on many of these issues.

Since a degree of climate change is now inevitable, adaptation to climate change is an essential component of sustainable development (IPCC-Synthesis, 2007). AR4 includes a chapter on the linkage between climate mitigation (reducing emissions of GHGs) and climate adaptation (Klein, et al., 2007). A co-benefit of some forms of RE which has not received much attention in the literature, despite that chapter, is the potential to assist adaptation to climate change, as in the following examples.

- Active and passive solar cooling of buildings [chapter 3] helps counter the direct impacts on humans of rising mean temperatures.
- Dams (used for hydro-power) are also important in smoothing out the impacts of droughts and floods, which are projected to be major impacts of climate change. Indeed, this is one of reasons for building such dams in the first place [chapter 5; see also World Commission on Dams ((WCD, 2000)).]
- Water pumps in rural areas, often powered by photovoltaics [chapter 3] or wind [chapter 7] are also important tools for raising agricultural productivity, especially in dry seasons and droughts.

- Tree planting and forest preservation along coasts and riverbanks is a key strategy for lessening the coastal erosion impacts of climate change. With suitable choice of species and silvicultural practice, these plantings can also yield a sustainable source of biomass for energy, e.g. by coppicing. [Chapter 2, section 2.5]

1.5 Role of policy, R&D, deployment, scaling up and implementation strategies

Policy sets the framework, the conditions and often the impetus under which publicly induced change can occur. If the advancement of RE in the context of climate change is seen as desirable or necessary, then actions will be required. Such actions cover every aspect of the progress of RE as a primary part of the energy system. The components of this advancement include development, testing, deployment, commercialization, market preparation, market penetration, maintenance, monitoring, etc. Chapter 11 reviews the various antecedents, policy developments, implementation and other conditions that allow for the appropriate policies to be put in to place.

The growth of RE systems in industrialised countries in the last decade or two has been greatest where it has been supported by policies such as feed-in tariffs, mandatory RE targets, or tax concessions for RE investment. But having such support switch on and off at short intervals, as the tax credits have done in the USA, results in bursts of quickly conceived projects followed by periods of inactivity as business are reluctant to invest because of uncertainty as to whether the support policy will continue. By contrast, the long-term certainty inherent in German feed-in-tariffs has propelled them into the lead in manufacturing RE technologies.

1.5.1 Policies for development of technologies

The debate surrounding technology development, its costs and its deployment is rich. The benefits and costs of R&D or of research, development and deployment (RD&D) involve discussions of two factor learning curves, where R&D expenditures are related to investment costs of technologies, mobilizing funds that includes coverage of deployment (RD&D) **(**(Sonntag-O'Brien & Usher, 2004)**),** the role of carbon pricing policies in technology development and more ((Bosetti, Carraro, & al., 2009)).

The question of who should cover the costs associated with the R&D for new technologies is complex. Should this be public funds or private, or some mixture of both? Ostensibly, commercial or economic benefits of the advancement in an existing technology or some more novel approach to capturing RE exist; these benefits should accrue to the investor. Historically, private enterprise has invested and consequently received the benefit while society has gained from advances made. Logically, one assumes that the bulk of the R&D should fall on the shoulders the firm / company / utility and it can be argued that public funds in R&D should be minimal or none. Others argue that the development and advancement of a new technology requires an initial impetus from foresighted planners and continued support to ensure commercialization in the future. Currently, the private sector is leading R&D of technologies that are close to market deployment, while public funding is essential for the longer term and basic research ((Fisher, et al., 2007), Section 3.4.2). Chapter 11.2.2 addresses these issues.

Market barriers exist that prevent the development and penetration of novel RE technologies into the energy system. Renewable supply companies are under sometimes significant disadvantages (risks) associated with the development of a new technology or service, especially when the market playing field is not level. For example, while many perceive RE to have qualities and values related to their cleanliness and renewability, the current market attributes no value as such to these characteristics. New technologies also face regulatory barriers that support existing systems, which by their nature discriminate against distributed energy sources such as rooftop solar PV or against wind and solar because of their variable nature.

Sufficient investment will be required to ensure that the best technologies are brought to market in a timely manner. These investments, and the resulting deployment of new technologies, provide an economic value and can act as ‘hedging’ strategies in addressing climate change. However, there remains significant uncertainty, in part due to a paucity of data, that enables one to link ‘inputs’ (R&D and market stimulation costs) to ‘outputs’ (technology improvements and cost reductions) ((Fisher, et al., 2007), Section 3.4.2). The role of the policy maker is important, whether to invest in R&D, to ameliorate the risks faced by R&D products in the market or to develop the pilot and demonstration projects so necessary for market acceptance.

1.5.2 Policies to move technologies to commercialization

The importance of policies to enhance technology development, described above, is crucial to the advancement of RE supply there is also a need for policies to drive deployment. (Bosetti, *et al.*, 2009), in their gaming analysis using the WITCH model, argue that the establishment of enduring and consistent carbon pricing policies are themselves sufficient to stimulate R&D and deployment (without affecting R&D in other areas; i.e., it was not a diversion of funds) (Bosetti, et al., 2009) Edmonds *et al*., 2004) consider advanced technology development to be far more important as a driver of emission reductions than carbon taxes (Edmonds, Clarke, Wise, Pitcher, & Smith, 2008). Weyant (2004) concluded that GHG stabilization will require the large-scale development of new energy technologies, and that costs would be reduced if many technologies are developed in parallel and there is early adoption of policies to encourage technology development (Weyant, 2004). Both statements speak to the need to ensure that newly developed technologies can move from the pilot/development state to the production/commercialization state. Costs of piloting and ultimate commercialization of a new technology/process can be very high and firms often find the greatest expense and the greatest risk in this area. Many institutional support mechanisms were and are available to move RE technologies into the market, e.g. grants, tax relief, feed-in tariffs and the like. The failure of many worthy technologies to move from R&D to commercialization has been coined the “valley of death” for new products (Markham, 2002); (Murphy & Edwards, 2003); Murphy, *et al.*, 2003) .This is discussed in Ch. 11.5 Attempts to move renewable technology into mainstream markets following the oil price shocks failed in most developed countries. Many of the technologies were not sufficiently developed or had not reached cost competitiveness and, once the price of oil came back down, interest in implementing these technologies faded. Solar hot water heaters were a technology that was ready for the market and with tax incentives many such systems were installed. But once the tax advantage was withdrawn, the market largely collapsed.

1.5.3 Implementation of policies (supply push vs. demand pull)

Policy and decision makers approach the market in a variety of ways: level the playing field in terms of taxes and subsidies, create a regulatory environment for effective utilization of the resource, internalize externalities of all options or modify or establish prices through taxes and subsidies, create command and control regulations, provide government support for R&D, provide for government procurement priorities or establish market oriented regulations, all of which shape the markets for new technologies. Some of these, such as price, which modify relative consumers’ preference, provide a demand-pull and enhance utilization for a particular technology. Other such as government supported R&D attempt to create new products through market push (Dixit & Pindyck, 1994); (Freeman & Soete, 2000); (Moore, 2002) (Dixit and Pindyck, 1994; Freeman and Soete, 2000; Moore, 2002). Requirements that set either technology or performance standards through regulation may also move in a direction that enhances the penetration of the product/service in the market.

There is now considerable experience with several types of policies designed to increase the use of renewable technology. Denmark became a world leader in the manufacture and deployment of large-scale wind turbines by setting long-term contracts for renewably generated electricity production. The Danes also made it relatively easy for farmer cooperatives to invest in wind turbines and used their domestically produced machines in their foreign assistance program. The Danish government left R&D to the private sector (Sawin, 2001). Germany has used a similar market pull mechanism through its feed-in-tariff that assured producers of wind, solar and other renewable sources of electricity that they would receive a higher rate for each kilowatt-hour of renewably generated electricity for a long and certain time period. Germany is the world's leading installer of solar PV, and until 2008 had the largest installed capacity of wind turbines (REN 21, 2009a). The U.S. has relied mostly on government R&D subsidies for RE technologies and this supply push approach has been less successful. Early attempts by the state of California to encourage wind power in the 1980s by an investment tax credit failed to produce an enduring wind turbine environment. Some form of a production tax credit has resulted in much more production of zero carbon electricity (Sawin, 2001).

The use of Renewable Portfolio Standards (RPS) has been moderately successful in some states in the U.S. China has encouraged renewable technology for water heating, solar PV and wind turbines by investing in these technologies directly. China is already the leading producer of solar hot water systems for both export and domestic use, and is now the largest producer of PV technology (REN 21, 2009a). After dropping its domestic incentives for PV technology, Japan fell behind as a major producer of PV technology. It has proven very difficult to take away existing subsidies to other technologies including fossil fuels and the construction of nuclear power plants in most countries. Governments may resort to levelling the playing field by granting similar subsidies to RE technologies.

1.5.4 Integrate policies into sectors

Since all forms of RE capture and production involve spatial considerations, policies need to consider land use, employment, transportation, agricultural, water, food security, trade concerns and other sector specific issues.

A major focus for RE is the electric power sector's need to introduce new technologies and to rebuild the transmission and distribution grid. The grid must be more compatible with a system that incorporates both large central power plants and a very distributed system of small renewable and other suppliers. Such a system must harmonize conventional and biofuel plants that utilize the otherwise lost heat associated with power production, rooftop solar PV, and mid-to-large scale hydro, wind, concentrated thermal solar and geothermal power plants. Many current regulations and laws support the structure and reliability of the current centralized grid locking in these technologies, and prevent the wide-scale introduction of renewable electric generating technology.

For the transport sector, there are major questions of developing the infrastructure for either biofuels, renewably generated hydrogen or battery and hybrid electric vehicles that are "fuelled" by the electric grid or from off-grid renewable electrical production (Tomic & Kempton, 2007).

The agriculture sector presents unique opportunities for capturing methane from livestock production and using manure and other crop wastes to provide on-farm fuels. There are now examples of farms that utilize methane from livestock to heat buildings including greenhouses, run electric generators and tractors. Brazil has been especially effective in establishing a rural agricultural development program around sugar cane. Bioethanol produced from sugar cane in Brazil is currently responsible for about 40% of the spark ignition travel and it has been demonstrated for use in diesel buses and even in a crop duster aircraft. The bagasse, which is otherwise wasted, is gasified and used to operate gas turbines for electricity production while the "waste" heat is used in the sugar to bioethanol refining process (Pousa, 2007).

1.5.5 Policies to avoid negative externalities

Any change in energy systems will alter the status quo of presently used fuels and technologies. No development stands on its own and policy makers need to critique and incorporate into any assessment all aspects of the impacts of a policy designed to enhance renewable fuels. It is necessary to incorporate externalities of a switch to RE supply (land use, alternative values, aesthetic concerns, etc.) as well as review co-benefits associated with the development of that particular form of RE (e.g., reduction in air pollutants, GHG emissions reduction). Some producers of fossil fuels are concerned that any policies that encourage a move away from the use of fossil fuels will adversely affect their markets. Two analyses of implementation of oil reductions concluded that the major impact would be on unconventional oil sources that produce high CO_2 emissions from oil shales, oil tars and heavy bitumen much more than conventional supplies (Barnett, Dessai, & Webber, 2004); (Persson, Azar, Johansson, & Lindgren, 2007). It is also critical to consider the potential of RE to reduce emissions from a life cycle perspective, an issue that each of the following technology chapter addresses. While the use of biofuels can offset GHG emissions from fossil fuels, direct and indirect land use changes must be also be evaluated in order to determine net benefits.[4] Such changes can include deforestation, conversion of grasslands to agricultural production, or diversion of agricultural production to fuel production. These may even result in increased GHG emissions, potentially overwhelming the gains from CO_2 absorption. An illustrative life cycle analyses, featuring expanded boundaries is shown in Figure 1.13.

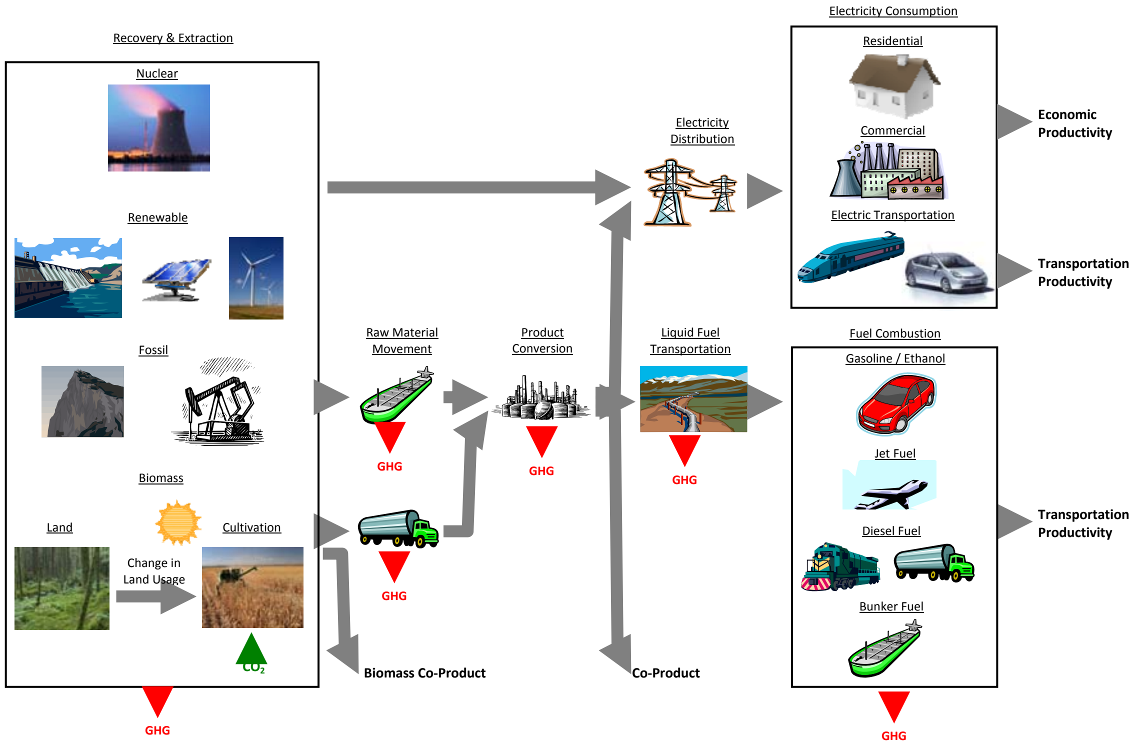

Figure 1.13. Illustrative system for energy production and use illustrating the role of RE along with other production options. A systemic approach is needed to conduct life cycle systems analysis.

1.5.6 Options are available if policies are aligned with goals

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[4] Note that such land use changes are not restricted to biomass based RE. For example, wind generation and hydro developments as well as surface mining for coal and storage of combustion ash also incur land use impacts.

An examination of alternative policies to encourage adoption of RE demonstrates that demand-pull policies are generally more effective than supply-push policies (Sawin, 2004). A recent analysis of alternative policies has found that wherever feed-in-tariffs are utilized to provide long-term certainty for higher production prices to RE, it has been more effective than renewable portfolio standards (Carpenter, 2009).

Germany, has proposed a goal of 100% RE by 2050 (BMU, 2009). According to David Wortmann, Director of RE and Resources, Germany Trade and Invest has stated, "The technical capacity is available for the country to switch over to green energy, so it is a question of political will and the right regulatory framework. The costs are acceptable and they need to be seen against the huge costs that will result if Germany fails to take action to cut its carbon emissions." (Burgermeister, 2009). Ultimately, we will need a basket of incentives to companies to develop the processing and refining capacity, and positive fiscal and legal frameworks to advance the economic viability of RE.

1.5.7 Integration of RE supply into the existing energy system

Our current energy system is the consequence of a set of energy choices often made in the absence of renewable supply (except for large hydro sources). As a result, institutional or operational barriers may hinder or prevent the advent of RE into the system. There still exist utilities that exhibit monopolies in all supply aspects – generation, transmission and distribution – and often maintain conditions that retain out-of-date transmission regulations, favour traditional power sources, do not recognize the benefits associated with new renewable supply sources and prevent the transition of the energy system to a more sustainable form.

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Chapter 2

Bioenergy

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	LAs:	Berndes, Göran; Dhamija, Parveen; Dong, Hongmin; Gabrielle, Benoît X; Goss Eng, Alison M; Lucht, Wolfgang; Mapako, Maxwell; Masera Cerutti, Omar; McIntyre, Terry Charles; Minowa, Tomoaki; Pingoud, Kim				
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Government and expert reviewers are kindly asked to note that, due to time constraints, this chapter has been formatted but has – unlike the other chapters - not gone through a preliminary screening by the TSU.

This chapter has been allocated 102 template pages, currently it counts 116pages (excluding this page and the bibliography), so it is 14pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened.

Chapter 2: Bioenergy

CONTENTS

EXECUTIVE SUMMARY

Bioenergy today. Chapter 2 discusses biomass, a primary source of fiber, food, fodder and energy. It is the most important renewable energy source, providing about 10% (46 EJ) of annual global primary energy demand. A major part of biomass use (37 EJ) is the use of charcoal, wood, and manure for cooking, space heating, and lighting generally by poorer populations in developing countries called traditional. Modern bioenergy use (for industry, power generation, or transport fuels) is making a significant 9 EJ contribution and its share is growing rapidly.

Modern bioenergy chains involve a range of feedstocks, conversion processes and end-uses. Feedstock types include annual and perennial plants including food crops; residues from agriculture, forestry, and related transformation industries; and recurrent organic waste streams. Several bioenergy systems can be deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions but still may require government subsidies. Deployed bioenergy usually provided economic development, including poverty elimination, energy security, environmental improvements, etc. Bioenergy system economics and yields vary across world regions and feedstock type/conversion processes, with costs from 5 to 80 US$/GJ for biofuels, from 5 to 20 US$/GJ for electricity, and from 1 to 5 US$/GJ for heat from solid fuels or waste.

Future potential. Between studies the expected medium to longer term deployment of bioenergy differs. Large scale deployment largely depends on: sustainable resource base development and governance of land use, development of infrastructure, and cost reduction of key technologies. Current analyses show the upper bound of resource potential by 2050 can amount to up to 400 EJ. This requires sophisticated land and water management, large worldwide plant productivity increases, land optimization, and other measures. Biomass potential is roughly in line with IPCC SRES A1 and B1 conditions and storylines, assuming sustainability and policy frameworks to secure good governance of land-use and improvements in agricultural and livestock management are secured.

If the right policy frameworks are *not* introduced, further biomass expansion can lead to significant regional conflicts for food supplies, water resources and biodiversity. Supply potential may be constrained to residues and organic waste use, cultivation of bioenergy crops on marginal/degraded and poorly utilized lands and regions where biomass is a cheaper energy supply option compared to reference options, which is the case for sugar cane ethanol production. Biomass supplies may then remain limited to ~100 EJ in 2050. The most likely biomass potential range is 100-300 EJ taking into account the literature available to date on environmental and social aspects of bioenergy.

Impacts. Bioenergy production has complex society and environmental interactions, such as climate change feedback, biomass production and land use. Bioenergy’s impact on social and environmental issues (e.g., health, poverty, biodiversity) may be positive or negative depending on local conditions and design/implementation of criteria for projects. Many conflicts can be avoided through synergies with better natural resources management and contributing to rural development. Policies need to take into account that optimal use and performance of biomass production is regional, incorporating the agricultural and livestock sector as part of good governance of land use and rural development interlinked with developing bioenergy.

Future options and cost trends. Further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring the costs of power (and heat) generation from biomass down in many regions, especially compared to natural gas. If carbon taxes of 20-30 U$/tonne were deployed (or when CCS would be deployed), biomass can be competitive with coal-based power generation and contribute significantly to carbon sequestration.

There is clear evidence that technological learning and related cost reductions occur in biomass technologies with comparable progress ratios to other renewable energy technologies. This is true for cropping systems (following progress in agricultural management when annual crops are concerned), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics), and in conversion (ethanol production, power generation, biogas and biodiesel).

Recent analyses of lignocellulosic biofuels, indicate potential improvement to compete at 60-70 U$/barrel oil. Scenario analyses indicate that strong short term R&D and market support could allow for ~2020 commercialization depending on oil and carbon pricing. Multiple biofuels and bioenergy options could become available under these conditions. In addition to ethanol and biodiesel, a range of hydrocarbons identical to petroleum could substitute for gasoline, diesel, jet fuel, and other markets. Biomass is the only unique renewable resource to provide high energy density fuels. Biobased products can continue to develop with biorefineries making multiple products and energy. Some short term options that can deliver important long term synergies, are co-firing, CHP, heat production and sugarcane based ethanol production. Significant improvements in other bioenergy is possible. Development of working bioenergy markets and facilitation of international bioenergy trade is another important facilitating factor to achieve such synergies.

Biobased materials and Bio-CCS concepts have limited literature cost estimates, future projections and learning studies although industrial production and use occurs. Advanced biobased materials, cascaded use of biomass, and bio-CCS may become attractive medium term mitigation options. More experience and detailed analyses of these options is needed.

GHG & Climate change impacts. Bioenergy has a significant GHG mitigation potential, provided resources are developed sustainably and provided the right bioenergy systems are applied. Perennial cropping systems and biomass residues and wastes are in particular able to deliver good GHG performance in the range of 80-90% GHG reduction compared to the fossil energy baseline. Climate change impacts influence and interact with biomass potentials. This interaction is still poorly understood, but there will be strong regional differences. Climate change impacts on feedstock production exist but if temperature raise is limited to 2 ^{o}C do not pose serious constraints. Combining adaptation measures and biomass resource production offers opportunities for bioenergy and perennial cropping systems.

The recently and rapidly changed policy context in many countries drives bioenergy to more sustainable directions, in particular development of sustainability criteria and framework/support for advanced biorefinery and second generation biofuel options. There is consensus on the critical importance of biomass management in global carbon cycles, and on the need for reliable and detailed data and scientific approaches to facilitate more sustainable land use in all sectors.

2.1 Introduction Current Pattern of Bioenergy Use and Trends

Biomass is the source of food, fodder and fibre as well as a renewable resource for use as a source of energy products such as heat, electricity, liquid fuels and chemicals. Bioenergy sources include forest, agricultural and livestock residues, short-rotation forest plantations, dedicated herbaceous energy crops, the organic component of municipal solid waste (MSW), and other organic waste streams. These are used as feedstocks, which through a variety of biological, chemical and physical processes produce energy carriers in the form of solid fuels (such as fuelwood, charcoal, chips, pellets, briquettes, and logs), liquid fuels (e.g., methanol, ethanol, butanol, biodiesel, and hydrocarbon fuels), and gaseous fuels (synthesis gas, biomethane, and hydrogen). These fuels can then be used to produce mechanical power (which can be used for transportation or other applications), electricity and heat as shown in Figure 2.1.1.

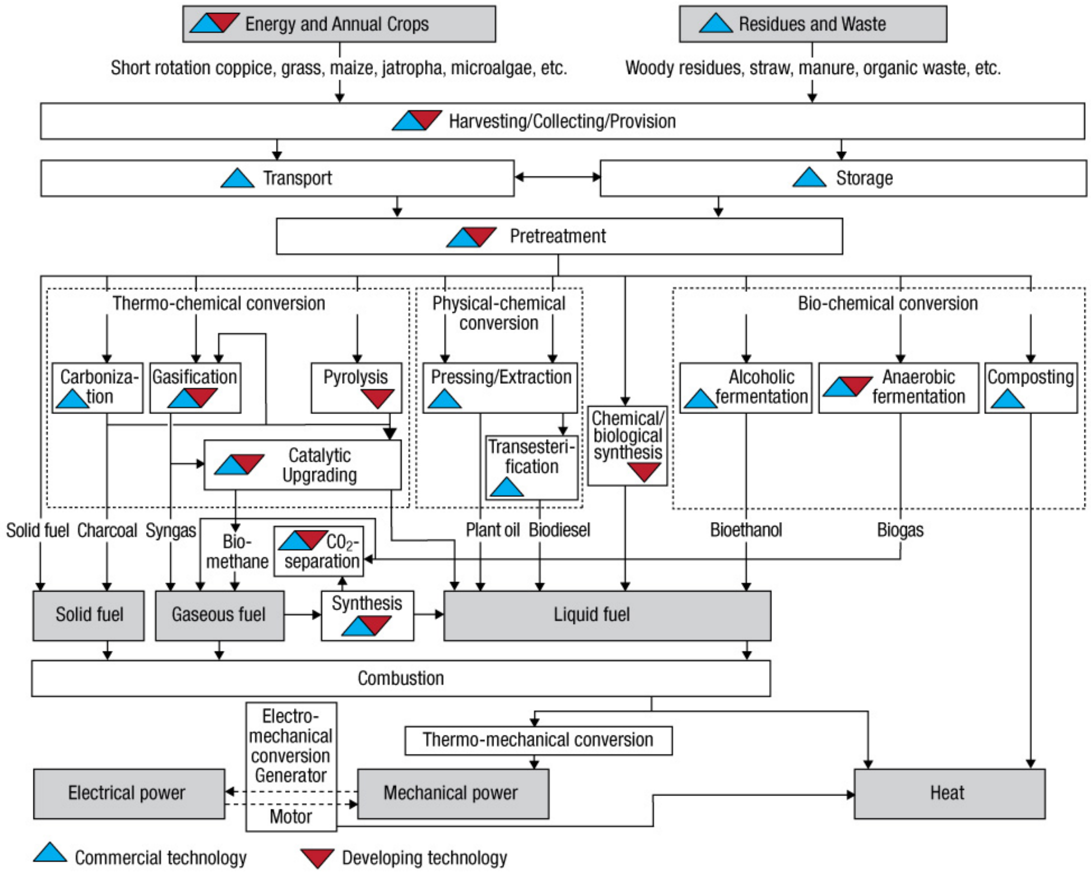

Figure 2.1.1. Pathways for producing energy products from biomass. Modified after Sterner 2009 and Karlschmitt and Hartmann 2001.

Sustainably produced and managed, bioenergy can provide a substantial contribution to climate change mitigation and at the same time provide large co-benefits in terms of local employment and regional economic development. Bioenergy options may help increase biospheric carbon stocks (for example through plantations on degraded lands), or reduce carbon emissions from unsustainable forest use (for instance through the dissemination of more efficient cookstoves). Additionally, bioenergy systems may reduce emissions from fossil fuel-based systems by replacing them in the generation of heat and power (for example by gasifying biomass in combined heat and power (CHP) systems, or in the provision of liquid biofuels such as ethanol instead of gasoline. Advanced bioenergy systems and end-use technologies, can also substantially reduce the emission of black carbon and other short-lived GHGs such as methane and carbon monoxide, which are related to the burning of biomass in traditional open fires and kilns. Not properly designed or implemented, the large-scale expansion of bioenergy systems is likely to also have negative consequences for climate and sustainability such as inducing direct and indirect land use changes that can alter surface albedo, release carbon from soils and vegetation, reducing biodiversity or negatively impacting local populations in terms of land tenure or reduced food security, among other effects.

Currently bioenergy is the most important renewable energy source (78% of all renewable energy produced) and provides about 10% (47 EJ) of the annual global primary energy demand. A full 97 percent of biofuels are made of solid biomass, 71 percent of which is used in the residential sector, as biomass provides fuel for the cooking needs of 2.4 billion people (Figure 2.1.2). Biomass is also used to generate gaseous and liquid fuels, and growth in demand for the latter has been significant over the last ten years (GBEP, 2008). Residues from industrialized farming, plantation forests, and food and fibre-processing operations that are currently collected worldwide and used in modern bioenergy conversion plants are difficult to quantify but probably supply approximately 6 EJ/yr. Current combustion of municipal solid waste (MSW) provides more than 1 EJ/yr though this includes plastics, etc. Landfill gas also contributes to biomass supply at over 0.2 EJ/yr (IPCC, 2007) (Figure 2.1.3)

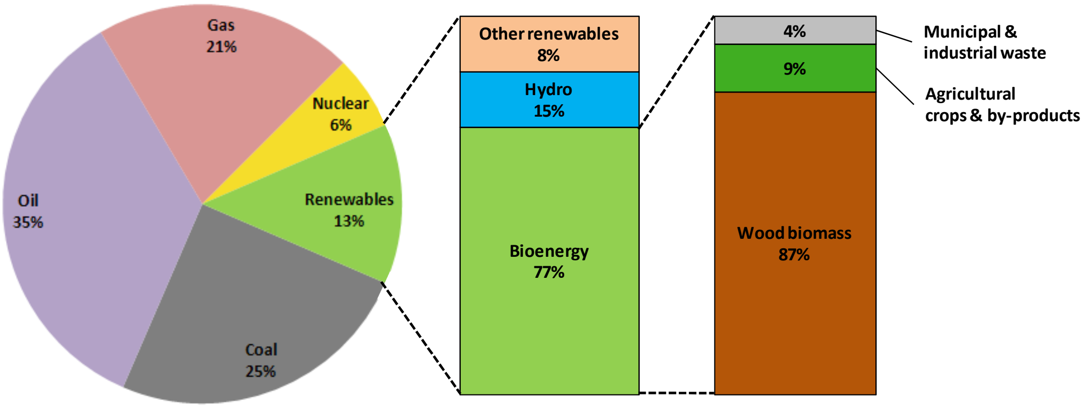

Figure 2.1.2. Share of bioenergy in the world primary energy mix. Source: based on IEA (2008) and IPCC (2007).

Global bioenergy use has been steadily growing worldwide in absolute terms in the last 40 years, with large differences among countries. Worldwide, China with its 9000 PJ/yr is the largest user of biomass as a source of energy, followed by India (6000 PJ/yr), USA 2300 PJ/yr, and Brazil (2000 PJ/yr).

Up to now biomass provides a relatively small amount of the total primary energy supply (TPES) of the largest industrialized countries (grouped as G8 countries: United States, Canada, Germany, France, Japan, Italy, United Kingdom, and Russia) (1-4 %), but this share is growing. The use of solid biomass for electricity production is important, especially from pulp and paper plants and sugar mills. Bioenergy's share in total energy consumption is increasing in the G8 Countries through the use of modern forms (e.g. co-combustion for electricity generation, buildings heating with pellets) especially Germany, Italy and the United Kingdom.

By contrast, bioenergy, mainly through the use of traditional forms (e.g. woodfuel and charcoal for cooking and heating) is a significant part of the energy supply in the largest developing countries representing from 5-27% of TPES (China, India, Mexico, Brazil, and South Africa) and more than 80% of TPES in the poorest countries. The bioenergy share in India, China and Mexico is decreasing, mostly as traditional biomass is substituted by kerosene and Liquified Petroleum Gas (LPG) within large cities, but consumption in absolute terms continues to grow. The latter is also true for most African countries, where demand has been driven by a steady increase in woodfuels, particularly in the use of charcoal in booming urban areas.

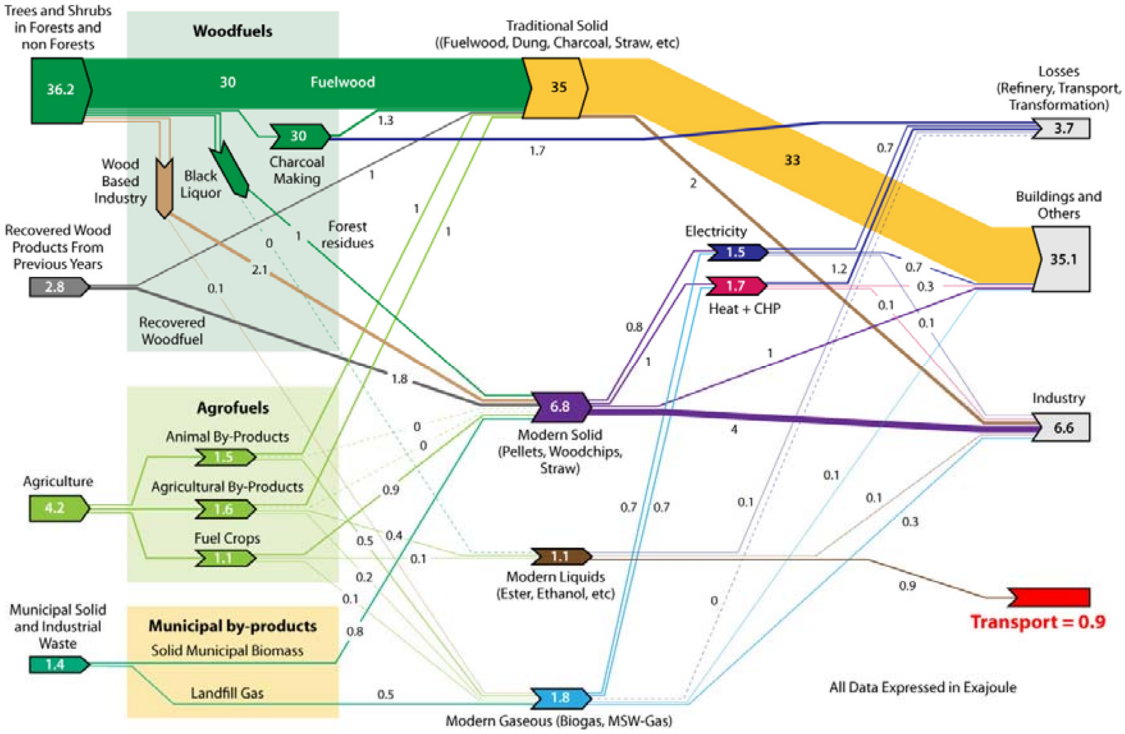

Figure 2.1.3. Global Biomass Energy Flows**.** Source: IPCC, 2007

While these statistics represent an essential reference, they tend to underestimate woodfuel consumption. Until recent years biomass fuels were regarded as marginal products in both energy and forestry sectors (FAO, 2005a). In addition to such historical disregard, production and trade of biomass fuels are largely informal, thus excluded from the conventional sources of energy and forestry data. International forestry and energy data are the main reference sources for policy analyses but they are often in contradiction, when it comes to estimate biomass consumption for energy. Moreover, detailed analyses indicate quite firmly that national statistics systematically underestimate the consumption of woody biomass for energy [Masera et al. 2005 (Mexico); Drigo and Veselič 2006 (Slovenia), Drigo et al. 2007 (Italy), and Drigo et al 2009 (Argentina)]

2.1.1 Previous IPCC Assessments

Bioenergy has not been examined in detail in previous IPCC reports. In the most recent assessment (4AR) the analysis of GHG mitigation from bioenergy was scattered among 7 chapters making it difficult to obtain an integrated and cohesive picture of its potential, challenges and opportunities. The main conclusions from the 4AR report (IPCC, 2007) are as follows:

i) Biomass Energy Demand: Demand projections for primary biomass for production of transportation fuel were largely based on IEA-WEO (2006) global projections, with a relatively wide range of about 14 to 40 EJ of primary biomass, or 8-25 EJ of fuel in 2030. However, higher estimates were also included, ranging between 45-85 EJ demand for primary biomass in 2030 (or roughly 30-50 EJ of fuel). Demand for biomass for heat and power was stated to be strongly influenced by (availability and introduction of) competing technologies such as CCS, nuclear power, wind energy, solar heating, etc). The projected demand in 2030 for biomass would be around 28-43 EJ according to the data used in AR4. These estimates focus on electricity generation. Heat is not explicitly modeled or estimated in the WEO, therefore underestimating total demand for biomass.

Also potential future demand for biomass in industry (especially new uses as biochemicals, but also expansion of charcoal use for steel production) and the built environment (heating as well as increased use of biomass as building material) was highlighted as important, but no quantitative projections were included in potential demand for biomass on medium and longer term.

ii) Biomass energy potentials (supplies). According to AR4, the largest contribution could come from energy crops on arable land, assuming that efficiency improvements in agriculture are fast enough to outpace food demand so as to avoid increased pressure on forests and nature areas. A range of 20-400 EJ is presented for 2050, with a best estimate of 250EJ/yr. Degraded lands for biomass production (e.g. in reforestation schemes: 8-110 EJ) can contribute significantly. Although such low yielding biomass production generally result in more expensive biomass supplies, competition with food production is almost absent and various co-benefits, such as regeneration of soils (and carbon storage), improved water retention, protection from (further) erosion may also off-set part of the establishment costs. An example of such biomass production schemes at the moment is establishment of Jathropa crops (oilseeds) on marginal lands.

The energy potentials in residues from forestry is estimated a 12-74 EJ/yr, from agriculture at 15-70 EJ/yr, and from waste at 13 EJ/yr. Those biomass resource categories are largely available before 2030, but also partly uncertain. The uncertainty comes from possible competing uses (e.g. increased use of biomaterials such as fibreboard production from forest residues and use of agro-residues for fodder and fertilizer) and differing assumptions on sustainability criteria deployed with respect to forest management and intensity of agriculture. The biogas fuel potentials from waste, landfill gas and digester gas, are much smaller.

iii) Carbon mitigation potential. The mitigation potential for electricity generation reaches 1,220 MtCO2eq for the year 2030, a substantial fraction of it at cost lower than 20 USD/tonne CO2. From a top-down assessment estimate the economic mitigation potential of biomass energy supplied from agriculture is estimated to range from 70–1260 MtCO2-eq/yr at up to 20 US$/tCO2-eq, and from 560–2320 MtCO2-eq/yr at up to 50 US$/tCO2-eq. The overall mitigation from the biomass energy coming from the forest sector is estimated to reach 400 MtCO2/yr up to 2030.

2.2 Resource Potential

2.2.1 Introduction

Bioenergy production interacts with food and forestry production in complex ways. It can compete for land, water and other production factors but can also strengthen conventional food and forestry production by offering new markets for biomass flows that earlier were considered as waste products. Bioenergy demand can provide opportunities for cultivating new types of crops and integrate bioenergy production with food and forestry production in ways that improves the overall resource management, but it can also lead to overexploitation and degradation of resources, e.g., too intensive biomass extraction from the lands leading to soil degradation, or water diversion to energy plantations that impacts downstream water uses including for terrestrial and aquatic ecosystem maintenance.

Thus, the biomass resource potential depends on the priority of bioenergy products vs. other products obtained from land – notably food and conventional forest products such as sawnwood and paper – and on how much biomass can be mobilized in total in agriculture and forestry. This in turn depends on natural conditions (climate, soils, topography) and on agronomic and forestry practices to produce the biomass, but also on how society understands and prioritizes nature conservation and soil/water/biodiversity protection and in turn how the production systems are shaped to reflect these priorities (Figure 2.2.1).

As a first view on biomass resource potentials, the total annual aboveground net primary production (NPP; the net amount of carbon assimilated in a given period by vegetation) on the earth's terrestrial surface is estimated at about 35 PgC, or 1260 EJ/year (assuming an average C content at 50% and 18 GJ/Mg average heating value) (PNAS, 2007), which can be compared with the world primary energy demand at about 500 EJ (WEO 2009). This comparison shows that terrestrial NPP is larger but not huge in relation to what is required to meet society's energy demand. Establishing bioenergy as a major future primary energy source requires that a significant part of global terrestrial NPP takes place within production systems that are shaped to provide bioenergy feedstocks. Possibly also that the total terrestrial NPP is increased from fertilizer, irrigation and other inputs on lands managed for food, fiber and bioenergy.

A comparison with the biomass production in agriculture and forestry can further give perspectives on prospective bioenergy supply in relation to what is presently harvested in land use. Today's global industrial roundwood production corresponds to 15-20 EJ/yr, and the global harvest of major crops (cereals, oil crops, sugar crops, roots & tubers and pulses) corresponds to about 60 EJ/yr (FAOstat, 2010). One immediate conclusion from this comparison is that the biomass extraction in agriculture and forestry will have to increase substantially in order to provide feedstock for a bioenergy sector large enough to make a significant contribution to the future energy supply.

At the same time, studies estimating the human appropriation of NPP (HANPP) suggest that society already today appropriate a substantial share of the aboveground NPP. Results of HANPP estimates vary depending on its definition as well as models and data used for the calculations. Haberl et al., (2007) estimated that aboveground HANPP amounted to almost 29% of the modelled aboveground NPP. Human biomass harvest alone was estimated to about 20% of aboveground NPP. Other HANPP estimates range from a similar level down to about half this level (Imhoff et al., 2004; Wright, 1990). The HANPP concept cannot be used to define a certain level of biomass use that would be "safe" or "sustainable" since the impacts of human land use depends on how agriculture and forestry systems are shaped (Bai et al. 2008). However, it can be used as a measure of the human domination of the biosphere and as such represent a complementary view on bioenergy potential assessments.

Besides biophysical factors, socioeconomic conditions also influence the biomass resource potential by defining how – and how much – biomass can be produced without causing unacceptable socioeconomic impacts. Socioeconomic restrictions vary around the world, change as society develops, and depends on how societies prioritize bioenergy in relation to specific more or less compatible socioeconomic objectives (see also Section 2.5 and Section 2.8).

This Section focuses on the longer term biomass resource potential and how this has been estimated based on considering the Earth's biophysical resources (ultimately NPP) and restrictions on their energetic use arising from competing requirements on these resources – including non-extractive requirements such as soil quality maintenance/improvement and biodiversity protection. First, approaches to assessing biomass resource potentials – and results from selected studies – are presented with an account of how the main determining factors have been taken into account. After that, these factors are treated explicitly including the constraints on their utilization. The Section ends by summarizing conclusions on biomass resource assessments including uncertainties and requirements for future research. The different bioenergy production systems are described in more detail in Section 2.3 and 2.6.

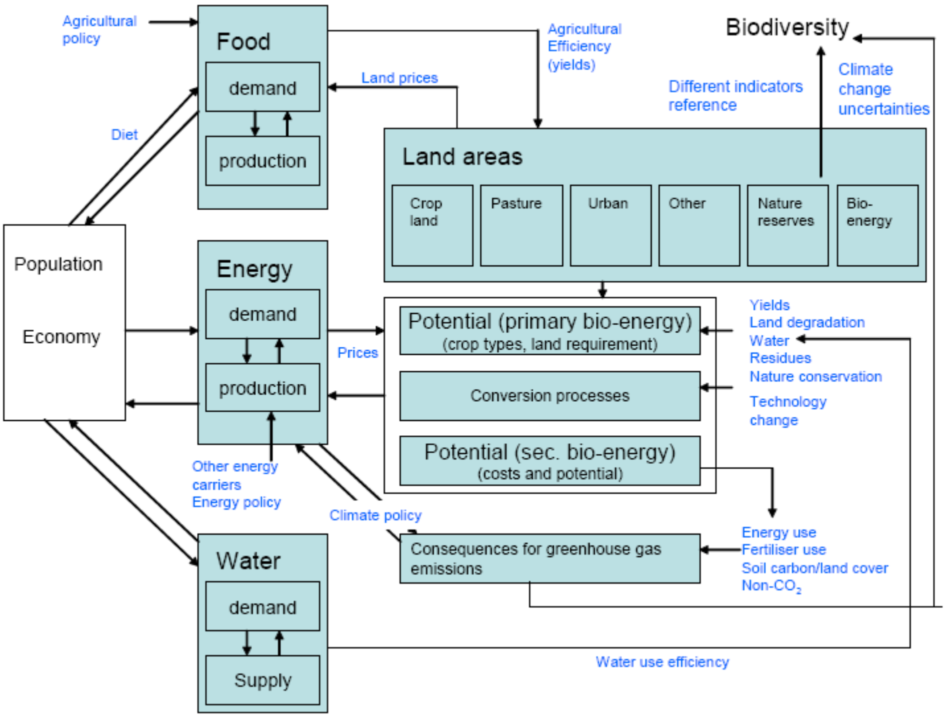

Figure 2.2.1. Overview of key relationships relevant to assessment of bioenergy potentials (Dornburg et al., 2008). Indirect land use issues and social issues are not displayed

2.2.2 Assessments of the biomass resource potential

Studies quantifying the biomass resource potential have in various ways assessed the resource base while to varying extent considering the influence of natural conditions (and how these can change in the future) and various types of limitations including socioeconomic factors, the character and development of agriculture and forestry, and restrictions connected to nature conservation and soil/water/biodiversity preservation (Berndes et al., 2003). The following types of potentials are commonly referred to:

- ***theoretical potential*** refers to the biomass supply as limited only by bio-physical conditions;
- ***technical potential*** considers limitations of the biomass production practices assumed to be employed, and also restrictions imposed by demand for food, feed and fiber, and area requirements for human infrastructure. Restrictions connected to nature conservation and soil/water/biodiversity preservation can be also considered. In such cases, the term ***sustainable potential*** is sometimes used;
- ***economic potential*** refers to the part of the technical potential that can be produced given a specified requirement for the level of economic profit in production. This depends not only on cost of production but also on the price of the biomass feedstock, which is determined by a range of factors such as characteristics of biomass conversion technologies, price on competing energy technologies, and prevailing policy regime. The term ***implementation potential*** is a variant of the economic potential that refers to a certain time frame and context taking into account institutional and social constraints on the pace of expansion.

Most assessments of the biomass resource potential considered in this Section are variants of technical/economic potentials employing a “food/fiber first principle” intending to ensure that the biomass resource potentials are quantified under the condition that global requirements of food and conventional forest products such as sawnwood and paper can be met (see e.g. WBGU, 2009 and Smeets and Faaij, 2007).

Studies that start out from such principles should not be understood as providing guarantees that a certain level of biomass can be supplied for energy purposes without competing with food or fibre production. They quantify how much bioenergy could be produced at a certain future year based on using resources not required for meeting food/fibre demands, given a specified development in the world or in a region. But they do not analyse how bioenergy expansion towards such a future level of production would – or should – interact with food and fibre production.

Studies using integrated energy/industry/land use cover models (see, e.g., Leemans et al, 1996; Strengers et al, 2004; Johansson and Azar, 2007; Müller et al, 2007; Van Vuuren et al, 2007; Wise et al, 2009; Melillo et al, 2009) can give insights into how an expanding bioenergy sector interacts with other sectors in society including land use and management of biospheric carbon stocks. Sector-focusing studies can contain more detailed information on interactions with other biomass uses. Restricted scope (only selected biofuel/land uses and/or regions covered) or lack of sufficiently detailed empirical data can limit the confidence of results – especially in prospective studies. This is further discussed in Section 2.5 and Section 2.8.
Three principal categories are – more or less comprehensively – considered in assessments of biomass resource potentials (see also Section 2.3.1.1):

- Primary residues from conventional food and fibre production in agriculture and forestry, such as cereal straw and logging residues;
- Secondary and tertiary residues in the form of organic food/ forest industry by-products and retail/ post consumer waste;
- Various plants produced for energy purposes including conventional food/feed/industrial crops, surplus roundwood forestry, and new types of agricultural, forestry or aquatic plants grown under varying rotation length.

Given that resource potential assessments quantify the availability of residue flows in the food and forest sectors – and as a rule are based on a food/fibre first principle – the definition of how these sectors develop is central for the outcome. Discussed further below, consideration of various types of restrictions connected to environmental and socioeconomic factors as a rule limits the assessed potential to lower levels.

Table 2.2.1 shows ranges in the assessed resource potential year 2050, explicit for various biomass categories. The ranges are obtained based on IEA Bioenergy (2009) and Lysen and van Egmond (2008), which reviewed a number of studies assessing the global and regional potential, and on selected additional studies not included in these reviews (Field et al, 2008; Smeets and Faaij, 2007; Fischer and Schrattenholzer, 2001; Hakala et al., 2009; Metzger and Huttermann, 2009; Van Vuuren et al, 2009; Wirsenius et al, 2009).

The wide ranges in Table 2.2.1 is due to that the studies differ in their approach to considering different determining factors, which are in themselves uncertain: population, economic, and technology development can go in different directions and pace; biodiversity and nature conservation requirements set limitations that are difficult to assess; and climate change as well as land use in itself can strongly influence the biophysical capacity of land. Biomass potentials can also not be determined exactly as long as uncertainty remains about agreed tradeoffs with respect to additional biodiversity loss or intensification pressure in food production as well as potential synergies in land use.

Table 2.2.1. Overview of the assessed global biomass resource potential of land-based biomass supply over the long term for a number of categories (primary energy, rounded numbers). The total assessed potential can be lower than the present biomass use at about 50 EJ/yr in instances of high future food and fiber demand in combination with slow productivity development in land use leading to strong restrictions on biomass availability.

Biomass category	Comment	Global biomass resource potential year 2050 (EJ/yr)
Category 1. Dedicated biomass production on surplus agricultural land	Includes both conventional agriculture crops and dedicated bioenergy plants including oil crops, lignocellulosic grasses, short rotation coppice and tree plantations. The potential biomass supply from agricultural land is usually assessed based on a "food first paradigm": only land not required for food, fodder or other agricultural commodities production is assumed to be available for bioenergy. However, surplus – or abandoned – agriculture land need not imply that development is such that less total land is needed for agriculture: the lands may become excluded from agriculture use in modeling runs due to land degradation processes or climate change (see also "marginal lands" below). Large potential requires global development towards high-yielding agricultural production. Zero potential reflects that studies report that food sector development can be such that no surplus agricultural land will be available.	0 – 700
Category 2. Dedicated biomass production on marginal lands	Refers to biomass production on deforested or otherwise degraded or marginal land that is judged unsuitable for conventional agriculture but suitable for some bioenergy schemes, e.g., via reforestation. There is no globally established definition of degraded/marginal land and not all studies make a distinction between such land and other land judged as suitable for bioenergy. Adding category 1 and 2 can therefore lead to double counting if numbers come from different studies. Zero potential reflects that studies report low potential for this category due to land requirements for e.g., extensive grazing management and/or subsistence agriculture, or poor economic performance of using the marginal lands for bioenergy.	0 – 110
Category 3. Residues from agriculture	By-products associated with food production and processing, both primary (e.g. cereal straw from harvesting) and secondary residues (e.g. rice husks from rice milling)	15 – 70
Category 4. Forest biomass	By-products associated with forest wood production and processing, both primary (e.g. branches and twigs from logging) and secondary residues (sawdust and bark from the wood processing industry). Biomass growth in natural/semi-natural forests that is not required for industrial roundwood production to meet projected biomaterials demand (e.g., sawnwood, paper and board) represents an additional resource. By-products provide up to about 20 EJ/yr implying that high potential numbers correspond to a much larger forest biomass extraction for energy than what is presently achieved in industrial wood production. Zero potential indicates that studies report that demand from other sectors than the energy sector can become larger than the estimated forest supply capacity.	0 – 110
Category 5. Dung	Animal manure. Population development, diets, and character of animal production systems are critical determinants.	5 – 50
Category 6. Organic wastes	Biomass associated with materials use, e.g. organic waste from households and restaurants, discarded wood products including paper, construction and demolition wood	5 – >50
Total		**<50 – >1000**

Although assessments employing improved data and modeling capacity have not succeeded in providing narrow distinct estimates of the biomass resource potential, they do indicate what the most influential parameters are that affect this potential. This is further discussed below, where approaches used in the assessments are treated in more detail.

2.2.2.1 The contribution from residues, dung, processing by-products and waste

Retail/post consumer waste, dung and primary residues/processing by-products in the agriculture and forestry sectors are judged to be important for near term bioenergy supplies since they can be extracted for energy uses as part of existing waste management and agriculture and forestry operations. As can be seen in Table 2.2.1 biomass resource assessments indicate that these biomass categories also have prospects for providing a substantial share of the total global biomass supply also on the longer term. Yet, the sizes of these biomass resources are ultimately determined by the demand for conventional agriculture and forestry products as well as the sustainability of the land resources.

Assessments of the potential contribution from these sources to the future biomass supply combines data on future production of agriculture and forestry products obtained from food/forest sector scenarios with so-called residue factors that account for the amount of residues generated per unit of primary product produced. For example, harvest residue generation in agricultural crops cultivation is estimated based on harvest index data, i.e., ratio of harvested product to total aboveground biomass (see, e.g., Wirsenius 2003; Lal, 2005; Hakala et al., 2009). The generation of logging residues in forestry, and of additional biomass flows such as thinning wood and process by-products, are estimated using similar residue factors.

The shares of the generated biomass flows that are available for energy – recoverability fractions – are then estimated based on considering competing uses, which can be related to soil conservation requirements or other extractive uses such as animal feeding and bedding in agriculture or fibre board production in the forest sector.

2.2.2.2 The contribution from unutilized forest growth

In addition to the forest biomass flows that are linked to industrial roundwood production and processing into conventional forest products, currently not used forest growth is considered in some studies. This biomass resource is quantified based on estimates of the biomass increment in forests assessed as being available for wood supply that is above the estimated level of forest biomass extraction for conventional industrial roundwood production – and sometimes for traditional bioenergy, notably heating and cooking. Smeets and Faaij (2007) provide illustrative quantifications showing how this “surplus forest growth” can vary from being a potentially major source of bioenergy to being practically zero as a consequence of competing demand as well as economic and ecological considerations. A comparison with the present industrial roundwood production at about 15-20 EJ/year shows that a drastic increase in forest biomass output is required for reaching the higher end potential assessed for the forest biomass category in Table 2.2.1.

2.2.2.3 The contribution from energy plantations

From Table 2.2.1 it is clear that substantial supplies from biomass plantations are required for reaching the very high levels of bioenergy supply. Land availability (and suitability) for dedicated biomass plantation, and the biomass yields that can be obtained on the available lands, are consequently two critical determinants of the biomass resource potential. Thus, food sector development is a critical aspect to consider when estimating biomass resource potentials. Determining land availability and suitability has to consider maintaining the economic, natural and social value of ecosystems by preventing ecosystem degradation and habitat fragmentation.

Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimating the potential of biomass plantations (Berndes et al. 2003), but the continuous development of modeling tools that combine databases containing biophysical information (soil, topography, climate) with analytical representations of relevant crops and agronomic systems has resulted in improvements over time (see, e.g., Fischer et al, 2008; Van Vuuren et al, 2007; Wise et al, 2009; Melillo et al, 2009; Lotze-Campen et al., 2009).

Figure 2.2.2 – representing one example (Fischer et al. 2009) – shows the modeled global land suitability for selected first generation biofuel feedstocks and for lignocellulosic plants (see Caption to Figure 2.2.2 for information about included plants). In this case a suitability index has been used in order to represent both yield potentials and suitability extent (see Caption to Figure 2.2.2). The map shows the case of rain-fed cultivation; including the possibility of irrigation would result in another picture. Land suitability also depends on which agronomic system is assumed to be in use (e.g., degree of mechanization, application of nutrients and chemical pest, disease and weed control) and this assumption also influence the biomass yield levels on the lands assessed as available for bioenergy plantations.

Based on overlaying information about the present global land cover – agricultural land, cities, roads and other human infrastructure, and distribution of forests and other natural/semi natural ecosystems – including protected areas – it is possible to quantify how much suitable land there is on different land cover types. For instance, almost 700 Mha, or about 20%, of currently unprotected grass- and woodlands was in (Fischer et al., 2009) assessed as suitable for soybean while less than 50 Mha was assessed suitable for oil palm (note that these land suitability numbers cannot be added since areas overlap). Considering instead unprotected forest land, roughly ten times larger area (almost 500 Mha) is assessed as suitable for oil palm. However, converting large areas of forests into biomass plantations would negatively impact biodiversity and might – depending on C density of converted forests – also lead to large CO2 emissions that can drastically reduce the climate benefit of substituting fossil fuels with the bioenergy derived from such plantations. Converting grass- and woodlands with high soil C content to intensively cultivated annual crops can similarly lead to large CO2 emissions. Conversely, if degraded and C depleted pastures are cultivated with herbaceous and woody lignocellulosic plants soil C may instead accumulate, enhancing the climate benefit. This is further discussed in Section 2.5.

Supply potentials for biomass plantations can be calculated based on assessed land availability and corresponding yield levels. Fischer et al. (2009) estimated the land availability for rain-fed lignocellulosic plants under a “food and environment first” paradigm excluding forests and land currently used for food and feed as unavailable. Lands with low productivity and steep sloping conditions were also excluded and a rough land balance was made based on subtracting land estimated to be required for livestock feeding. The results, shown in Table 2.2.2, represent just one example corresponding to a specific set of assumptions regarding for example nature protection requirements, crop choice and agronomic practice determining attainable yield levels, and livestock production systems determining grazing requirements. Furthermore, it corresponds to the present situation concerning agriculture practice and productivity, population, diets, climate, etc. and quantifications of future biomass resource potentials need to consider how such parameters change over time.

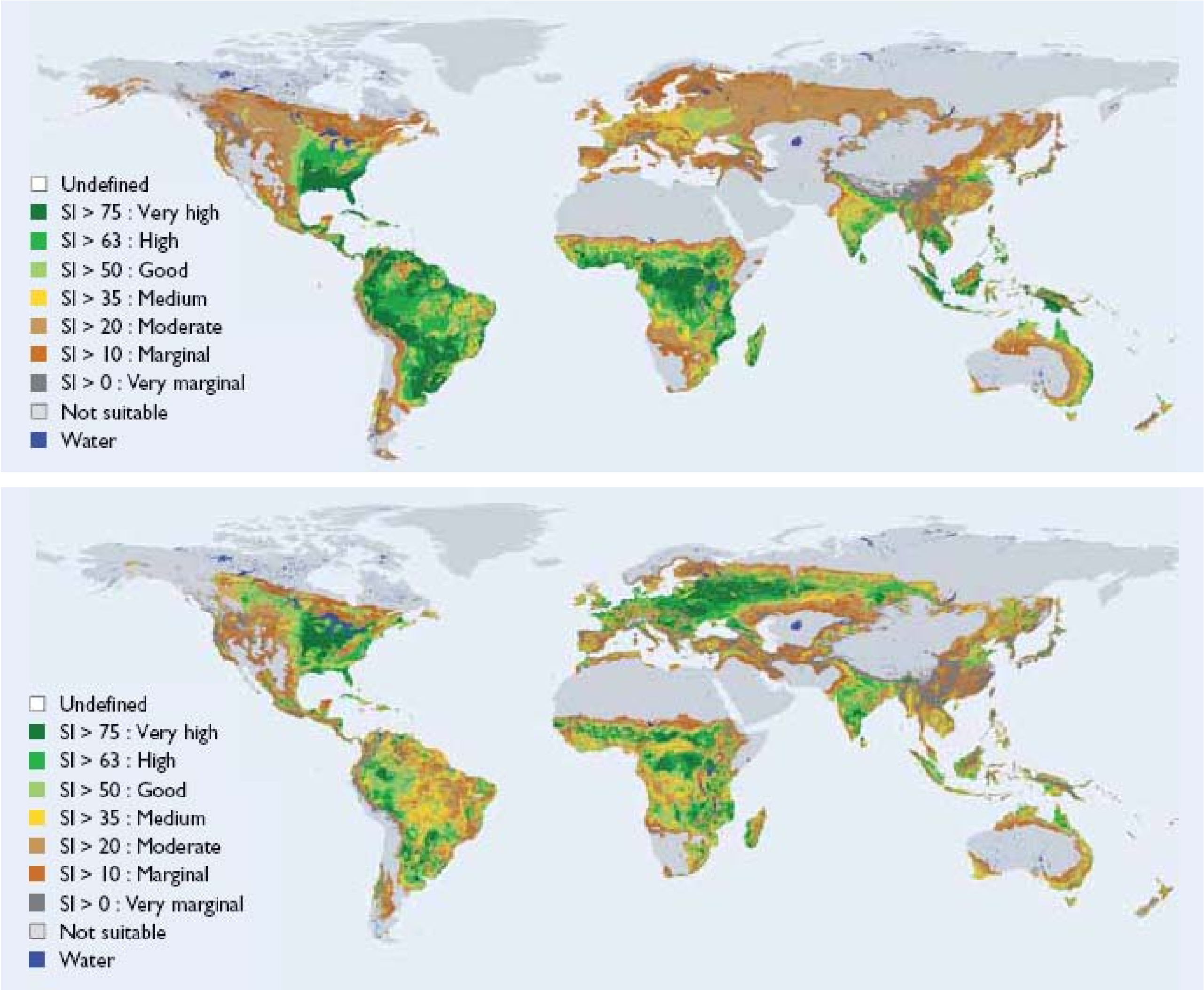

Figure 2.2.2. Global land suitability for bioenergy plantations. The upper map shows suitability for herbaceous and woody lignocellulosic plants (miscanthus, switchgrass, reed canary grass, poplar, willow, eucalypt) and the lower map shows suitability for 1st generation biofuel feedstocks (sugarcane, maize, cassava, rapeseed, soybean, palm oil, jatropha). The suitability index SI used reflects the spatial suitability of each pixel and is calculated as $SI=VS*0.9+S*0.7+MS*0.5+mS*0.3$, where VS, S, MS, and mS correspond to yield levels at 80-100%, 60-80%, 40-60% and 20-40% of modelled maximum, respectively (Fischer et al. 2009).

In a similar analysis (WBGU, 2009) reserved current and near-future agricultural land for food and fibre production and also excluded unmanaged land from being available for bioenergy if its conversion to biomass plantations would lead to large net CO2 emissions to the atmosphere, or if the land was degraded, a wetland, environmentally protected, or rich in biodiversity. If dedicated biomass plantations were established in the available lands an estimated 34-120 EJ/year could be produced.

Water constraints can in several regions limit the potential to lower levels than what is assessed based on approaches that do not involve geo-explicit hydrological modeling. The use of areas with sparse vegetation for establishment of high-yielding bioenergy plantations may lead to substantial reductions in downstream water availability. This can become an unwelcome effect requiring management of trade-offs between upstream benefits and downstream costs.

Illustrative of this, Zomer et al. (2006) report that large areas deemed suitable for forestation within the Clean Development Mechanism would exhibit evapotranspiration increases and/or decreases in runoff in case they become forested, i.e. a decrease in water potentially available off-site for other uses. This was particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Similarly, based on a global analysis of 504 annual catchment observations, Jackson et al. (2005) report that afforestation dramatically decreased stream flow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands or croplands decreased stream flow by, on average, 38%. Average losses for 10- to 20-year-old plantations were even greater, reaching 52% of stream flow (see also Section 2.2.5.3)

Table 2.2.2. Potential biomass supply from rain-fed lignocellulosic plants on unprotected grassland and woodland (i.e., forests excluded) where land requirements for food production including grazing have been considered. Calculated based on Fischer et al. (2009). Areas given in million hectares.

	Total grass- & woodland (Mha)	**Of which (Mha)**		**Balance available for bioenergy (Mha)**	**Biomass potential**	
Regions		Protected areas	Unproductive or very low productive areas	Rough balance where areas req. for grazing has been excluded	Average yield[1] (GJ/ha)	Total bioenergy (EJ)
North America	659	103	391	110	165	18
Europe & Russia	902	76	618	110	140	15
Pacific OECD	515	7	332	110	175	19
Africa	1086	146	386	275	250	69
S&E Asia	556	92	335	14	235	3
Latin America	765	54	211	160	280	45
M East & N Afr.	107	2	93	1	125	0.2
World	**4605**	**481**	**2371**	**780**	**225**	**176**

[1] Calculated based on average yields for total grass- & woodland area given in Fischer (2009) and assuming energy content at 18 GJ/Mg dry matter(rounded numbers).

Studies by Hoogwijk et al (2003), Wolf et al. (2003), Smeets et al. (2007), and van Minnen et al. (2008) are also illustrative of the importance of biomass plantations for reaching higher global biomass resource potentials, and also of how different determining parameters are highly influential on the resource potential. For instance, in a scenario having rapid population growth and slow technology progress, where agriculture productivity does not increase from its present level and little biomass is traded, Smeets et al. (2007) found that no land would be available for bioenergy plantations. In a contrasting scenario where all critical parameters were instead set to be very favorable, up to 3.5 billion hectares of former agricultural land – mainly pastures and with large areas in Latin America and sub-Saharan Africa – was assessed as not required for food in 2050. A substantial part of this area was assessed as technically suitable for bioenergy plantations.

2.2.3 Economic considerations in biomass resource assessments

Some studies exclude areas where attainable yields are below a certain minimum level. Other studies, exclude biomass resources judged as being too expensive to mobilize, given a certain biomass price level. The potential of bioenergy plants can also be quantified based on combining land availability, yield levels and production costs to obtain plant- and region-specific cost-supply curves (Walsh 2000). These are based on projections or scenarios for the development of cost factors, including opportunity cost of land, and can be produced for different context and scale –

including feasibility studies of supplying individual bioenergy plants to describing the future global cost-supply curve (Figure 2.2.5). Studies using this approach at different scales include (Dornburg et al. 2007, Hoogwijk et al. 2008, de Wit et al. 2009, van Vuuren et al. 2009). (Gallagher et al. 2003) exemplify the production of cost-supply curves for the case of crop harvest residues and (Gerasimov and Karjalainen, 2009) for the case of forest wood.

The biomass production costs can be combined with techno-economic data for related logistic systems and conversion technologies to derive economic potentials on the level of secondary energy carriers such as bioelectricity and biofuels for transport (see, e.g., Gan, 2007, Hoogwijk et al. 2008, van Dam et al. 2009). Using biomass cost and availability data as exogenously defined input parameters in scenario-based energy system modeling can provide information about implementation potentials in relation to a specific energy system context and possible climate and energy policy targets. Cost trends are discussed further in more detail in Section 2.7.

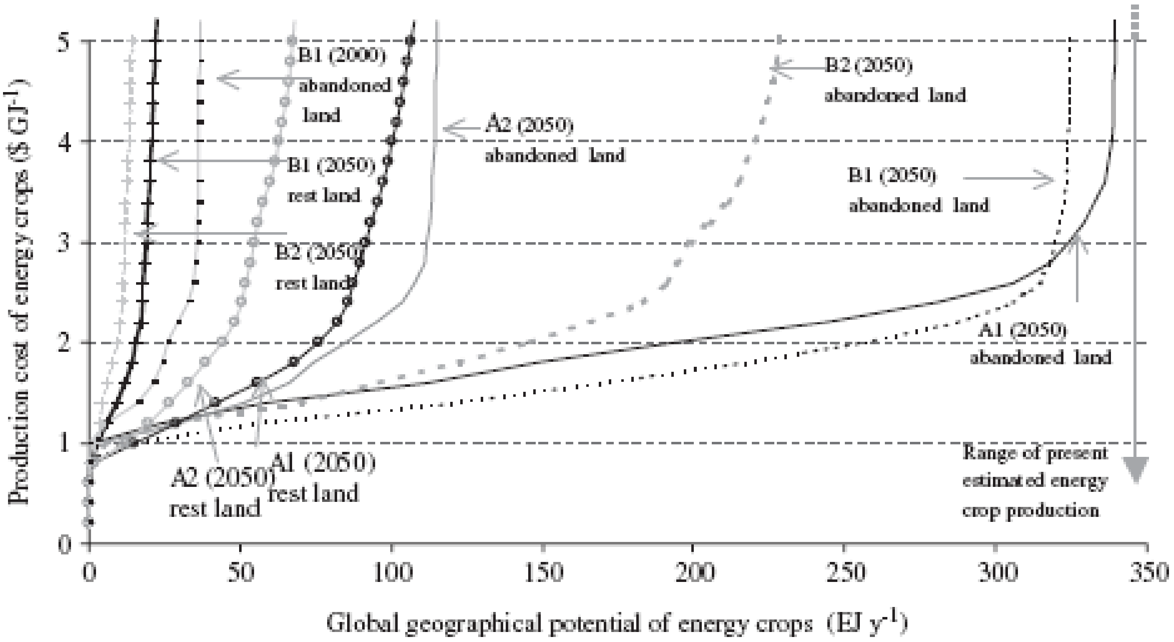

Figure 2.2.5. Global average cost-supply curve for the production of bioenergy plants on the two land categories “abandoned land” (agriculture land not required for food) and “rest land” (), year 2050. The curves are generated based on IMAGE 2.2 modeling of four SRES scenarios (IMAGETeam 2001). The cost-supply curve at abandoned agriculture land year 2000 (SRES B1 scenario) is also shown. Source: Hoogwijk et al. 2008. The scenarios A1, A2, B1, B2 correspond to the storylines developed for the IPCC Special Report on Emission Scenarios.

As examples of region/country scale assessments, biomass potentials for selected countries are illustrated in Figure 2.2.5. Using data from Europe, a scenario was constructed based on the land area needed in 2030 to meet food demand under specific population growth and economic assumptions (Fischer et. al. 2009). Then, by introducing restrictions on land availability focused on nature protection requirements and infrastructure development the study identified land with capacity to support cultivation of selected energy crops. The estimated biomass supply potential of this area, added to the potential of agriculture harvest residues, resulted in the total potential for Europe in 2030 shown in Figure 2.2.5(a). A high growth scenario with limited pasture conversion was estimated to reach about 27 EJ by 2030. Key factor determining the size of the potential was the development of agricultural productivity per ha, including animal production. Figure 2.2.5(b) displays the resulting cost-supply curves showing production costs for different crops using the part of total assessed surplus agricultural land that is suitable for their production (de Wit and Faaij 2009).

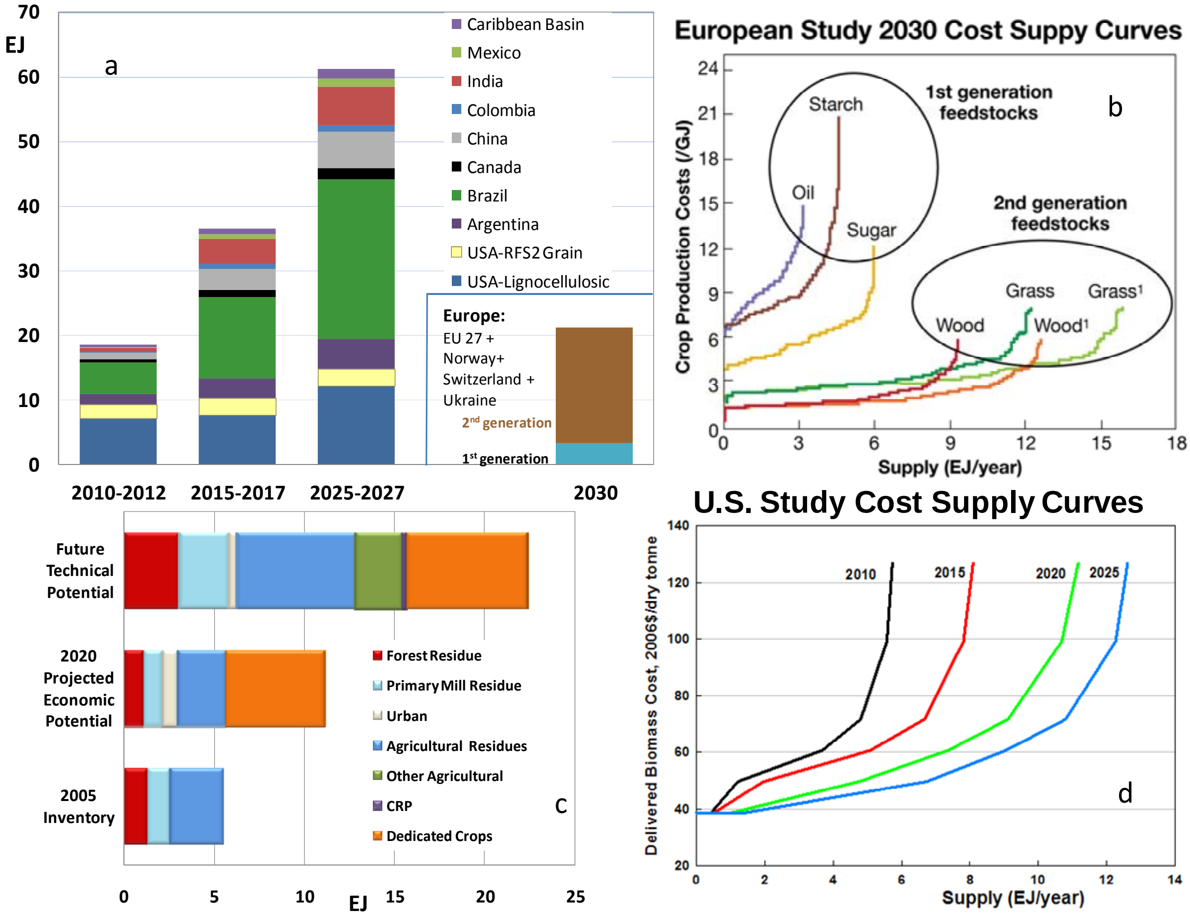

Figure 2.2.5. Regional/country-level potentials as assessed in recent studies. See text for further information about countries and biomass systems assessed.

The other estimate shown in Figure 2.2.5 was based on historic production trends and the structure of average production costs at the state/province level for selected feedstock/country combinations. Feedstocks included were sugarcane, corn, soybeans, wheat, palm oil, recoverable agricultural residues, a percentage of wastes and biomass associated with current forestry activities and fuelwood supplies, and potential perennial biomass crops. Biomass potentials were estimated as a function of arable land availability for energy use considering environmental restrictions and infrastructure. Figure 2.2.5(a) shows the estimated high-growth economic resource potential (Kline et al. 2007) for the years of 2012, 2017, and 2027. In the baseline case, roughly half the potential was estimated for 2027, but the baseline and high-growth estimates for 2017 were similar. The U.S. potentials come from similar but more detailed county-level analysis for cellulosic materials in 2010, 2015 and 2025 (Walsh 2008). Biofuel contributions from grain feedstocks are added with data of the same spatial resolution (EPA 2010). Individual data for the U.S. Figure 2.2.5(c) further illustrate the U.S. inventory for biomass resources (Milbrandt 2005); projected economic potential including considerations of restrictions relative to soil sustainability of agriculture residues and dedicated crops for 2020 (NRC 2009 b); and a higher future technical potential that could be achieved with successful research and development in energy crops and considering some sustainability factors (Perlack et al. 2005). Example of supply curves for the U.S. are given in

Figure 2.2.5(d) for multiple years that are shown used in Figure 2.2.5(a) (Walsh 2008 at $17/dry Mg delivery cost).

2.2.4 Analysis of factors influencing the biomass resource potentials

As described briefly above, many studies that quantify the biomass resource potential consider a range of factors that restrict the potential to lower levels than those corresponding to unconstrained technical potentials. These constraints are connected to various impacts arising from the exploitation of the biomass resources, which are further discussed in Section 2.5. Below, important factors are presented and analyzed in relation to how they influence the future biomass resource potential

2.2.4.1 Constraints on residue supply in agriculture and forestry

Soil conservation and biodiversity requirements set constraints on residue potentials for both agriculture and forestry. Organic matter at different stages of decay has an important ecological role to play in conserving soil quality as well as biodiversity in soils and above-ground.

In forests, wood ash application can recycle nutrients taken from the forest and mitigate negative effects of intensive harvesting. Yet, dying and dead trees, either standing or fallen and at different stages of decay, are valuable habitats (providing food, shelter and breeding conditions, etc.) for a large number of rare and threatened species (Grove and Hanula 2006). Thresholds for desirable amounts of dead wood at the forest stands are difficult to set and the most demanding species require amounts of dead wood that are difficult to reach in managed forests (Ranius and Fahrig 2006).

In agriculture, overexploitation of harvest residues is one important cause to soil degradation in many places of the world (Lal 2008, Ball 2005, Blanco-Canqui 2006, Wilhelm 2004). Fertilizer inputs can compensate for nutrient removals connected to harvest and residue extraction, but maintenance or improvement of soil fertility, structural stability and water holding capacity requires recirculation of organic matter to the soil (Lal and Pimentel 2007, Wilhelm et al. 2007, Blanco-Canqui and Lal 2009). Residue recirculation leading to nutrient replenishment and storage of carbon in soils and dead biomass not only contributes positively to climate change mitigation by withdrawing carbon from the atmosphere but also by reducing soil degradation and improving the soil productivity since this leads to higher yields and consequently less need to convert land to croplands for meeting future food/fibre/bioenergy demand (often leading to GHG emissions when vegetation is removed and soils are cultivated). Residue removal can, ceteris paribus, be increased when total biomass production per hectare becomes higher and if ‘waste’ from processing of crop residues that is rich in refractory compounds such as lignin is returned to the field (Johnson et al 2004; Reijnders 2007; Lal 2008).

Overexploitation of harvest residues is one important cause to soil degradation in many places of the world (Lal 2008, Ball 2005, Blanco-Canqui 2006, Wilhelm 2004). Residue recirculation leading to nutrient replenishment and storage of carbon in soils and dead biomass not only contributes positively to climate change mitigation by withdrawing carbon from the atmosphere but also by reducing soil degradation and improving the soil productivity since this leads to higher yields and consequently less need to convert more land to croplands (often leading to GHG emissions when vegetation is removed and soils are cultivated) for meeting future food/fibre/bioenergy demand.

Besides the difficulties in establishing sustainable residue extraction rates, there are also large uncertainties linked to the possible future development of several factors determining the residues generation rates. Population growth, economic development and dietary changes influence the demand for products from agriculture and forestry products and materials management strategies (including recycling and cascading use of material) influence how this demand translates into demand for basic food commodities and industrial roundwood.

Furthermore, changes in food and forestry sectors influences the residue/waste generation per unit product output which can go in both directions: crop breeding leads to improved harvest index (less residues); implementation of no-till/conservation agriculture requires that harvest residues are left on the fields to maintain soil cover and increase organic matter in soils (Lal, 2004); shift in livestock production to more confined and intensive systems can increase recoverability of dung but reduce overall dung production at a given level of livestock product output; increased occurrence of silvicultural treatments such as early thinning to improve stand growth will lead to increased availability of small roundwood suitable for energy uses and development of technologies for stump removal after felling increases the generation of residues during logging (Näslund-Eriksson and Gustafson, 2008)

Consequently, the longer term biomass resource potentials connected to residue/waste flows will continue to be uncertain even if more comprehensive assessment approaches are used. It should be noted that it is not obvious that more comprehensive assessments of restrictions will lead to lower residue potentials; earlier studies may have used conservative residue recovery rates as a precaution in the face of uncertainties (see, e.g., Kim and Dale 2004).

2.2.4.2 Constraints on dedicated plant production in agriculture and forestry

The prospects for intensifying conventional long-rotation forestry to increase forest growth and total biomass output – for instance by fertilizing selected stands, introducing alien forest species and using shorter rotations – are not thoroughly investigated in the assessed studies of biomass resource potentials. Intensification in forestry is instead related to shifts to higher reliance on fast-growing wood plantations that are in many instances similar to the bioenergy plantation systems assumed to become established on surplus agricultural land.

Intensification in agriculture is on the other hand a key aspect in essentially all of the assessed studies since it influences both land availability for biomass plantations (indirectly by determining the land requirements in the food sector) and the biomass yield levels obtained. High assessed potentials for energy plantations rely on high-yielding agricultural systems and international bioenergy trade leading to that biomass plantations are established globally where the production conditions are most favorable. Increasing yields in existing agricultural land is also in general proposed a key component for agriculture development (Ausubel, 2000; Tilman et al., 2002; Fischer et al 2002, Cassman et al., 2003; Evans, 2003; Balmford et al., 2005; Green et al., 2005; Lee et al., 2006; Bruinsma, 2009). Van Vuuren et al. (2009) show that yield increases for food crops in general have a more substantial impact on bioenergy potentials than yield increase for bioenergy plants specifically. Studies also point to the importance of diets and the food sector's biomass use efficiency in determining land requirements for food (Gerbens-Leenes and Nonhebel 2002; Smil 2002; Carlsson-Kanyama et al. 2003; de Boer et al. 2006; Elferink and Nonhebel 2007; Stehfest et al. 2010; Wirsenius et al. 2010).

Studies of agriculture development (see, e.g., Koning 2008, IAASTF 2009, Alexandratos 2009) show lower expected yield growth than studies of the biomass resource potential that report very high potentials for biomass plantations. Some observations indicate that it can be a challenge to maintain yield growth in several main producer countries and that much cropland and grazing land undergo degradation and productivity loss as a consequence of improper land use (Cassman, 1999; Pingali and Heisey, 1999; Fischer et al. 2002). The possible consequences of climate change for agriculture are not firmly established but indicate net global negative impact, where damages will be concentrated in developing countries that will lose in agriculture production potential while developed countries might gain (Fischer et al. 2002, Cline 2007, Schneider et al 2007, Lobell et al 2008, Fischer 2009). Water scarcity can limit both intensification possibilities and the prospects for expansion of bioenergy plantations (Berndes 2008, De Fraiture et al. 2008, De Fraiture and Berndes 2009, Rost et al. 2009, Van Vuren 2009). Biomass potential studies that use biophysical datasets and modelling can consider water limitations in land productivity modelling. However, assumptions about productivity growth in land use may implicitly presume irrigation development that could lead to challenges in relation to regional water availability and use. There is a need of empirical data for use in hydrological process models to better understand and predict the hydrological effects of various land use options on the landscape level (Malmer et al 2009). Water related aspects are further discussed in Section 2.5.

Conversely, some observations indicate that rates of gain obtained from breeding have increased in recent years and that yields might increase faster again as newer hybrids are adopted more widely (Edgerton 2009). Theoretical limits also appear to leave scope for further increasing the genetic yield potential (Fischer et al. 2009). It should be noted that studies reaching high potentials for bioenergy plantations points primarily to tropical developing countries as major contributors. In these countries there are still substantial yield gaps to exploit and large opportunities for productivity growth – not the least in livestock production (Wirsenius et al. 2010, Edgerton 2009, Fischer et al 2002). There is also a large yield growth potential for dedicated bioenergy plants that have not been subject to the same breeding efforts as the major food crops, as is the case for sugar cane. Selection of suitable plant species and genotypes for given locations to match specific soil types and climate is possible, but is at an early stage of understanding for some energy plants, and traditional plant breeding, selection and hybridization techniques are slow, particularly in woody plants but also in grasses. New biotechnological routes to produce both non-genetically modified (non-GM) and GM plants are possible. GM energy plant species may be more acceptable to the public than GM food crops, but there are concerns about the potential environmental impacts of such plants, including gene flow from non-native to native plant relatives.

There can be limitations and negative aspects of further intensification aiming at farm yield increases; high crop yields depending on large inputs of nutrients, fresh water, and pesticides, can contribute to negative ecosystem effects, such as changes in species composition in the surrounding ecosystems , groundwater contamination and eutrophication with harmful algal bloom, oxygen depletion and anoxic “dead” zones in oceans being examples of resulting negative impacts (Donner and Kucharik 2008, Simpson et al. 2009. See also Section 2.5). However, intensification is not necessarily equivalent to an industrialization of agriculture, as agricultural productivity can be increased in many regions and systems with conventional or organic farming methods (Badgley et al. 2007). Potential to increase the currently low productivity of rainfed agriculture exists in large parts of the world through improved soil and water conservation (Lal 2003, Rockström et al 2007, 2010), fertilizer use and crop selection (Cassmann 1999; Keys and McConnell, 2005). Available best practices are not at present applied in many world regions (Godfray et al. 2010), e.g. mulching, low tillage, contour ploughing, bounds, terraces, rainwater harvesting and supplementary irrigation, drought adapted crops, crop rotation and fallow time reduction, due to a lack of dissemination, capacity building, availability of resources and access to markets, with distinct regional differences (Neumann et al. 2010).

Conservation agriculture and mixed production systems (double-cropping, crop with livestock and/or crop with forestry) hold potential to sustainably increase land and water productivity as well as carbon sequestration and to improve food security and efficiency in the use of limited resources such as phosphorous (Kumar 2006, Heggenstaller 2008, Herrero et al 2010). Integration can also be based on integrating feedstock production with conversion – typically producing animal feed that can replace cultivated feed such as soy and corn (Dale 2008) and also reduce grazing requirement (Sparovek et al, 2007).

Investment in agricultural research, development and deployment could produce a considerable increase in land and water productivity (Rost et al. 2009, Sulser et al 2010, Herrero et al 2010) as well as improve robustness of plant varieties (Ahrens et al. 2010, Reynolds and Borlaug, 2006). Multi-functional systems (IAASTD 2009) providing multiple ecosystem services (Berndes et al 2004, 2008; Folke et al 2004, 2009,) represent alternative options for the production of bioenergy on agricultural lands that could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity (Vandermeer and Perfecto 2006).

Biomass potential studies also point to that marginal/degraded lands – where productive capacity has declined temporarily or permanently – can be used for biomass production. Advances in plant breeding and genetic modification of plants not only raise the genetic yield potential but also adapts plants for more challenging conditions (Fischer et al. 2009). Improved drought tolerance can improve average yields in drier areas and in rain-fed systems in general by reducing the effects of sporadic drought (Nelson et al., 2007; Castiglioni et al., 2008) and can also reduce water requirements in irrigated systems. Thus, besides reducing land requirements for meeting food and materials demand by increasing yields, plant breeding and genetic modification can make lands earlier considered as unsuitable become available for rainfed or irrigated production.

Some studies show a significant technical potential of marginal/degraded land, but it is uncertain how much of this technical potential that can be realized. Main challenges in relation to the use of marginal/degraded land for bioenergy include (i) the large efforts and long time period required for the reclamation of more degraded land; (ii) the low productivity levels of these soils; and (iii) ensuring that the needs of local populations that use degraded lands for their subsistence are carefully addressed. Studies point to benefits of local stakeholder participation in appraising and selecting appropriate measures (Schwilch et al 2009) and suggest that land degradation control could benefit from addressing also aspects of biodiversity and climate change and that this could pave the way for funding via international financing mechanisms and the major donors (Knowler 2004, Gisladottir and Stocking 2005). In this context, the production of properly selected plant species for bioenergy can be an opportunity, where additional benefits involve C sequestration in soils and aboveground biomass and improved soil quality over time.

Besides that biodiversity consideration can limit residue extraction and intensification, it can limit agriculture land expansion. WBGU (2009) shows that the way biodiversity is considered can have a larger impact on bioenergy potential than either irrigation or climate change. The common way of considering biodiversity requirements as a constraint is by including requirements on land reservation for biodiversity protection. Biomass potential assessments commonly exclude nature conservation areas from being available for biomass production, but the focus is as a rule on forest ecosystems and takes the present level of protection as a basis. Other natural ecosystem also needs protection – not the least grassland ecosystems – and the present status of nature protection may not be sufficient for a certain target of biodiversity preservation. While many highly productive lands have low natural biodiversity, the opposite is true for some marginal lands and, consequently, the largest impacts on biodiversity could occur with widespread use of marginal lands.

Some studies indirectly consider biodiversity constraints on productivity implicitly by assuming a certain expansion of alternative agriculture production (to promote biodiversity) that yields lower than conventional agriculture and therefore requires more land for food production (Fischer et al. 2009, EEA, 2007). However, for multi-crop systems a general assumption of lower yields in alternative cropping systems is not consistent. Biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Integrated energy system - land use/vegetation cover modeling have better prospects for analyzing these risks. They are further discussed in Section 2.2.6 below.

2.2.5 Summary conclusions

As shown above, narrowing down the biomass resource potential to distinct numbers is not possible. But it is clear that several hundred EJ per year can be provided for energy in the future, given favourable developments. It can also be concluded that:

- The size of the future biomass supply potential is dependent on a number of factors that are inherently uncertain and will continue to make long term biomass supply potentials unclear. Important factors are population and economic/technology development and how these translate into fibre and food demand (especially share and type of animal food products in diets) and development in agriculture and forestry.
- Additional important factors include (i) climate change impacts on future land use including its adaptation capability; (ii) restrictions set by biodiversity and nature conservation requirements; and (iii) consequences of land degradation and water scarcity.
- Studies point to residue flows in agriculture and forestry and unused (or extensively used) agriculture land as an important basis for expansion of biomass production for energy, both on the near term and on the longer term.
- Grasslands and marginal/degraded lands are also considered to have potential for supporting substantial bioenergy production, but biodiversity considerations may limit this potential. The possibility that conversion of such lands to biomass plantations reduces downstream water availability also needs to be considered
- Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoid soil degradation also set limits on residue extraction in agriculture and forestry.
- Yet, several hundred EJ per year of biomass could be provided for energy in the future, given favourable developments. This can be compared with the present biomass use for energy at about 50 EJ per year
- The cultivation of suitable plants crops can allow for higher potentials by making it possible to produce bioenergy on lands where conventional food crops are less suited – also due to that the cultivation of conventional crops would lead to large soil carbon emissions (further discussed in Section 2.5.2).
- Landscape approaches integrating bioenergy production into agriculture and forestry systems to produce multi-functional land use systems could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and helps restore/maintain soil productivity and healthy ecosystems
- Water constraints may limit production in regions experiencing water scarcity. But the use of suitable energy crops that are drought tolerant can also help adaptation in water scarce situations. Assessments of biomass resource potentials need to more carefully consider constrains and opportunities in relation to water availability and competing use.

While recent assessments employing improved data and modeling capacity have not succeeded in providing narrow distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various factors are on the potential. The insights from the resource assessments can improve the prospects for bioenergy by pointing out the areas where development is most crucial and where research is needed. A summary is given in Section 2.8.

2.3 Technology

Bioenergy chains involve a wide range of feedstocks, conversion processes and end-uses (Figure 2.1.1). This section covers the existing commercial technologies used in the various steps of these chains worldwide, and details some of the major systems which are deployed. Developing technologies which are in various stages of the research and development phases are presented in detail in section 2.6 and summarized in Figure 2.3.1.

2.3.1 Feedstock

2.3.1.1 Feedstock production and harvest

Tables 2.3.1 and 2.3.2 summarize performance criteria of major biomass production systems across the world regions, whether using dedicated plants and primary residues (Table 2.3.1) or secondary residues (Table 2.3.2). The management of energy plants includes the provision of seeds or seedlings, stand establishment and harvest, soil tillage, and various rates of irrigation, fertilizer and pesticide inputs, which depend on crop requirements, target yields, and local pedo-climatic conditions, and may vary across world regions for a similar species (Table 2.3.1). Strategies such as integrated pest management or organic farming may alleviate the need of synthetic inputs for a given output of biomass.

Wood for energy is obtained as fuelwood from the logging of natural or planted forests, and from trees and shrubs from agriculture fields surrounding villages and towns. While natural forests are not managed toward production per se, problems arise if fuelwood extraction exceeds the regeneration capacity of the forests, which is the case in many parts of the world. The management of planted forests involves silvicultural techniques similarly to those of cropping systems, from stand establishment to tree fallings (Nabuurs et al., 2007).

Biomass may be harvested several times a year (for forage-type feedstocks such as hay or alfalfa), once a year (for annual species such as wheat, or perennial grasses), or every 2 to 50 years or more (for short-rotation coppice and conventional forestry, respectively). Biomass is typically transported to a collection point on the farm or at the edge of the road before transport to the bioenergy unit or an intermediate storage. It may be preconditioned and densified to make storage, transport and handling easier (see section 2.3.2.).

Table 2.3.1. Typical characteristics of the production technologies for dedicated species and their primary residues. Management inputs symbols: +: low; ++: moderate; +++: high requirements.

Feedstock type (Status: C=commercial	**Region**	**Yield (GJ/ha/yr)**	**Management**			**Co-products**	**Costs USD$_{2005}$/GJ**	**Refs.**
D=developing)			**N/P/K use**	**Water needs**	**Pesticides**			
OIL CROPS		As oil						
Oilseed rape (C)	Europe	40-70	+++	+	+++	Rape cake, straw	7.2	1,2,3
Soybean (C)	N America Brazil	16-19 18-21	++ ++	+ +	+++ +++	Soy cake, straw	11.7	3,12
Palm oil (C)	Asia Brazil	135-200 169	++ ++	+ +	+++ +++	Fruit bunches, press fibers	12.6	3
Jatropha (D)	World	17-88	+/ ++	+ +	- -	Seed cake (toxic), wood, shells	2.9	3,4,5,10, 11
STARCH CROPS		As ethanol						
Wheat (C)	Europe	54-58	+++	++	+++	Straw, DDGS	5.2	3
Maize (C)	N America	72-79	+++	+++	+++	Corn stover, DDGS	10.9	3
Cassava (D fuel)	World	43	++	+	++	DDGS		3
SUGAR CROPS		As ethanol						
Sugar cane (C)	Brazil India	116-149 95-112	++	+	+++	Bagasse, straw	1.0-2.0	3,20 3
Sugar beet (C)	Europe	116-158	++	++	+++	Molasses, pulp	5.2	3,13
Sorghum (sweet) (D)	Africa China	105-160	+++	+	++	Bagasse	4.4	3, 24
LIGNOCELLULOSIC CROPS								
Miscanthus (D)	Europe	190-280	+/++	++	+		4.8-16	6,8
Switchgrass (D)	Europe N America	120-225 103-150	++ ++	+ +	+ +		2.4-3.2 4.4	10,14
Short rotation Eucalyptus (C for materials; D energy)	S Europe S America	90-225 150-415	+ +/++	++ +	+ +	Tree bark	2.9-4 2.7	2,2219,2 2
S.rotation Willow (D)	Europe	140					4.4	3,7
Fuelwood (chopped) (C)	Europe	110				Forest residues	3.4-13.6	17
Fuelwood (from native forests, renewable)	C America	80-150				Forest residues	2-4	
PRIMARY RESIDUES								
Wheat straw (D for fuels)	Europe USA	60 7-75	+				1.9	2 14, 23

Sugar cane straw	Brazil	90-126	+					21
Corn stover (D for fuels)	N America	15-155	+					9,14
	India	22-30	+				0.9	21
Sorghum stover (D)	World	85	+					9
Forest residues (C)	Europe World	2-15					1-7.7	17

References: 1: EEA, 2006; 2: JRC, 2007; 3: Bessou et al., 2009; 4: Jongschaap et al., 2007; 5: Openshaw, 2000; 6: Clifton-Brown et al., 2004: 7: Ericsson et al., 2009; 8: Fargernäs et al., 2006; 9: Lal, 2005; 10: WWI, 2006; 11: Maes et al., 2009; 12: Gerbens-Leenes et al., 2009; 13: Berndes, 2008; 14: Perlack et al., 2005; 15: Yokoyama and Matsumura, 2008; 16: Kärhä,et al., 2009; 17: Karjalainen et al., 2004; 18: Nabuurs et al., 2007; 19: Scolforo, 2008; 20: Folha, 2005; 21: Guille, 2007; 22: Diaz-Balteiro & Rodriguez, 2006; 23: Lal, 2005; 24: Grassi, 2005.

The species listed in Table 2.3.1 are not equivalent in terms of possible energy end-uses. Starch, oil and sugar crops are grown as feedstock first-generation liquid biofuels (ethanol and bio-diesel – see 2.3.3.), which only use a fraction of their total above-ground biomass, the rest being processed in the form of animal feed or lignocellulosic residues. Sugar cane bagasse and even sugar cane straw are being used as a source of process heat and power in many sugar and ethanol producing countries (Dantas et al, 2009). On the other hand, lignocellulosic crops (such perennial grasses or short-rotation coppice) may be entirely converted to energy, and feature 2 to 5 times higher yields per ha than most of the other feedstock types, requiring far less synthetic inputs when managed carefully (Hill, 2007). However, their plantation and harvest is more resource intensive than annual species, and their impact on soil organic matter after the removal of stands is poorly known (Anderson-Texeira et al., 2009; Wilhelm et al., 2007). In addition, with the current technology lignocellulose can only provide heat and power (and products) whereas the harvest products of oil, sugar and starch crops may be readily converted to liquid biofuels. Costs for dedicated plants vary widely according to the prices of inputs and machinery, labor and land-related costs (Ericsson et al., 2009). If energy plantations are to compete with land dedicated to food production, the opportunity cost of land (the price a farmer should be paid to switch to an energy crop) may become dominant and scales with the demand for energy feedstock (Bureau et al., 2009). Cost-supply curves are needed to account for these effects in the economics of large-scale deployment scenarios. See examples of cost supply curves in Figure 2.2.5.

2.3.1.2 Synergies with the agriculture, food & forest sectors

As underlined in section 2.2.1., bioenegy feedstock production competes with other usages for resources, chief of which land, with possible negative effects on biodiversity, water availability, soil quality, and climate. However, synergistic effects may also emerge through the design of integrated production systems, which might also provide additional environmental services. Intercropping and mixed cropping are interesting options to maximize the output of biomass per unit area farmed (WWI, 2006). Mixed cropping systems result in increased yields compared to single crops, and may provide both food/feed and energy feedstock from the same field (Tilman et al., 2006; Jensen, 1996). Double-cropping systems have the potential to generate additional feedstocks for bioenergy and livestock utilization and potentially higher yields of biofuel from two crops in the same area in a year (Heggenstaller, 2008).

Agroforestry systems make it possible to use land for both food and energy purposes with mutual benefits for the associated species (Bradley et al., 2008). The associated land equivalent ratios may reach up to 1.5 (Dupraz and Liagre, 2008), meaning a 50% saving in land area when combining trees with arable crops respective to mono-cultures. Another option would consist in growing an understory food crop and coppicing the ligneous specie (to produce residual biomass for energy (similarly to short-rotation coppice). (Dupraz and Liagre, 2008). Integration may also occur with the by-products of bioenergy conversion processes. Typically, animal feed by-products can replace cultivated feed such as soy and corn (Dale 2008) and also reduce grazing requirement (Sparovek et al, 2007).

Perennial species create positive externalities such as erosion control, improved fertilizer use efficiency, reduction in nitrate-N leaching relative to annual plants. Lastly, the revenues generated from growing bioenergy feedstock may provide access to technologies or inputs enhancing the yields of food crops, provided the benefits are distributed to local communities (Practical Action Consulting, 2009).

Table 2.3.2: Typical characteristics of the production technologies for selected secondary residues and waste stream.

Feedstock type	Region	Energy content	Cost USD$_{2005}$/GJ	Ref.
Sugar cane bagasse	Brazil	15.5 GJ/odt	1.6-5.3	10,2
Rice husk	India	15 GJ/odt	2	21
Waste wood	Europe	18 GJ/odt	2.2	2
Wood pellets and briquettes	N Europe US/Canada	18 GJ/odt	8.8 5-5.3	16
MSW	USA	3.4 GJ/inhab.(organic)	May be negative for a while	10
Cattle slurry	Asia N America	14-17/cattle head 14-32/cattle head		15
Black liquor	Europe	12 GJ/odt		
Waste cooking oil	Global	40 GJ/t		3

Same references as Table 2.3.1; odt = oven dry tons

2.3.2 Logistics and supply chains

Since biomass is mostly available in low density form, it demands more storage space, transport and handling than fossile equivalents, with consequent cost implications. It often needs to be processed (pre-treated) to improve handling. For most bioenergy systems and chains, handling and transport of biomass from the source location or area to conversion plant is an important contributor to the overall costs of energy production. Including e.g. harvest of crops, storage, transport, pre-treatment and delivery can amount 20 to up to 50% of total costs of energy production (Allen et al, 1998.

Use of a single agricultural biomass feedstock for year-round energy generation necessitates relatively large storage since this is available for a short time following harvest. Among the characteristics that complicate the biomass supply chain and that are to be taken into account when organizing biomass supplies for conversion capacity over time are (Rentizelas et al, 2008; Junginger et al., 2001):

- Multiple feedstocks with their own complex supply chains.
- Storage challenges including space constraints, fire hazards, moisture control, and health risks from fungi and spores.
- Seasonal variation in supply.

Over time (i.e. starting in the eighties) several stages may be observed in biomass utilization and market developments in biomass supplies. Different countries seem to follow these stages over time, but clearly differ in the stage of development (Faaij, 2006).

1. Waste treatment (e.g. MSW and use of process residues (paper industry, food industry) 'on site' of production facilities is generally the starting phase of a developing bio-energy system. Resources are available and often have a negative value, making utilization profitable and simultaneously solving waste management problems.
2. Local utilization of resources from forest management and agriculture. Such resources are more expensive to collect and transport, but usually still economically attractive. Infrastructure development is needed.
3. Biomass market development on regional scale; larger scale conversion units with increasing fuel flexibility are deployed; increasing average transport distances further improved economies of scale. Increasing costs of biomass supplies make more energy efficient conversion facilities necessary as well as feasible. Policy support measures such as feed-in tariffs are usually already needed to develop into this stage.
4. Development of national markets with increasing number of suppliers and buyers; creation of a market place; increasingly complex logistics. Often increased availability due to improved supply systems and access to markets. Price levels may therefore even decrease (see e.g. Junginger et al., 2005).
5. Increasing scale of markets and transport distances, including cross border transport of biofuels; international trade of biomass resources (and energy carriers derived from biomass). Biomass is increasingly becoming a globally traded energy commodity (see e.g. Junginger et al., 2008). Bio-ethanol trade has come closest to that situation (see e.g Walter et al., 2008)
6. Growing role for dedicated fuel supply systems (biomass production largely or only for energy purposes). So far, dedicated crops are mainly grown because of agricultural interests and support (subsidies for farmers, use of set-aside subsidies), which concentrates on oil seeds (like rapeseed) and surplus food crops (cereals and sugar beet).

Countries that have gained large commercial experience with biomass supplies and biomass markets were generally also able to obtain substantial cost reductions in biomass supply chains over time. In Finland and Sweden cost of delivery went down from some 12 US$/GJ delivered halfway the 70-ies to less than 5 US$/GJ at present. This was due to many factors - scale increase, technological innovations, increased competition, etc. Similar trends are observed in logistics around the corn ethanol industry in the US and cane ethanol in Brazil (see also section 2.7 on cost trends).

Analyses of regional and international biomass supply chains show that road transport of untreated and bulky biomass becomes uncompetitive, as well as a significant factor in energy use when crossing distances of 50-150 km (see e.g. (Dornburg & Faaij, 2001) and (Hamelinck et al., 2005a)). It is also obvious that when long distance transport is required, early pre-treatment and densification in the supply chain (see 2.3.2.1 and 2.6) pays off to minimize longer distance transport costs. Taking into account energy use and related GHG emissions, well organized logistic chains can require less than 10% of the initial energy content of the biomass (Hamelinck et al., 2005b; Damen & Faaij, 2006), but this requires substantial scale in transport, efficient pre-treatment and minimization of road transport of untreated biomass.

Such organization is observed in rapidly developing international wood pellet markets (see also section 2.4 and below). Furthermore, (long distance) transport costs of liquid fuels such as ethanol and vegetal oils contributes only in a minor way to overall costs and energy use of bioenergy chains (Hamelinck et al., 2005b).

2.3.2.1 Wood pellet logistics and supplies

Wood pellets are one of the most successful bioenergy-based commodities traded internationally. Wood pellets offer a number of advantages compared with other solid biomass fuels: they generally have a low moisture content and a relatively high heating value (about 17 MJ/kg), which allows long-distance transport by ship without affecting the energy balance (Junginger et al, 2008). Local transportation is carried out by trucks, which sets a feasible upper limit for transportation (assuming 150 km transportation for raw biomass, 50 km for pellets) and necessary storage usually represent more than 50% of the final cost. Bulk delivery of pellets is very similar to a delivery of home heating oil and is carried out by the lorry driver blowing the pellets into the storage space, while a suction pump takes away any dust. Storage solutions include underground tanks, container units, silos or storage within the boiler room. Design of more efficient pellet storage, charging and combustion systems for domestic users is on-goings (Peksa-Blanchard et al, 2007). International trade is done by ships and ports suitability for handling the product is one of the major logistic barriers. In most potential exportation countries ports are not yet equipped with storage and modern handling equipments or are poorly managed, which implies in high shipping cost. Another barrier is freight costs, which are very sensitive to international trade demand (Junginger et al, 2008).

2.3.2.2 Biomass and charcoal supplies in developing countries

Developing countries have some specific issues. Charcoal in Africa is predominantly produced in inefficient traditional kilns by the informal sector, often illegally. Current production, packaging and transportation of charcoal is characterised by low efficiencies and poor handling, leading to losses. To introduce change to this industry requires that it be recognised and legalised, where it is found to be sustainable and not in contradiction with environmental protection goals. Once legalised it would be possible to regulate it and introduce standards including fuel quality, packaging standards, production kiln standards and what tree species could be used to produce charcoal (Kituyi, 2004).

The majority of households in the developing world depend on solid biomass fuels such as charcoal for cooking, and millions of small-industries (such as brick and pottery kilns) generate process heat from these fuels. Despite this pivotal role of biomass, the sector remains largely unregulated, poorly understood, and the supply chains are predominantly in the hands of the informal sector (GTZ, 2008).

When fuelwood is marketed, trees are usually felled and cut into large pieces and transported to local storage facilities from where they are collected by merchants to wholesale and retail facilities, mainly in rural areas. Some of the wood is converted to charcoal in kilns and packed into large bags and transported by hand, animal drawn carts and small trucks to roadside sites from where they are collected by trucks to urban wholesale and retail sites. Thus charcoal making is an enterprise for rural populations to supply urban markets. Crop residues and dung are normally used by the owners as a seasonal supplement to fuelwood.

2.3.2.3 Preconditioning of biomass

Shredded biomass residues may be densified by briquetting or pelletizing, typically in screw or piston presses that compress and extrude the biomass (FAO, 2009c). Briquettes and pellets can be good substitutes for coal, lignite and fuelwood as they are renewable, have consistent quality, size, better thermal efficiency, and higher density than loose biomass.

There are briquetting plants in operation in India and Thailand, using a range of secondary residues and with different capacities, but none as yet in other Asian countries. There have been numerous, mostly development agency-funded briquetting projects in Africa, and most have failed technically and/or commercially. The reasons for failure include deployment of new test units that are not proven, selection of very expensive machines that do not make economic sense, low local capacity to fabricate components and provide maintenance, and lack of markets for the briquettes due to uncompetitive cost and low acceptance (Erikson and Prior, 1990).

Wood pellets are made of wood waste such as sawdust and grinding dust. Pelletization produces somewhat lighter and smaller pellets of biomass compared to briquetting. Pelletization machines are based on fodder making technology. Wood pellet are easy to handle and burn since their shape and characteristics are uniform; transportation efficiency is high; energy density is high. Wood pellets are used as fuel in many countries for cooking and heating application (EREC, 2009).

Chips are mainly produced from plantations waste wood and wood residues (branches and nowadays even spruce stumps) as a by-product of conventional forestry. They require less processing and are cheaper than pellets. Depending on end use, chips may be produced on-site, or the wood may be transported to the chipper. Chips are commonly used in automated heating systems, and can be used directly in coal fired power stations or for combined heat and power production (Fargernäs et al., 2006).

Charcoal is a product obtained by heating woody biomass to high temperatures in the absence of oxygen, with a twice higher calorific value than the original feedstock. It burns without smoke and has a low bulk density which reduces transport costs. In many African countries charcoal is produced in traditional kilns in rural areas with efficiencies as low as 10% (Adam, 2009), and typically sold to urban households while rural households use fuelwood. Hardwoods are the most suitable raw material for charcoal, since softwoods incur possibly high losses during handling/transport. Charcoal from granular materials like coffee shells, sawdust, and straw is in powder form and needs to be briquetted with or without binder. Charcoal is also used in large-scale industries as iron reducer, particularly in Brazil, and in many cases, in conjunction with sustainably produced wood, and also increasingly as co-firing in oil-based electric power plants. Charcoal is produced in large-scale efficient kilns and fuelwood comes from high-yielding eucalyptus plantations (Scolforo, 2008).

2.3.3 Conversion technologies

Different end-use applications require that biomass be processed through a variety of conversion steps depending on the feedstock and its chemical composition. Sugar-rich feedstocks like sugarcane and beets require the least amount of processing because simple sugars are present in the juice after pressing that can be fermented into liquid fuels such as ethanol or butanol or a variety of other products. Grains and tubers contain starches that are complex polymeric carbohydrates that break down by enzymes into simpler fermentable sugars. However, as one moves to biomass present in short rotation wood, stalks of annual plants, and herbaceous plants, the presence of the more intractable carbohydrates, cellulose and hemicelluloses and additional phenolic polymers has to be overcome by mechanical, chemical, thermal or combined processes to generate the desired final energy product.

Combustion with excess oxygen at high temperatures requires the least amount of prior processing. To obtain stable chemical intermediates, compatible with the chemical and petroleum industry of today, intermediate severity processes need to be used. For instance, through a partial oxidation of biomass, gasification, intermediates that resemble synthesis gas usually derived from natural gas – hydrogen and carbon monoxide mixture - are obtained. From synthesis gas, a variety of catalytic processes have been developed by the chemical industry to make hydrocarbons in the diesel range or methanol, ethanol, other alcohols, or ethers such as dimethylether, and other fuels. Today these oils provide specialty chemicals, or can be burned to generate electricity in diesel engines, or if the pyrolysis process is done slowly, charcoal becomes the main product (e.g., Huber et al.2006).

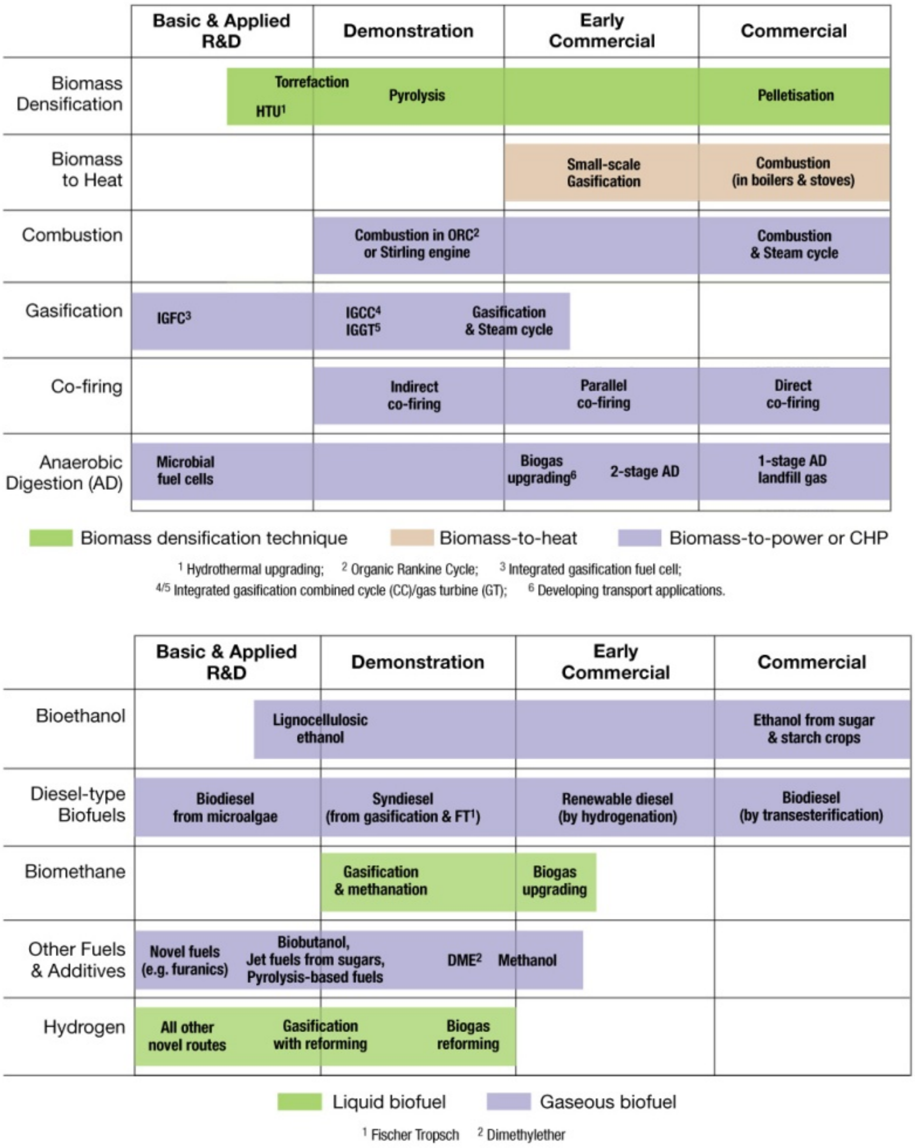

Figure 2.3.1 Development status of the main technologies to produce from biomass energy products such as heat, power, or its combination (CHP), and fuels in the solid, liquid, or gaseous state. Liquid and gaseous fuels are used for transport (modified from E4tech 2008).

To use fermentation processes, the cellulosic and hemicellulosic fractions have to be converted into mixtures of simple six and five carbon sugars with glucose and xylose being dominant. Sugars are the other stable intermediates from which fuels, chemicals, and materials identical to those made by the petrochemical industry or new ones can be made. For these reasons lignocellulosic biomass thermal processes, principally combustion, are commercial while other thermal, chemical, biochemical, or hybrid of those, or biological synthesis routes are developing technologies. So, simpler sources of sugars than lignocellulosic biomass, such as sugarcane, beet, and starch from grains, are the prime sources of liquid fuels from fermentation today.

Figure 2.3.1 shows the snapshot of the stage of development of multi-step conversion processes to transform biomass into energy products for both small and large scale applications. Commercial technologies are presented in Table 2.3.3 with specific characteristics such as energy efficiency, estimated production costs, and anticipated technological advances and anticipated potential costs, and an indication of their potential to mitigate climate change through the relationship between the direct emissions of the life cycle of the biofuels compared to the fossil fuel being replaced. Developing technologies, many of which are already at demonstration or even design and construction of first commercial plants, are discussed in Section 2.6 and are listed on Tables 2.6.2 and 2.6.3. Industrial activities in these areas have been discussed in reports such as IEA Task 39 (2008)[1], and E4Tech (2009) for aviation fuels.

2.3.3.1 Thermo-chemical Processes

Biomass combustion is a process where carbon and hydrogen in the fuel react with oxygen to form carbon dioxide and water with a release of heat. Direct burning of biomass is popular in rural areas for cooking. Wood and charcoal is also being used as a fuel in industry. Combustion of biomass for generating electricity through fluidised bed technology has the advantages of more flexibility for fuels, and lower emissions of sulphur, nitrogen oxides and unburned components (Fargernäs et al., 2006).

Pyrolysis is the thermal decomposition of the biomass into gaseous, liquid, and solid products without oxygen or steam. Depending on the residence times, temperature, and heating rate the process can be optimized to produce one or the other product. At high heating rates and moderate temperature range (450-550°C) the oxygenated oils are the major product (70%-80%), with the remainder split into char and gases.

Cogeneration is the process of using a single fuel to produce more than one form of energy in sequence. In cogeneration mode, the heat generated as steam is not wasted but used to meet process heating requirement, with an overall efficiency of 60% or even higher (over 90%) in some cases (Williams et al., 2009). Technologies available for high-temperature/high pressure steam generation using bagasse as a fuel make it possible for sugar mills to operate at higher level of energy efficiency and generate more electricity than what they require. Similarly black liquor, an organic pulping product containing the pulping chemicals is produced in paper and pulp industry is being burnt efficiently in boilers for producing energy that is used back as process heat and recovers the expensive chemicals (Faaij, 2006). District heating Scandinavian is very popular through cogeneration mode for meeting commercial and residential space heating and water heating.

Biomass Gasification occurs through a partial combustion as it converts the biomass to a syngas (mixture of mostly CO and H2, with other components such as H2O, CO2, CH4, and tars). The end-use product determines the desired syngas composition, and thus the gasifier reactor's design and operating conditions. After gasification, the syngas must be cleaned of particulates, tars, and gaseous components such as sulfur compounds that can inhibit the activity of the catalyst the biofuel desired. The equipment downstream of the gasifier for conversion to H2, methanol, methane, or Fischer Tropsch (FT) diesel is the same as that used to make these products from natural gas. A gas turbine or boiler, and a steam turbine optionally employ the unconverted gas fractions for electricity co-production. Synthesis gas can be used as a fuel in place of diesel in suitably designed/adapted internal combustion (IC) engines coupled with generators for electricity generation. Most commonly available gasifiers use wood/woody biomass; some can use rice husk as well. Many other non-woody biomass materials can also be gasified, specially designed gasifiers to suit these materials (Yokoyama and Matsumura, 2008).

Biomass gasifier stoves are also being used in many rural industries for heating and drying (Yokoyama and Matsumura, 2008; Mukunda et al., 2009).

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[1] **http://biofuels.abc-energy.at/demoplants/projects/mapindex**

2.3.3.2 Chemical Processes

Transesterification is the process where the alcohols (often methanol) react with triglycerides oils contained in vegetable oils or animal fats to form an alkyl ester of fatty acids, in the presence of a catalyst (acid or base with byproducts of glycerin and oil cake/meal ; WWI, 2006). The production of this fuel referred to as biodiesel thus involves extraction of vegetable oils from the seeds, usually with mechanical crushing or chemical solvents. The protein-rich by-product of oil (cake) is sold as animal feed or fertilizers, but may also be used to synthesize higher-value chemicals.

A diesel analog is obtained by hydrogenolysis of the vegetable oils, usually coupled to a refinery. Many companies throughout the world have patents, demonstrations, and have tested this technology at commercial scale for diesel and also jet fuel applications (IEA Bioenergy, 2009). Hydrogenated biofuels have higher cetane number, low sulphur content, high viscosity with 97% biodegradable content. The high cost of the vegetable oil in many locations makes the process less cost-effective.

2.3.3.3 Biochemical Processes

Fermentation is the process to breakdown sugars by yeasts to produce a variety of end products such as ethanol. The major feedstocks are sugarcane, sweet sorghum, sugar-beet and starch crops (such as corn, wheat or cassava). Ethanol from sugarcane or sugar-beets is generally available as a by-product of sugar mills, but it can also be directly produced from extraction juices and molasses. The fermentation either takes place in single-batch or fed batch, or continuous processes, the latter becoming widespread and being much more efficient since yeasts can be recycled. The ethanol content in the fermented liquor is about 10%, and is subsequently distilled to increase purity to about 95%. As the ethanol required for blending with gasoline should be anhydrous, the mixture has to be further dehydrated to reach a grade of 99.8%-99.9% (WWI, 2006).

Anaerobic digestion involves the breakdown of organic matter in agricultural feedstock such as animal dung, human excreta, leafy plant materials, and urban solid and liquid wastes by a consortium of micro-organisms in the absence of oxygen to produce biogas, a mixture of methane (60-70%) and carbon dioxide. In this process, the organic fraction of the waste is segregated and fed into a closed container (biogas digester). In the digester, the segregated waste undergoes biodegradation in presence of methanogenic bacteria under anaerobic conditions, producing methane-rich biogas and effluent. The biogas can be used either for cooking/heating applications or for generating motive power or electricity through dual-fuel or gas engines, low-pressure gas turbines, or steam turbines; it can also be upgraded to a higher heat content biomethane gas mixed with the natural gas grid (IEA Bioenergy, 2009; IEA, 2005). The sludge from anaerobic digestion, after stabilization, can be used as an organic amendment. It can even be sold as manure depending upon its composition, which is determined mainly by the composition of the input waste. Many developing countries like India and China are making use of this technology extensively in rural areas. Many German and Swedish companies are market leaders in large size biogas plants (Faaij, 2006). In Sweden multiple wastes and manures are also used.

2.3.4 Bioenergy Systems and Chains: Description of existing state of the art systems

Table 2.3.3 shows the most relevant commercial bioenergy systems that operate presently in the world. The table lists by end use sector and biomass energy product(s) the feedstock used along with processes used in specific countries. Processes are briefly described with their current efficiency and estimated current production costs (or as close to current based on literature available) along with 2030 (or 2020) estimated production costs. Since the costs are obtained from the literature, no special effort was made to bring all these costs into comparable basis (a major undertaking). Process costs provided by the same reference are usually done under the same conditions and thus enable a firmer comparison. That is why we provided several references for these estimated production costs. Information on the current markets and potential is provided in Section 2.4 for bioenergy products along with examples of specific countries are provided. Another characteristic provided was the measure of the ability of the current chain to reduce GHG emissions compared to the fossil fuel it replaces. A more detailed discussion of this metric of the biofuels is provided in Section 2.5.

Liquid biofuels are mainly used in the transport sector, although in some developing countries they are also used to generate household or village electricity. Ethanol costs are usually lower than biodiesel for the systems which are already in commercial use (the ones based in rapeseed, soya and oil palm), although in Asian countries like Thailand the production costs are close to each other for the two biofuels. The conversion efficiency (from feedstock to end-use product) is modest, from a little over 50% to around 10%, but the low conversion cases are those in which the fuel is a byproduct of a grain to food/feed production process (soya, for instance). Space for better use of the feedstock and, mainly the total biomass produced, is remarkable.

Solid biomass, mostly used for heat, power and combined heat and power (CHP) has usually lower estimated production costs than liquid biofuels. Unprocessed solid biomass is less costly than pre-processed type (via densification), but for the final consumer the transportation and other logistic costs have to be added, which justify the existence of a market for both types of solid biomass. Some of the bioenergy systems are under demonstration for small scale application due cost barriers imposed by economies of scale and consequently it is necessary to identify a different technology than the one used successfully for large scale applications (such as combustion for electricity generation).

From the data in table 2.3.3, the lowest cost liquid biofuels is ethanol from sugarcane as produced in Brazil, followed by ethanol from corn in the United States (including coproduct revenues), molasses in Thailand, sugar beet in Europe (including coproduct revenues), and cassava in Thailand, although the differences in these costs can be within the uncertainties of the various estimates. The higher cost production including coproducts is from wheat in the U.K. Significant projected cost reductions are shown for sugarcane and corn, and there is room for increased efficiency of all other routes.

Biodiesel production costs reach those of ethanol range for countries with higher productivity plants or lower cost base such as Indonesia/Malaysia and Brazil/Argentina. Next come the European countries and the United States. The projected 2022 EPA’s projected costs based on the use of the model FASOM to projected grain costs evolution are significantly lower than current and even corn oil from dry mill expansion into fractionation processes could lead to biodiesel. Similarly, 2030 costs for the OECD project cost reductions for rapeseed biodiesel.

A significant number of electricity generation routes are available and co-combustion (cofiring) is a relatively high efficiency process for use of solid biomass fuel products compared to direct combustion at medium to large sizes. Small plants provide usually heat and electricity at a higher production cost than the larger systems although that varies somewhat with location (see India’s example for small scale application of gasifier/engines) compared to a higher efficiency Japanese case. Heat and power systems are available in a variety of sizes and with high efficiency. The reductions of GHG emissions from these systems is usually very high – in the high 90% (see Section 2.5) compared to the fossil fuel replaced.

Small systems have been improving in efficiency from cooking stoves to small gasifier systems and also in anaerobic digestion systems. Several European countries are advancing mixed solid biomass, food, and manures digestion systems and are obtaining high quality methane from upgrading. Many applications, including transportation systems, are developing and have the potential to further increase their effectiveness. Similarly, at the low scale, the primary use is for lighting and heating of cleaner stoves. These applications too have significant room to improve.

Technologies for the use of biomass for the existing commercial applications are mature but many have room for significant improvement. They provide direct climate change benefits as shown by the GHG emissions reductions compared to the fossil baseline for that particular application principally with a lower fossil carbon source as primary energy.

To illustrate the technological progress ethanol production in Brazil and North America over time, Table 2.3.4 shows the chains' performance including feedstocks, conversion processes, and fuel use in terms of GHG emissions for the full lifecycles. Major variables are feedstock mass, overall fossil energy consumed, produced (heat and power) in the case of Brazil, energy delivered per unit of land used or volume of fuel delivered. Also shown are impacts of bagasse to ethanol as a source of additional ethanol while maintaining the ability of the mills to generate electricity as well, as more field residues are collected through mechanical harvesting. Finally, the table also illustrates the evolution of other routes such as carbon sequestration coupled with these chains (see Section 2.5 for additional details).

North American corn ethanol emissions relative to gasoline (2005) reached the GHG emissions savings per unit biofuel energy is 37% for an individual plant; the average North American natural gas industry is at 34-35% (Plevin, 2009) having evolved from about 18% (Farrell et al., 2006). Sugarcane, a perennial plant harvested every 5-6 years, has a higher GHG performance relative to gasoline, of 86% in 2005/2006. The emissions savings increases by a factor of nearly four per hectare of land going from the annual to the perennial (5-6 year rotation). Technology improvements increased use of field residues from mechanical harvest for electricity or for additional fuel production could increase emissions savings in both cases by factors of two to three. However, the amount of fuel per hectare is half for the annual crop compared to the perennial plant in 2005 and also in the projections shown where biomass productivity increases in both cases.

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy

Transport Fuels: Ethanol

Feedstock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Sugarcane	Pressed, washed, and separated into a syrup and solid residue, bagasse, combusted in boilers for process heat and power (CHP). Sugar solution (sucrose) fermented by yeasts to ethanol recovered by distillation. The hydrous fraction sold as neat ethanol (6 wt% water). Further drying with molecular sieves or cyclohexane azeotropic distillation makes anhydrous ethanol for blending with gasoline. Excess electricity is already sold to the grid.	Brazil	Eff. = 0.38[1]; 0.41[2] (only ethanol production). Mill size (170 million),[2] advanced power generation and optimised energy efficiency and distillation can reduce costs further in the longer term/surplus electricity, 50kWh/t sugar cane	10 to 15[1] 14[2] w/ coproduct revenue (CR)	86 [24]	Projected 2030 US$ 9 to 10/GJ[1]. Projected 2020 Eff. = 0.50.[3] Biological Carbon Capture and Storage (BCCS) from sugar fermentation. Efficient use of sugar cane straw and leaves as an extra source of heat & power through mechanized harvest.[5] Widespread use of GMO. Evolution of the biorefinery approach with multiple products.[6] Improved yeasts.
			250 Mi l/yr plant, feedstock costs at $7.7/GJ, conversion costs (including capex + opex) at $7/GJ without co-products revenue.	14.7[4] no CR		
Corn grain	Grain soaked in dilute sulfurous acid; resulting slurry ground to separate the germ (for corn oil food or biodiesel) from the fiber (for food/feed), gluten (protein), and starch components which are further separated and upgraded into various products such as high fructose corn syrup. Starch solution is hydrolyzed to glucose and fermented by yeasts to ethanol.	USA	Eff. = 0.56[7,8] wet milling; 11 plants, 11% production; Average size: 600 million l (up to 1000 million l).[3]	20[9] 2005/2006 net production cost; 15.9[9] 2006/2007	15 [23]	Projected Eff.=0.62[3] BCCS from sugar fermentation Membrane separation for ethanol separation. Incorporation of CHP including sales of power to the grid . Widespread use of GMO for increased yields with lower inputs.[3]
	Whole grain hammer milled into course flour and cooked to form a slurry hydrolyzed with alpha amylase enzymes forming dextrins, followed by cooking with gluco-amylase to sugars and fermentation by yeasts. Last two processes can be combined. 35.4d w/o coproduct revenue		Dry Mill only Eff. = 0.62 (150 plants; 88% production). Production cost estimated used 170 million l/yr.[2,11] Dry milling technical progress leading to more co-products. 30% coproduct feed DDGS sold wet.[3] 250 Mi l/y plant, feedstock costs at $29.4/GJ, conversion costs (including capex + opex) at $6/GJ without co-products revenue.[4]	20[2]-21[11] w/ CR 17.5 [3] w/CR 35.4 [4] no CR	35-56 Depending on co-product credit method[25]	2020 Projected US$ 18/GJ[12] with $6/GJ capex/opex. 2020 Eff. = 0.64 [4]; industry Eff.=0.65-0.68[4] with projected 2020 $16/GJ; FASOM modeled cost used.[3] BCCS. Low temperature starch enzyme hydrolysis and fermentation. Corn dry fractionation and corn oil to biodiesel production in 90% mills. Membrane separation and CHP. Increase % wet feed sold.[4]
	Only three corn ethanol plants continue to operate with corn. Operated for years with distressed corn unfit for animal consumption	China	Estimated cost (60% is feedstock cost) includes subsidy which is 8.9% of gasoline price[12]	26-30[13]	-42 [26]	Process and energy efficiency improvements

Transportation Fuels: Ethanol Continued

Feedstock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Sugar beet	Sugar beet is crushed and then soluble sugars are extracted by washing through with water. Yeast is added and fermentation and ethanol recovered by distillation.	EU	Eff. = 0.12.[1] 250 Mi l/y plant, feedstock costs at $21.6/GJ, conversion costs (including capex + opex) at $11/GJ with co-products revenue $8.2/GJ (UK costs).[4]	24.4[4] w/ CR	32-65 Alternate co-product use[27]	2020 Eff. = 0.15[1]
Wheat	Process similar to that described for corn dry milling starting with the malting. Either enzyme or acid hydrolysis can lead to sugars for fermentation	EU	Eff. = 0.53 to 0.59[14, 15, 6] IEA, 2002 NDDC 2002. 250 Mi l/y plant, feedstock costs at $36.2/GJ, conversion costs (including capex + opex) at $10.5/GJ and $6/GJ co-products revenue for UK.[4]	40.7[4] w/ CR (UK)	40% DDGS to energy[27]	2020 Eff.=0.64[4]
Cassava	High starch content tuber mashed, cooked and fermented in a simultaneous saccharification and fermentation, followed by ethanol distillation.	Thailand, China	China plant of 200 thousand tonnes of ethanol which is operating at partial capacity.[13] Thailand's process described by Nguyen[15] produces about 10 Mi Gal,[17 ,18] productivity 20-25 tonnes/ha, highest in world.	26[4] Thailand estimate	45 [28]	Production expected to continue to increase in Thailand and become more important than molasses
Molasses	By product of sugar separation from the cooking liquor. Contains glucose and fructose from sucrose decomposition	India, Colombia, Thailand	By product utilization; about 3 % molasses could be used for ethanol in Thailand leading.	22[18] Thailand estimate	27-59 Depending on co-product credit method[29].	

Transport Fuels: Biodiesel

Feedstock	Major Process	Country	**Efficiency and process economics** Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Rape seed	Vegetable oil extracted from seed is reacted with alcohol (usually methanol) to produce fatty acid methyl esters (FAME) in a base-catalyzed process, the most common process with high yields (>98%). Called biodiesel when it meets user country specifications. Alternative processes are direct acid catalyzed esterification of the oil with the alcohol or conversion of the oil to fatty acids, and then to alkyl esters with acid catalysis.	Germany	Eff. = 29%. For the total system it is assumed that surpluses of straw are used for power production[19]	31 to 50[1]	31 [30]	2030 Projected US $25 to $37/GJ[1] for OECD. US Projected 2020 soya biodiesel cost $20/GJ based on FASOM modeled feedstock cost.[3] US Projected 2020 waste oil cost $18/GJ.[3] New methods using bio-catalysts; Supercritical alcohol processing.[20] Heterogeneous catalysts or bicatalysts. New uses for glycerin.[21] Improved feedstock yields.
		France	55 GJ/ha/yr (EU). 220 Mi l/y plant, feedstock costs at $40.5/GJ, conversion costs (including capex + opex) at $2.7/GJ and $1.7/GJ co-products revenue.	41.4[4] w/ CR	75 [31]	
		UK	Same size plant, $35.2/GJ, conversion costs at $4.2/GJ and $11.3/GJ coproduct revenue	28.5[4] w/ CR	39-49 Alternate co-product use[27].	
Soya		USA	20 GJ/ha/yr. Same size plant, $100.6/GJ, conversion costs at $4.2/GJ and $55.6/GJ coproduct revenue	49.2[4] w/ CR	67-100 Depending on co-product credit method[32].	
		Brazil/ Argentina	Same size plant, $22.6/GJ, conversion costs at $2.7/GJ and $1.7/GJ coproduct revenue. Agrolink 2009 reports that ranges of production cost are $24-$34/GJ	23.5[4] w/ CR	NA	
Oil palm		Indonesia Malaysia	163 GJ/ha/yr. Same size plant, $25.1/GJ, conversion costs at $2.7/GJ and $1.7/GJ coproduct revenue	26.1[4] w/ CR	35-66 Alternate co-product use[33].	
Vegetable oils	Starting from the oils	109 countries	Based on total lipids exported costs. Neglects few countries with high production costs.[22] Oil at $0.48/l.[11]	7 to 30[22] 15.9[11] US 10.5[2]US trap grease	NA	

Abbreviations: capex=capital expenses; opex=operating expenses; CR = Coproduct Revenue; References

[1]IEA Bioenergy: ExCo,2007; [2]Tao, Aden 2009; [3]EPA 2010; [4]IEA Bioenergy: ExCo, 2009; [5]Seabra et al., 2008; [6]Seabra et al., 2010; [7]UK DFT 2009; [8]Hamelinck 2004; [9]F.O. Licht 2007; [10]Rendleman and Shapouri 2007; [11]Bain 2007; [12]Hettinga et al. 2009; [13]Qiu et al. 2010; [14]Reith, 2002;[15]IEA 2002; [16]Nguyen et al. 2008; [17]Koizumi 2008; [18]Milbrandt, Overend 2008; [19]CSIRO, 2000 [20]Egsgaard et al., 2009; [21]Bhojvaidad 2008 [22]Johnston, Holloway 2007; [23]Wang et al, 1999; [24]Macedo et al, 2008; [25]Wang et al., 2010; [26]Ou et al., 2009; [27]Edwards et al., 2008; [28]Nguyen et al., 2008; [29]Beer et al., 2001; [30]Reinhardt et al., 2006; [31]Ecobilan,2002: [32]Hou et al., 2009; [33]Wiche et al, 2008

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued

Power from Solid Biomass Fuels

Feedstock	Major Process	Country	**Efficiency and process economics** Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Wood residue	Co-combustion with coal	Worldwide	Eff. ~ 0.35-0.4[1]. Production cost assumes biomass cost $3/GJ, discount rate of 10%. More than 50 power plants operated or carried experimental operation, from which 16 are operational using coal. More than 20 pulverised coal plants in operation.[2] Usually the operation requires subsidies[3]	4.2/GJ (0.05/kWh)[1]	10[14]	Reduce the cost of fuel, by improved pre-treatment, better characterisation and measurement methods.[10] Promising technology is torrefaction. The treatment yields a solid uniform product with lower moisture content and higher energy content compared to those in the biomass feedstock and make biomass very suitable for pulverized coal plants[3]
MSW			Eff. ~ 0.22, due low temperature steam to avoid corrosion[9]. Few coal-based plants cofire MSW, but at least 2 are in commercial operation[2,3].		NA	New CHP plant designs using MSW are expected to reach 28%-30% electrical efficiency, and above 85%-90% overall efficiency in CHP[9]. Working environment problems, caused by dust and micro-organisms, need further attention [10]
Wood log/Wood residue	Direct combustion	Worldwide	Plant size: 1–20 MWe[5]	4.2-10/GJ (0.05-12/kWh)[5]	96[15]	
			Plant size: 20-100 MWe. Eff.= 20 to 40%[1,13]. Investment cost = 3.000 –1900 US$/kW[1]. Well established technology, especially deployed[1]. According to most energy scenarios, global electricity production from biomass is projected to increase from its current 1.3% share (231 TWh/year) to 3%-5% by 2050 (~1400-1800 TWh/year).[7] Major variable is supply costs of biomass[1] in Scandinavia and North America; various advanced concepts using fluid bed technology giving high efficiency, low costs and high flexibility. Commercially deployed waste to energy (incineration) has higher capital costs and lower (average) efficiency. Overall energy delivered: 0.57 -0.74 EJ[5,4,12]	Worldwide: 4.2-10/GJ (0.05-12/kWh)[1,13] U.S.:[15] 7.5/GJ (0.09/kWh) Stoker: 7.5/GJ (0.09/kWh) 50 MW Fluidized Bed: 8.3/GJ (0.1/kWh)	97[16]	Worldwide: 2.1 - 6.7/GJ (US$0.021 - 0.096/kWh)[6] U.S. 2020 projections:[15] 6.3-7.8/GJ (0.076-0.092/kWh) Stoker: 7.5-8.1/GJ (0.091-0.096/kWh
Wood residues/Agricultural residues	Gasification for small scale application/gas engine	Worldwide	eff., 17%, India	4.5-6.3/GJ (0.054-0.076/kWh	NA	Reduce feedstock production price[10]
			eff., 20%, Japan; Assumptions: 1) Biomass cost $3/GJ; Discount rate 10%; 2) Heat value $5/GJ[9].	7.5/GJ (0.09/kWh)[9]	95[17]	

Briquettes	Drying /Mechanical compression	EU	Large and continuously increasing co-combustion market[10]		NA	Improve feedstock supply[10]
Wood pellets			Used in 2 operating power plants in cofiring with coal[2]		NA	http://www.pelletsatlas.info (EU price)

Power from Solid Biomass Fuels continued

Feedstock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Wood chips	Co-combustion with coal/ Direct combustion	EU	Used in at least 5 operating power plants in cofiring with coal.[2] Used in large scale direct combustion plants (150-300 MWe)[13]		9[18]	CAPEX 2000-3000 US$/kW[13]
Ag residues		EU	Straw used in at least 10 operating power plants in cofiring with coal[2.] Long-term storage of willow chips is very difficult due moisture content (55-58 %).[10]	$4.7/GJ[11]	9[19]	Concentration of chloride and potassium salts. Straw contains a lot of these salts, which can cause corrosion and slagging problems. The need to make power plants from corrosion-resistant materials has increased the cost of energy from straw, at least in Denmark[8]

[1]IEA Energy, 2007; [2]IEA Task 32, 2010; [3]IEA Bioenergy Task 32, 2009; [4]WEO, 2009; [5]REN21, 2007; [6]IEA BIOENERGY: EXCO: 2007:02; Helynen et al., 2002; [7]COMPETE, 2010; [8]Egsgaard et al, 2009; [9]IEA EnergyTechnology Essentials, 2007; [10]Econ Pöyry, 2008; [11]Hoogwijk, 2004; [12]IEA Balances, 2009; [13]IEA Task 32, 2009; [14]Pehnt, 2006; [15]Elsayed et al., 2003; [16]Forsberg, 2000; [17]Searcy and Flynn, 2008; [18]Styles and Jones, 2007; [19]Hartmann and Kaltschmitt, 1999; [20]NRC Electricity, 2009.

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued

Heat from Solid Biomass Fuels

Feed-stock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Fuelwood	Combustion for residential use (cooking and 5-50 kWhth heating)[z]	Mostly in Developing countries	Eff.= 10-20%[1]. Of the 45 EJ of biomass supplied to the global primary energy mix in 2006, an estimated 39 EJ (i.e. 87%) is burnt in traditional stoves for domestic heating and cooking primarily in developing countries[4,5.] Traditional devices are inefficient and generate indoor pollution. Improved	Costs are extremely variable (from 0 monetary costs when fuelwood is collected to 8 GJ or more when fuelwood is scarce)	1-2 tCO2e/yr for the simplest improved stoves 3-9 tCO2e/yr for the advanced systems (see section	Improved cookstoves are presently available/reduce fuel use (up to 60%)/cut 70% indoor pollution. Optimized design of cookstoves and new materials, gasifier stoves for household use. Combined heat/electric. Production already in demonstration. New stoves with 35-50% efficiency.[15] Indoor air pollution reduced more than 90%. Replacement by modern heating systems (i.e., automated, flue gas cleaning, pellet firing) in e.g., Austria, Sweden, Germany

			cookstoves are available that reduce fuel use (up to 60%) and cut 70% indoor pollution. About 2.5 EJ usable energy generated.		2.5)	ongoing for years[1].

Heat from Solid Biomass Fuels Continued

Feed-stock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Fuelwood	Combustion for small scale industries and few large scale industries (1-20 MWth)[2]	Mostly in Developing countries	Eff.= Up to 70-90% for modern furnaces[1]. Existing industries have low efficiency kilns that are also high polluting. Improved kilns are available that cut consumption in 50-60%. Total 1 to 6 EJ generated[2]	Costs are extremely variable (from 0 monetary costs when fuelwood is collected to $8/ GJ or more when fuelwood is scarce)	NA	1.2 to 5.9 US$/GJ[1] Improved kilns cut consumption in 50-60%. There are very large cobenefits of improved technologies in terms of public health and environment.
Fuelwood	Pyrolysis for charcoal production mainly in small-scale industrial activities	Mostly in Developing countries	Wood in smaller pieces is easier to dry in the air and hence the yield in carbonising is higher and is also required for the mechanised feeding systems used in most industrial type carbonising processes. Generally any industrial system adopted must face quite large wood preparation costs[10]	Ranges from US$6.3/GJ for brick kiln to US$7.6/GJ for continuous retort assuming US$23/t wood; US$ 9.6/GJ using continuous retort and forestry residues at US$7.0/tonne[10]	NA	One of the most important steps forward in the production of charcoal is the use of continuous carbonisers[10]. By causing the raw material wood to pass in sequence through a series of zones were carbonisation are carried out it is possible to introduce economies in use of labour and heat[10]. Recovery of the heat from the top of the carboniser is achieved by burning the gas and vapours under controlled conditions in hot blast stoves[10]. Use of liquids and gases from carbonization can yield valuable coproducts[10]. All these technologies available but poorly used in Developing Countries.
Wood residues/Agric. Wastes	Gasification	Mostly in Developing countries	Eff. 80-90%. Typically hundreds kWth[3]. Commercially available and deployed; but total contribution to energy production to date limited[3]. Investment: several hundred/ kWth, depending on capacityf. Example: $300-$800/kWhth	$0.009-0.048/kWh fuel[3]	NA	
Wood	Combustion	Worldwide	Processes are in demonstration for small-scale applications between 10 kW and 1 MWe using Stirling engines (SE), with Eff. = 11-20%[8] or Organic Rankine Cycle (ORC), with Eff.=10-14%[12]. Steam turbine based systems 1-10 MWe are widely deployed throughout the	$0.021-0.15/kWh electricity. High costs for small scale power gen. with high-quality feedstock. [9]Value of heat $03/kWh, value of electricity $0.10/kWh (2006) Low costs for large-	NA	Stirling engines with future Eff.=15 to 30%[12], steam screw type engines, steam engines, and organic rankine cycle (ORC) processes for small-scale applications between 10 kW and 1 MWe[6]. Mass production will reduce investment costs[12]
Wood residues	Combustion	Worldwide				

Briquettes	Combustion	Worldwide	world. Efficiency of conversion to electricity in the range of 30-35%[1]	scale (i.e., >100 MWth) state-of-art.[1,7,8,]		
Wood residues/Agric. Wastes	Gasification and gas engines	Worldwide	Effi. 15-30%(electrical); 60-80% (overall).[1] Various systems on the market[1]. Deployment limited due to relatively high costs, critical operational demands, and fuel quality[1]. Size 0.1 - 1.0 MWe[1]	Investment 1,180-3,550 US$/kW[1]	NA	

Heat from Solid Biomass Fuels Continued

Feed-stock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Sugar cane bagasse&waste	Combustion	Worldwide	limited use due to relatively abundance. Critical operational demand and fuel quality	About $0.058/kWh[11]	NA	Large potential availability either using high-pressure steam boilers or gasification. Concentration of chloride and potassium salts. Straw contains a lot of these salts, which can cause corrosion and slagging problems. The need to make power plants from corrosion-resistant materials has increased the cost of energy from straw, at least in Denmark[7]
Wood residues/Agric. Wastes	Pyrolysis for production of bio-oil	USA	Eff. 60-70% bio oil/feedstock and 85% for oil+char[1]. Commercial technology available. Bio-oil is used for power production in gas turbines, gas engines, for chemicals and precursors, direct production of transport fuels, as well as for transporting energy over longer distances[1].	$4-6/GJ of bio-oil[13,14] Scale and biomass supply dependent; capital cost $690 for 10 MWth[1]	NA	Cost: 10% – 100% more than fossil fuel. Availability: limited supplies for testing; Standards: lack of standards and inconsistent quality inhibits wider usage. Incompatibility with conventional fuels. Unfamiliarity of users. Dedicated fuel handling needed. Poor image[13]

[1]IEA Energy 2007 [2]REN21,2007 [3]IEA BIOENERGY: EXCO: 2007:02 [4]Third Periodic Activity Report, 2010 [5]IEA BIOENERGY ANNUAL REPORT 2009; [6]IEA Bioenergy: ExCo,2007 [7]Egsgaard et al, 2009 [8]IEA Energy Technology Essentials, 2007 [9]Hoogwijk, 2004 [10]FAO, 1985 [11]EPE, 2008l [12]Ragossnig, 2008 [13]Bain, 2004 [14]Bridgewater, 2003; [15]Mukunda et al, 2010; [16]NRC electricity, 2009

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued
Solid Biomass Fuel Products for Energy

Feedstock	Major Process	Country	Comments Eff. = literature energy product energy/biomass energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances

Pellets	Combustion for heating houses and combustion under co-firing for electricity	EU	Lower prices are for wholesale to industrial and power plant use as cofiring. Higher price for bagged or packet used in residential market[1]. The production capacity in all EU 27 states is estimated at about 9 million tonnes (2007). Globally it might be as much as 12–14 million tonnes capacity[3]	FOB Brazil 0.6-1.4; FOB Brazil 2.2;FOB Canada 3.2; Netherland 6.2; Norway 12.3; UK 6.1[2]	NA	1. Removal of indirect trade barriers for import in certain areas of Europe. 2. Establish common standard for pellets. Some countries in Europe have pellet standards, some have none, and even those that have are different. 3. Freight costs reduction due market increase[2]

[1]E4Tech,2010 [2]Junginger et al, 2008 [3]Renewable Energy World, 2010

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued
Heat, Power or Transport Fuel from Animal Manures (AM), Organic Wastes (OW - includes municipal), Agricultural or Wood Residues (AR, WR)

Feedstock	Major Process	Country	Comments Eff. = literature energy product energy/biomass energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
OW/MSW	Landfill with methane recovery	Worldwide	Eff. 10-15%[1].Widely applied for electricity generation and, in general, part of waste treatment policies of many countries[1]		89[6]	Large expectation for further use. In some European countries the biogas technology developed in the last years very impressive (Germany, Austria, Sweden). In Europe it increased by 35% between 2004 and 2006[2].
OW/AR/AM	Anaerobic co-digestion, gas clean up, compression, and distribution	EU	In the city of Linkoping, Sweden, since 1999, a multiple waste streams plant produces methane upgraded to high quality to fuel in a local grid the rail commuter train and buses (slow fill).	13[4]	108[7] Heat & Power	Trend to large scale biogas installations, where the biogas is upgraded to bio-methane and injected into gas pipelines, as well as biogas as transport fuel[2].
		USA	By product credit not considered for fertilizer[3]	14[3]	NA	State of California study showing the potential for utilization of these residues and augmenting the natural gas distribution.
Manures	Household digestion	Worldwide	Cooking, heating and electricity applications. Use also human wastes. By product- liquid fertilizer.	1 to 2 years payback time	NA	Large reductions in costs by using geomembranes; improved designs and reduction in digestion times. Use of waste food and leafy material as input
Manures	Farms	Finland	Biogas from farms etc. 18-50kWe; Investment: 400-720 k$(2009)[5]	$0.28-0.29/kWh[5]	NA	Improved designs and reduction in digestion times. Improvements in the understanding of anaerobic digestion, metagenomics of complex consortia of microorganisms
Manures and food processing residues			Biogas from combined farm animal residues and food processing residues at 145-290kWe; Investment: 2200-3600k$ (2009) [5]	$0.25-0.32/kWh[5]	NA	

[1]IEA Energy, 2007; [2]Ragossnig, 2008; [3]Krich et al., 2005; [4]Sustainable Transportation Solutions, 2006; [5]Kuuva et al., 2009; [6]Norstrom et al., 2001; [7]Chevalier and Meunier, 2005

Table 2.3.4 Ethanol from Corn and Sugarcane Ethanol – Past and projected carbon mitigation potential

Indicators/	**Corn Ethanol - North America, Natural Gas**	**Sugarcane Ethanol - Brazil**
Biomass type kg GHG savings per tonne of biomass feedstock or waste (absolute values)	Company Data 1995 **330** 2005 **440** 2015 Projection (a) CHP **560** (b) CHP + CCS **930** CHP = combined heat and power CCS = carbon capture and storage from fermentation	Industry Data Cases based on dry cane stalk (70% wet) 2002 (specific mill) **735** 2005/2006(44 mills) **530** 2020 Mechanical Harvest Scenarios (a) w/8x 2005/6 electricity proj. **775; +CCS 1050** (b) w/3x 2005/6 electricity and 40% more than 2005/6 ethanol (from bagasse) proj. **860; + CCS 1210**
Bioenergy output and fossil energy use in processing expressed in kg GHG per unit output (GJ - LHV basis) and (Primary fossil energy - renewable credit/ biofuel energy output)	1995 **64 (0.9)** 2005 **54 (0.7)** 2015 (a) proj **0.1 (0.5)** 2015 (b) proj **12 (0.6)**	2002 115 (0.04) 2005/2006 80 (-0.02) 2020(a) proj. 115 (-0.4) 2020(b) proj. 90 (-0.04)
Biomass and process productivity -- land use in kg GHG savings by biomass production per ha of available land and (thousand liters/ha)	1995 **2600 (3.0)** 2005 **3900 (3.5)** 2015 (a) proj **6400 (4.5)** 2015 (b) proj **10600 (4.5)**	Calculated per harvested ha 2002 **18000 (7.1)** 2005/2006 **14000 (7.5)** 2020 (a)proj. **22000 (8.8)** 2020(b)proj. **25000 (12)**
	(S&T)2 Consultants Inc., 2009	Macedo et al., 2004; Macedo, Seabra, 2008; Molersten et al., 2003

2.4 Global and Regional Status of Market and Industry Development

2.4.1 Current bioenergy production and outlook[2]

Biomass is the most important renewable energy source, providing about 10% (48 EJ) of the annual global primary energy demand. A major part of this biomass (38 EJ) is used locally in rural areas and relates to charcoal, wood, agricultural residues, and manure used for cooking, lighting, and space heating, generally by the poorer part of the population in developing countries. Modern bioenergy use (for industry, power generation, or transport fuels) is making already a significant contribution of 10 EJ and this share is growing. Today, biomass (mainly wood) contributes some 10% to the world primary energy mix, and is still by far the most widely used renewable energy source (Figure 2.4.1).

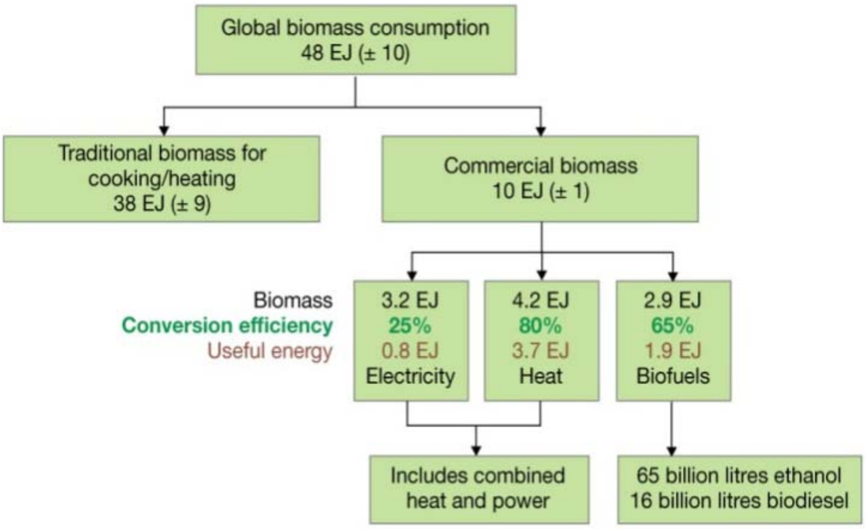

Figure 2.4.1. Global biomass consumption for bioenergy and biofuels in 2008. Source: based on IEA 2009 update of 2007

One of the fastest-growing applications of biomass is the production of biofuels based on agricultural crops – current global biofuels preliminary supply estimates at 1.9 EJ (2008) or about 2% of transportation fuel, a significant growth from 1.43 EJ in 2007. Most of the increase in the use of biofuels in 2007 and 2008 occurred in the OECD, mainly in North America and Europe. There is currently an excess of installed capacity and underutilization of facilities, more in biodiesel than in ethanol, but Asia Pacific and Latin American markets are growing, primarily in developing countries for economic development. The recent surge in biofuels production is not expected to continue in the near term. This depends largely on the continuation of blending mandates in OECD countries, oil prices, and the overall global economy.

Despite this anticipated short term downturn, world use of biofuels is projected to recover from 2015 and in the longer term. According to the 2009 World Energy Outlook scenarios, biofuels may contribute 5.7 to 11.6 EJ to the global transport fuel demand, thus meet about 5% to 11% of total world road-transport energy demand, up from about 2% today (IEA, 2009). In the 450

Scenario, biomass consumption also increases and in 2030 is 14.7 EJ higher than in the Reference Scenario. The use of biomass in CHP and in electricity-only power plants increases by 67% by 2030, to 7.2 EJ above the level in the Reference Scenario. Major increases in global biofuels production are seen in the 450 Scenario (to meet the CO2 intensity standards set by international

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[2] This section is largely based on the World Energy Outlook 2009 (IEA, 2009) and Global Biofuels Center Assessments (GBC 2010).

sectoral agreements), with consumption in 2030 reaching 11.6 EJ, more than double that in the Reference Scenario. The last decade of the projection period sees a strong increase in the production of lignocellulosic biofuels. Regions that currently have strong policy support for biofuels take the largest share of the eight-fold increase over the Outlook period, led by the United States (where one third of the increase occurs) and followed by the European Union, Brazil and China. To highlight the scale of the challenge, the 7 EJ of biofuels required in 2030 in the 450 Scenario is greater than India’s current oil consumption and is derived from the advanced technologies discussed in Section 2.6 which are at various stages of development. To achieve this would require accelerated research and development efforts, operational demonstration plants in the next few years, and significant public and private investment.

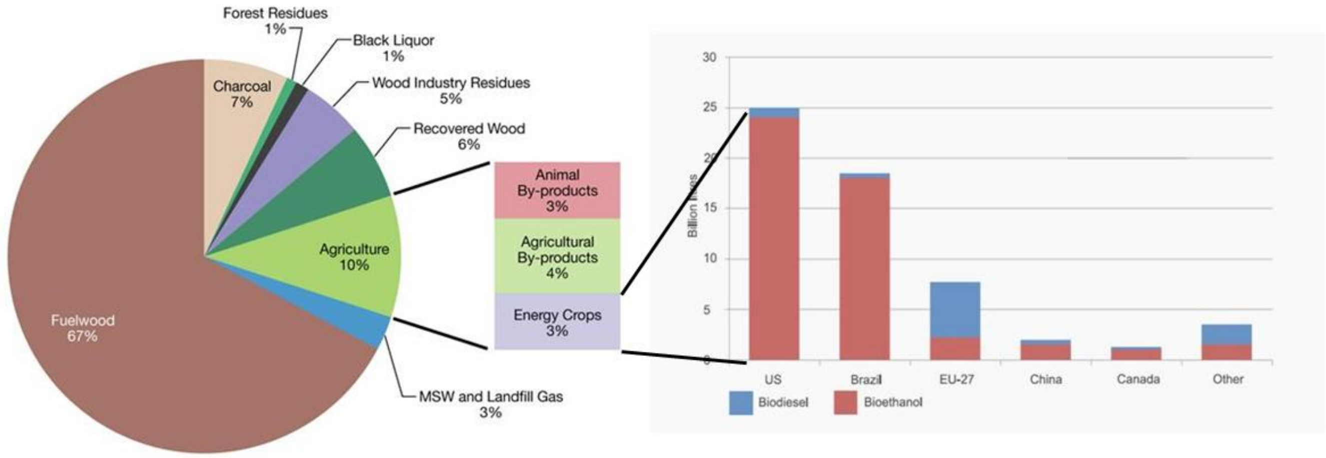


Figure 2.4.2. Share of the biomass sources in the primary bioenergy mix. Source: Bauen et al. (2009c), based on data from IPCC, 2007 and end-use energy built in major biofuel producers in 2007 (in billion litres). Actually, energy crops provide, on top of the biofuels shown, electricity and heat not properly quantified. Source: Prepared by authors based in Bauen et al. (2009c), Lichts, 2007 and national sources.

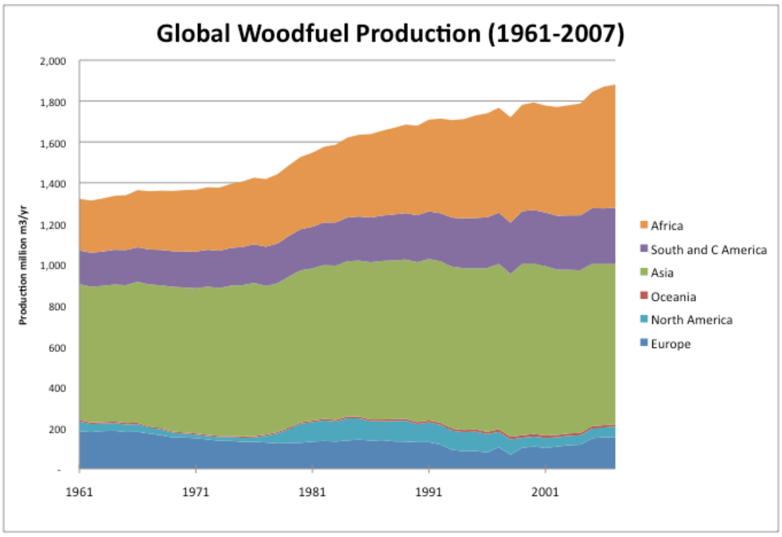


Figure 2.4.3 The evolution of global fuelwood production in the period 1961-2007 Source: FAOSTAT 2009

Figure 2.4.2 provides an overview of the biomass sources in the primary bioenergy mix, illustrating the importance of fuelwood. The WEO-2009 scenarios foresee that the transition towards modern fuels for cooking and heating and technologies drives down demand for traditional biomass in developing countries, but it is still possible that the absolute amount consumed may still grow with increasing world population. However, there is significant scope to improve efficiency and environmental performance, which will reduce biomass consumption and related impacts (Bauen et al. 2009c).

The use of solid biomass for electricity production is important, especially from pulp and paper plants and sugar mills. Bioenergy's share in total energy consumption is increasing in the G8 Countries (e.g. co-combustion for electricity generation, buildings heating with pellets), especially in Germany, Italy and the United Kingdom.

2.4.2 Traditional Biomass, Improved Technologies and Practices, and Barriers

While bioenergy represents a mere 3% of primary energy in industrialised countries, it accounts for 22% of the energy mix in developing countries, where it contributes largely to domestic heating and cooking, mostly in low efficiency cooking stoves. An estimated 2.5 billion people depend on biomass primary energy for cooking (IEA WEO 2009). Most developing countries initiated some type of improved cooking stove (ICS) since the 1980s and many are in operation as shown in Figure 2.4.3, sponsored by development agencies, governments, NGOs, and the private sector. China had the major initial success with 250 million improved cookstoves installed. Other countries were not as successful, but programmes of the past 10 years led to a new generation of advanced biomass-based cookstoves, dissemination approaches, and innovation. An estimated 820 million people in the world are currently using some type of improved cookstove for cooking (WHO, 2009). The new generation of cookstoves shows clear reductions in biomass fuel use, indoor air pollution, and also mitigation of GHG emissions with regards to open fires (see Section 2.5). Technologies used include direct combustion, small scale gasification, and small scale anaerobic digestion, or direct use of a liquid fuel (ethanol) discussed in Section 2.3 or combinations of technologies.

In general, successful stoves programs are those that included: a) a proper diagnose of people´s needs, traditional cooking practices and devices, as well as the institutional setting; the undertaking of regional market surveys and studies on people´s preferences has been key in this area; b) technology innovation, many times with critical input from local users and artisans. Two main lines of technology development have been followed, mass-scale approaches that rely on centralized production of stoves or critical components, with distribution channels that can even include different countries (e.g., Stovetec and Envirofit); a second approach relies more on strengthening regional capabilites, giving more emphasis to local employment creation, sometimes the stoves are built on site rather than sold on markets, such as the Patsari Stove in Mexico, GERES in Cambodia; c) the use of financial mechanisms and incentives to facilitate the dissemination of the stoves. The incentives given are very diverse and can be directed to stove's producers to lower production costs, to end-users in the form of microfinance schemes or subsidies, and other forms. Carbon offset projects are increasingly entering as a major source of stove financing in particular regions; d) an enabling institutional environment, largely facilitated by Governments (as in the case of the Chinese cookstove program); and e) the accurate monitoring and evaluation (M&E) of impacts from the new stoves. Programs with good M&E activities have been able to detect problems early on in the dissemination phase and make changes accordingly.

Drivers for increased adoption of improved cookstoves have included cooking environments where smoke caused health problems and annoyance; a short consumer payback (few months) donor or government support extended over at least five years and designed to build local institutions and develop local expertise. Government assistance has been more effective in technical advice, and quality control.

Convenient cooking and lighting are also provided by biogas production with household scale biodigestors, which reach today 25 million households, the majority in China and India (REN21

2009, REN/GTZ/BMZ 2008). China and India, for example, are promoting biogas on a large scale, and there is significant experience of commercial biogas use in Nepal (Hu, 2006; Rai, 2006; India, 2006). Early stage results have been mixed because of quality control and management problems, which have resulted in a large number of failures. Smaller scale biogas experience in Africa has been often disappointing at the household level as the capital cost, maintenance, and management support required have been higher than expected. Under subsistence agriculture, access to cattle dung and to water that must be mixed together with slurry has been more of an obstacle than expected. More actively managed livestock and where dung supply is abundant, as in rearing feedlot-based livestock, would facilitate technology adoption. (Hedon Household Network, 2006)

Experience of NGOs that are members of the Integrated Sustainable Energy and Ecological Development Association (INSEDA) for the last two decades in the transfer, capacity building, extension and adoption of household biogas plants in rural India has shown that for successful implementations of biogas and other RET programmes in the developing countries, the important role of NGOs networks/associations needs to be recognized. These may provide funding and support under the Clean Development Mechanism (CDM) in the implementation of household biogas programmes in target regions through north-south partnerships in which both groups gain.

Legal barriers to increased biogas adoption include: lack of proper legal standards; insufficient economic mechanisms to achieve desired profits related to the investment costs, installations and equipments; relatively high costs of technologies and of labour (e.g. geological investigations to site installations). Many information barriers related to projects feasible for technical applications, installations producers, suppliers and contractors, and reliability and performance of the designs and construction of scale anaerobic digestion systems. Also there is limited application of knowledge gained from the operation of existing plants in the design of new plants.

2.4.2.1 Small-Scale Bioenergy Initiatives

Linkages between livelihoods and small-scale bioenergy initiatives were studied based on a series of 15 international case studies conducted between September and November 2008 in Latin America, Africa and Asia (Energy Research Programme Consortium, 2009). The cases were selected to highlight the use of a range of bioenergy resources (residues from existing agricultural, forestry or industrial activities; both liquid and solid energy crops) for cooking, mobility, productive uses and electricity. The approach taken also considers the non-energy by-products of production processes where these form, or could form, a significant added benefit in terms of livelihoods, revenues and efficiency. A summary of preliminary lessons and conclusions that are drawn from these case studies are summarised as follows (Practical Action Consulting, 2009):

- Natural resource efficiency is possible in small-scale bioenergy initiatives
- Local and productive energy end-uses develop virtuous circles
- Where fossil energy prices dominate, partial substitution is an option (i.e., hybrid systems)
- Longer term planning and regulation plays a crucial role for the success of small-scale bioenergy

At the project level, important lessons include:

- Flexibility and diversity can reduce producer risk
- Collaboration in the market chain is key at start up
- Long local market chains spread out the benefits
- Adding value to feedstocks by processing them into modern fuels increases project viability

- Any new activity raising demand will raise prices, even those for wastes
- Cases do not appear to show local staple food security to be affected
- Small-scale bioenergy initiatives offer new choices in rural communities

In summary, if improved cooking stoves (ICS) and other advanced biomass systems for cooking that are currently entering the market energy and climate-change benefits could be significant. About 600 million households cook with solid biofuels worldwide. Assuming fuel savings from 30-60% (Jetter and Kariher, 2009; Berrueta et al 2008) and average energy use of 40 GJ/HH/yr for cooking with open fires, the technical energy mitigation potential ranges from 10-17 EJ/yr (GEA, 2010). The reduction in fuelwood and charcoal use from the adoption of ICS will help reduce the pressure on forest and agriculture areas, with major benefits in terms of increasing aboveground biomass stocks, soil and biodiversity conservation (Ravindranath et al, 2006; Röther et al., 2010).

2.4.3 Global Trade in Biomass and Bioenergy

Global trade in biomass feedstocks (e.g. wood chips, vegetable oils and agricultural residues) and especially of processed bioenergy carriers (e.g. ethanol, biodiesel, wood pellets) is growing rapidly. Present estimates indicate that bioenergy trade is modest – around 1 EJ (about 2% of current bioenergy use) (Junginger et al. 2009). In the longer term, much larger quantities of these products might be traded internationally, with Latin America and Sub-Saharan Africa as potential net exporters and North America, Europe and Asia foreseen as net importers (Heinimö and Junginger, 2009). Trade will be an important component of the sustained growth of the bioenergy sector.

Table 2.4.1: Overview of global production and trade of the major biomass commodities in 2008. Source: Junginger et al. (2010 forthcoming)

	Bioethanol [b]	Biodiesel [c]	Wood pellets [d]
Global production in 2008 (million tonnes)	52.9	10.6	11.5
Global net trade in 2008 (million tonnes)[a]	3.72	2.92	Approx. 4
Main exporters	Brazil	USA, Argentina, Indonesia, Malaysia	Canada, USA, Baltic Countries, Finland, Russia
Main importers	USA, Japan, European Union	European Union	Belgium, Netherlands, Sweden, Italy

a. While biodiesel and wood pellets are almost exclusively traded as an energy carrier, bioethanol may also be used of in other end-uses. Approximately 75% of the traded bioethanol is used as transport fuel.
b. Based on FAPRI (2009), EurObserv'ER (2009) and Martinot and Sawin (2009)
c. Based on FAPRI (2009), Martinot and Sawin (2009), CARD (2008) and EurObserv'ER (2009)
d. Based on Sikkema et al. (2009), Bradley et al. (2009) and Spelter and Toth (2009).

In 2008, the two leading *ethanol* producers were the United States (26.8 million tonnes) and Brazil (21.3 million tonnes), accounting for 91% of the world production (FAPRI, 2009). The US is the largest bioethanol consumer: about 28.4 million tonnes in 2008, of which about 4.6% was imported. Brazilian consumption amounted to approximately 16.5 million tonnes. In the EU, total consumption for transportation was 2.6 million tonnes, the largest users being France, Germany, Sweden and The Netherlands (EurObserv'ER, 2009). Data related to fuel bioethanol trade are imprecise on account of the various potential end-uses of ethanol (i.e. fuel, industrial, and beverage use) and also because of the lack of proper codes for biofuels in the Harmonized System.

World *biodiesel* production increased six-fold from about 1.8 million tonnes in 2004 to about 10.6 million tonnes in 2008 (Martinot and Sawin, 2009). The EU produces about two-thirds of this, with

Germany, France, Italy and Spain being the top EU producers. European biodiesel production rose to 7.8 million tonnes in 2008, equivalent to a 35.7% increase compared to 2007 and 2008. However, EU production declined 7% in 2009 because of strong competition from abroad (FAPRI, 2009). Other main biodiesel producers include the United States, Argentina, and Brazil. Biodiesel consumption in the EU amounted to about 9.2 million tonnes (EurObserv'ER, 2009), with Germany alone consuming 2.9 million tonnes. International b*iodiesel trade h*as been increasing strongly since 2005 (EBB 2009c compared to net export about 1.175 million tonnes, FAPRI, 2009, EBB, 2009b).

Production, consumption and trade of *wood pellets* have grown strongly within the last decade. *Production* mainly takes place in Europe and North America. As a rough estimate, in 2008, about 8 million tonnes of pellets were produced in 30 European countries, compared to 1.8 million tonnes in the US and 1.4 million tonnes in Canada. *Consumption* is high in many EU countries and the US. The largest EU consumers are Sweden (1.8 million tonnes), Denmark, the Netherlands, Belgium, Germany and Italy (all roughly one million tonnes). The first intercontinental wood pellet *trade* has been reported in 1998, for a shipment from British Columbia (Canada) to Sweden. Since then, Canada has been a major exporter to Europe (especially Sweden, the Netherlands and Belgium) and to the US. In 2008, the US started to export wood pellets to Europe, while Canadian producers started to export to Japan. Total imports of wood pellets by European countries in 2009 were estimated to be about 3.4 million tonnes, of which about half of it can be assumed to be intra-EU trade. Total export is estimated at 2.7 million tonnes, predominantly intra –EU trade.

2.4.4 Overview of support policies for biomass and bioenergy

Typical examples of support policies for *liquid biofuels* include the Brazilian Proálcool program, the Common Agricultural Policy (CAP) in the EU, and several farm bills and state and federal incentives for ethanol production in the US (WWI, 2006). The majority of successful policies in biomass for *heat* in recent decades have focused on more centralised applications for heat or combined heat and power, in district heating, and industry (Bauen et al., 2009c). For these sectors, a combination of direct support schemes with indirect incentives has been successful in several countries, such as Sweden (Junginger, 2007). In the *power sector*, feed-in tariffs have gradually become the most popular incentive for bioenergy and for renewables in general. In contrast, quota systems have so far been less successful in getting renewables (and bioenergy) off the ground (van der Linden et al., 2005). Next to feed-in tariffs or quotas, almost all countries that have successfully stimulated bioenergy development have applied additional incentives relating to investment support, such as fiscal measures or soft loans (GBEP, 2007). Additionally, grid access for renewable power is an important issue that needs to be addressed. This can be a particular bottleneck for distributed, medium-scale technologies such as biogas-to-power. Priority grid access for renewables is applied in most countries where bioenergy technologies have been successfully deployed (Sawin, 2004).

The main drivers behind government support for the sector have been concerns over climate change and energy security as well as the desire to support the farm sector through increased demand for agricultural products (FAO, 2008). According to the REN21 global interactive map, a total of 69 countries had one or several biomass support policies in place in 2009 (REN21, 2010). These include Canada and the US, most Latin American countries, all EU countries, China, India, many South-East Asian countries, and Australia. On the other hand, in the Near- and Middle East and many African countries, no biomass support policies are currently implemented. The most dominant support policies are feed-in tariffs for electricity (in 41 countries) followed by biofuels blending mandates (29) as shown in Figures 2.4.5. Other instruments included hot water/heating policies (21), public investments, loans or financing (17), tradable renewable energy certificates (17), sales tax, energy excise tax or VAT exemption (16), capital subsidies, grants or rebates (13), investment tax credits (11), energy production payments / production tax credits (9) and public competitive bidding (7). In Table 2.4.2 an overview of current policies is listed for electricity, heat and transport fuels.

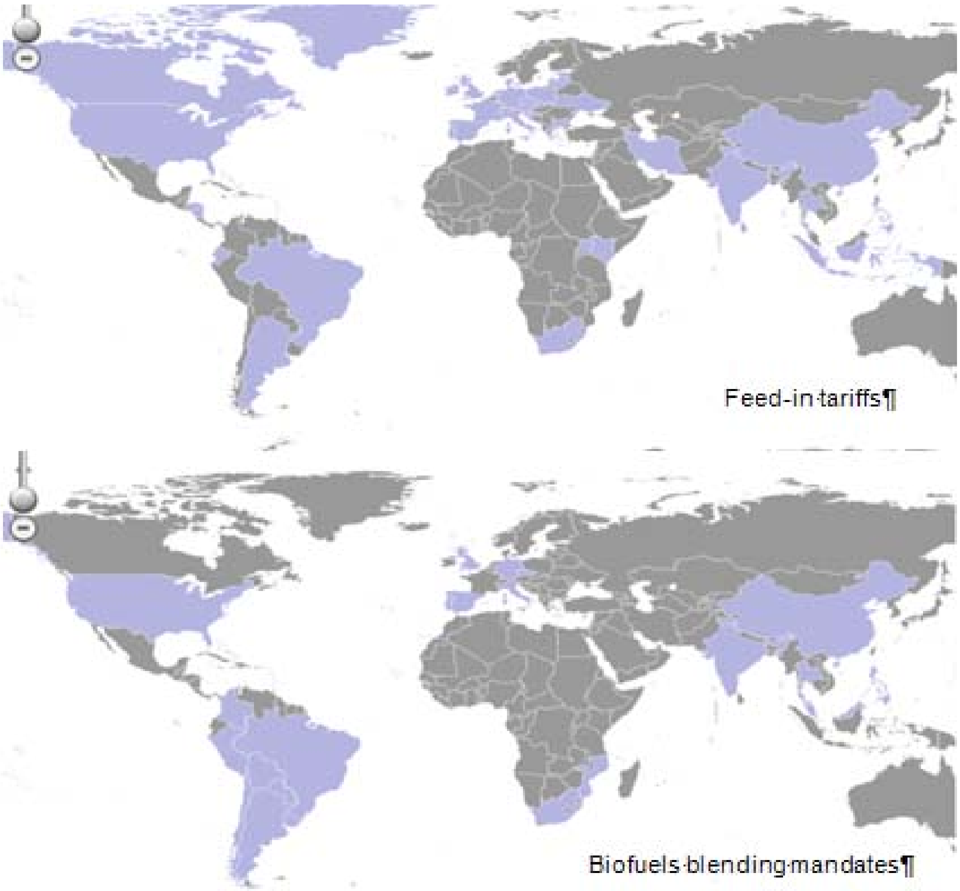
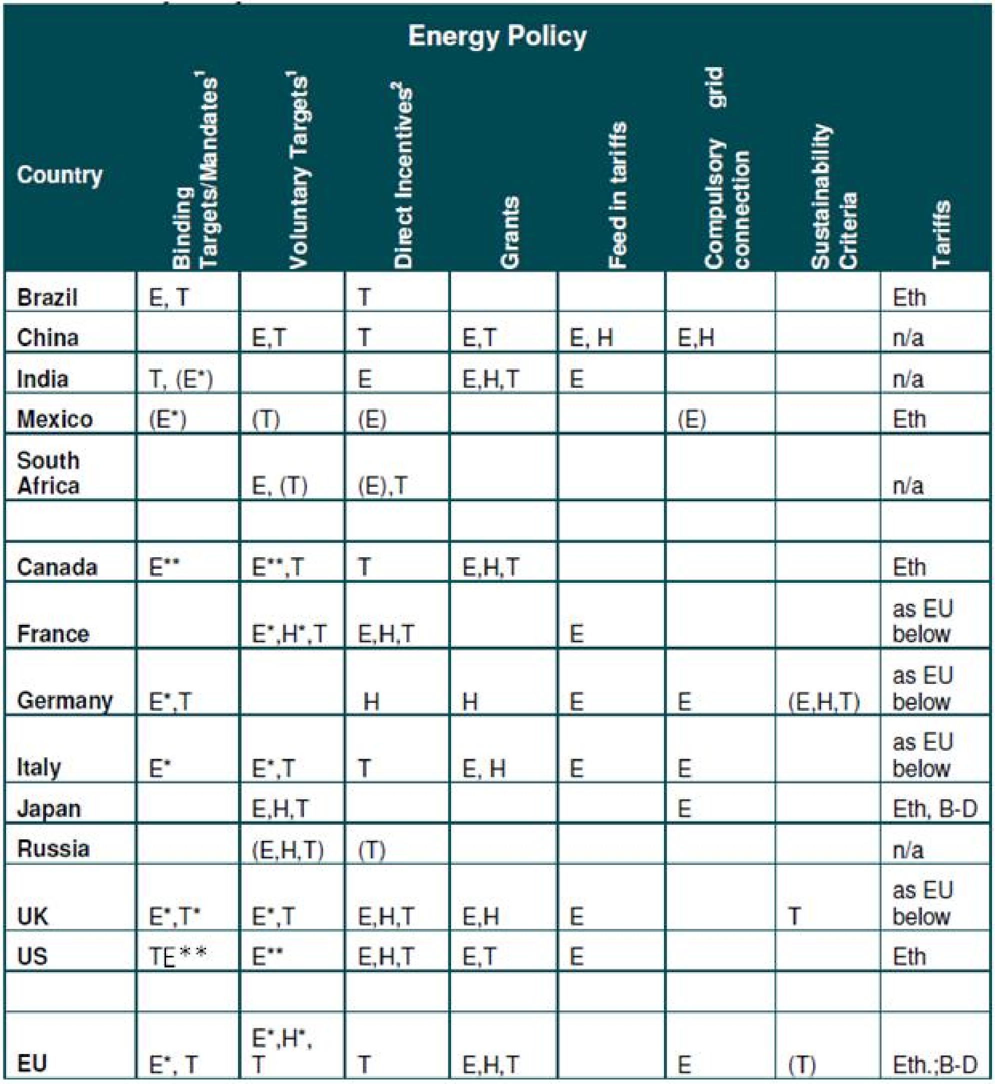


Figure 2.4.6: Global overview of feed-in tariffs for electricity from biomass and biofuels blending mandates in place in 2009. Source: Ren21 (2010).

Support policies have strongly contributed in past decades to the growth of bioenergy for electricity, heat and transport fuels. However, several reports also point out the costs and risks associated with support policies for biofuels. As an estimate in 2006, about 11.3 billion US$ were spent on subsidies for liquid biofuels in OECD countries, of which the vast majority in the US (6.33 billion US$ driven by energy security and import fossil fuel reduction) and the EU (4.7 billion US$) (FAO, 2008). Concerns about food prices, greenhouse-gas emissions, and environmental impacts have also seen many countries rethinking biofuels blending targets. For example, Germany revised downwards its blending target for 2009 from 6.25% to 5.25% (IEA, 2009). Although seemingly effective in supporting domestic farmers, the effectiveness of biofuel policies in reaching the climate-change and energy security objectives is coming under increasing scrutiny. In most cases, these policies have been costly and have tended to introduce new distortions to already severely distorted and protected agricultural markets – at the domestic and global levels. This has not tended to favour an efficient international production pattern for biofuels and their feedstocks (FAO, 2008). On the other hand, energy and fossil fuels contribute to these distortions. These arguments are reiterated by a recent UNEP report (Bringezu et al., 2009), which warns that uncoordinated targets for renewables and biofuels without an overall biomass strategy may enhance competition for biomass. An overall biomass strategy would have to consider all types of use of food and non-food biomass (Bringezu et al., 2009).

Table 2.4.2 Key policy instruments in selected countries where E: electricity, H: heat, T: transport, Eth: ethanol, B-D: biodiesel (modified after GBEP 2007 and REN21 2010)



	Energy Policy							
Country	Binding Targets/Mandates[1]	Voluntary Targets[1]	Direct Incentives[2]	Grants	Feed in tariffs	Compulsory grid connection	Sustainability Criteria	Tariffs
Brazil	E, T		T					Eth
China		E,T	T	E,T	E, H	E,H		n/a
India	T, (E*)		E	E,H,T	E			n/a
Mexico	(E*)	(T)	(E)			(E)		Eth
South Africa		E, (T)	(E),T					n/a
Canada	E**	E**,T	T	E,H,T				Eth
France		E*,H*,T	E,H,T		E			as EU below
Germany	E*,T		H	H	E	E	(E,H,T)	as EU below
Italy	E*	E*,T	T	E, H	E	E		as EU below
Japan		E,H,T				E		Eth, B-D
Russia		(E,H,T)	(T)					n/a
UK	E*,T*	E*,T	E,H,T	E,H	E		T	as EU below
US	TE**	E**	E,H,T	E,T	E			Eth
EU	E*, T	E*,H*, T	T	E,H,T		E	(T)	Eth.;B-D

* target applies to all renewable energy sources

** target is set at a sub-national level

1. blending or market penetration

2. publicly financed incentives: tax reductions, subsidies, loan support/guarantees

2.4.4.1 Intergovernmental Platforms for Exchange on Bioenergy Policies and Standardization

Several multistakeholder initiatives exist in which policy makers can find advice, support, and the possibility to exchange experiences on policy making for bioenergy. Examples of such international organizations and fora supporting the further development of sustainability criteria and methodological frameworks for assessing GHG mitigation benefits of bioenergy include the Global Bioenergy Partnership (GBEP from the G8+5), the IEA Bioenergy, the International Bioenergy Platform at FAO (IBEP); the OECD Roundtable on Sustainable Development; and standardization organizations such as European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) are active working toward the development of standards.

The Global Bioenergy Partnership (GBEP) provides a forum to inform the development of policy frameworks, promote sustainable biomass and bioenergy development, facilitate investments in bioenergy, promote project development and implementation, and foster R&D and commercial bioenergy activities. Membership includes individual countries, multilateral organizations, and associations (www.globalbioenergy.org).

The International Energy Agency (IEA) Bioenergy Agreement provides an umbrella organisation and structure for a collective effort in the field of bioenergy. It brings together policy makers, decision makers, and national experts from research, government and industry across the member countries. (www.ieabioenergy.com)

2.4.4.2 Sustainability frameworks and standards

Governments are stressing the importance of ensuring sufficient climate change mitigation and avoiding unacceptable negative effects of bioenergy as they implement regulating instruments. Examples include the new Directive on Renewable Energy in the EU (Directive 2009/28/EC); UK Renewable Transport Fuel Obligation; the German Biofuel Sustainability Ordinance; the U.S. Energy Independence and Security Act and the California Low Carbon Fuel Standard. The development of impact assessment frameworks and sustainability criteria involves significant challenges in relation to methodology and process development and harmonization.

As of a 2010 review, there are nearly 70 ongoing certification initiatives to safeguard the sustainability of bioenergy (van Dam et al., 2010 forthcoming). Most recent initiatives are focused on the sustainability of liquid biofuels including primarily environmental principles, although some of them such as the Council for Sustainable Biomass Production and the Better Sugarcane Initiative (BSI) include explicit socio-economic impacts of bioenergy production, and many others such as the Roundtable for Sustainable Biofuels (RSB) and the Roundtable for Responsible Soy, include social criteria as well. Principles such as those from the RSB have already led to a Biofuels Sustainability Scorecard used by the Interamerican Development Bank for the development of projects. The proliferation of standards that took place over the past three years, and continues, shows that certification has the potential to influence direct, local impacts related to environmental and social effects of direct bioenergy production. Many of the bodies involved conclude that for an efficient certification system there is a need for further harmonization, availability of reliable data, and linking indicators on a micro, meso and macro levels. Considering the multiple spatial scales, certification should be combined with additional measurements and tools on a regional, national and international level. The role of bioenergy production on indirect land use change (iLUC) is still very uncertain and current initiatives have rarely captured impacts from iLUC in their standards and the time scale becomes another important variable in assessing such changes (see Section 2.5). Addressing unwanted LUC requires first of all sustainable land use production and good governance, regardless of the end-use of the product or of the feedstocks.

2.4.5 Main opportunities and barriers for the market penetration and international trade of bioenergy

The main drivers behind the development of bioenergy in many OECD countries have been concerns over increasing and strongly fluctuating oil prices and consequent concerns regarding energy security and fuel diversification, climate change mitigation through a reduction in greenhouse gas emissions and a desire to support rural areas and promote rural development. To emphasize this point, global CPI deflated values of March 2008 compared to January of 1998, show an increase of nearly 500% for oil prices while food increased 36% and the non-food biomass raw materials (cotton, wool, timber, and leather) went down about 10% (Velasco, 2008). Additionally, the prospects for biofuels depend on developments in competing low-carbon and oil-reducing technologies for road transport (e.g., electric vehicles). Finally, biofuels may in the longer term be increasingly used within the aviation industry, for which high energy density carbon fuels are necessary (see Section 2.6).

However, major risks and barriers to deployment are found all along the bioenergy value chain and concern all final energy products (bioheat, biopower, and biofuel for transport)[3]. On the supply side, there are challenges in relation to securing quantity, quality, and price of biomass feedstock irrespective of the origin of the feedstock (energy crops, wastes, or residues). There are also technology challenges related to the varied physical properties and chemical composition of the biomass feedstock, and challenges associated with the poor economics of current power and biofuel technologies at small-scales. On the demand side, some of the key factors affecting bioenergy deployment are cost-competitiveness, stability and supportiveness of policy frameworks, and investors' confidence in the sector and its technologies, in particular to overcome financing challenges associated with demonstrating the reliable operation of new technologies at commercial scale. Some governments have jointly financed first-of-a-kind commercial technological development with the private sector in the past five years but the financial crisis is making it difficult to complete the private financing needed. In the power and heat sectors, competition with other renewable energy sources may also be an issue. Public acceptance and public perception are also critical factors in gaining support for energy crop production and bioenergy facilities.

As pointed out in section 2.4.3, international bioenergy trade is increasing rapidly. The development of truly international markets for bioenergy has become an essential driver to develop available biomass resources and bioenergy potentials, which are currently underutilised in many world regions. This is true for both (available) residues as well as possibilities for dedicated biomass production (through energy crops or multifunctional systems such as agro-forestry). The possibilities to export biomass-derived commodities for the world's energy market can provide a stable and reliable demand for rural communities in many (developing) countries, thus creating an important incentive and market access that is much needed in many areas in the world. The same is true for biomass users and importers that rely on a stable and reliable supply of biomass to enable (often very large) investments in infrastructure and conversion capacity. Fair trade concept and sustainability challenges need to be resolved before biomass reaches global markets as an energy commodity. Some of the issues have been listed below.

2.4.5.1 Opportunities and drivers for international bioenergy trade

1. Raw material/biomass push. These drivers are found in most countries with surplus of biomass resources. Ethanol export from Brazil and wood pellet export from Canada are examples of successful push strategies. These inexpensive resources may also become available due to (unexpected) economic events. For example, the recent decline of the US housing market led to low prices for wood products, which in turn triggered the establishment of very large pellet plants on the south-east coast of the US, using timbers as feedstock for pellet production dedicated for export to Europe.

2. Market pull. Import of wood pellets to countries such as the Netherlands and Belgium is facilitated by the very suitable structure of the leading large utility companies, making efficient transport and handling possible and low fuel costs.

3. Utilizing the established logistics of existing trade. Most of the bioenergy trade between countries in Northern Europe is conducted in integration with the trade in forest products. The most obvious example is bark, sawdust, and other residues from imported roundwood. However, other types of integration have also supported bio-energy trade, such as use of ports and storage facilities, organizational integration, and other factors that kept transaction costs low even in the initial

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[3] The remainder of this paragraph is taken from Bauen et al. (2009).

phases. Import of residues from food industries to the UK and the Netherlands are other examples in this field.

4. Effects of incentives and support institutions. The introduction of incentives based on political decisions is a driving force and triggered an expansion of bioenergy trade. However, the pattern has proved to be very different in the various cases, due partly to the nature of other factors, partly to the fact that the institutions related to the incentives are different. Institutions fostering general and free markets such as CO_2 taxes on fossil fuels appear to be more successful than specific and time-restricted support measures.

2.4.5.2 Barriers for international bioenergy trade

On the basis of literature review, a number of barriers for international bioenergy trade have been identified. Junginger et al. (2008, 2010) have listed the main barriers as follows:

1. Tariff barriers. Especially for ethanol and biodiesel, import tariffs apply in many countries. Tariffs are applied on bioethanol imports by both by EU (0.192 € per litre) and the US (0.1427 US$ per litre and an additional 2.5% ad valorem). In general, the most-favoured nation (MFN) tariffs range from roughly 6% to 50% on an ad valorem equivalent basis in the OECD, and up to 186% in the case of India (Steenblik, 2007). Biodiesel used to be subject to lower import tariffs than bioethanol, ranging from 0% in Switzerland to 6.5% in the EU and the USA. Tariffs applied by developing countries are generally between 14% (e.g., Brazil although Brazil lifted its tariff in 2010) and 50% (Steenblik, 2007). However, in July 2009, the European Commission confirmed a five-year temporary imposition of antidumping and anti-subsidy rights on American biodiesel imports, with fees standing between €213 and €409 per tonne (EurObserv'ER, 2009). These trade tariffs were a reaction to the so-called "splash-and –dash' practice, in which biodiesel blended with a 'splash' of fossil diesel was eligible for a $1/ gallon (equivalent to $300 per tonne).

2. Technical standards / Technical barriers to trade. Technical standards describe in detail the physical and chemical properties of fuels. Regulations pertaining to the technical characteristics of liquid transport fuels (including biofuels) exist in all countries. These have been established in large part to ensure the safety of the fuels and to protect consumers from buying fuels that could damage their vehicles' engines. Regulations include: maximum percentages of biofuels which can be blended with petroleum fuels; and regulations pertaining to the technical characteristics of the biofuels themselves. The latter may in the case of biodiesel depend on the vegetables oils used for the production, and thus might be used to favour biodiesel from domestic feedstocks over biodiesel from imported feedstocks. In practice, most market actors have indicated that they see technical standards as an opportunity enabling international trade rather than a barrier (Junginger et al., 2010; see also Section 2.4.7.8).

3. Sustainability criteria and certification systems for biomass and biofuels. In the past years, binding legislation on sustainability criteria for the production of biofuels was scarce. With the recent publication of sustainability criteria in the Renewable Energies Directive (RED) (European Commission, 2009) for liquid transport fuels, this situation has changed. The directive notably provides requirements for greenhouse gas emission reductions, the biofuels in question must not be produced from raw materials being derived from land of high value in terms of biological diversity or high carbon stocks. Also in the USA, the Renewable Fuel Standard (RFS) - included in the 2007 Energy Independence and Security Act (EISA) - provides provisions on the promotion of biofuels (especially cellulosic biofuels). EISA mandates minimum GHG reductions from renewable fuels, discourages use of food and feed crops as feedstock, permits use of cultivated land and discourages (indirect) land-use changes and sets thresholds for GHG reductions including major international land use change impact. Certification topics were discussed above. Regarding the development of sustainability criteria and certification systems, two major concerns in relation to international bioenergy trade may be distinguished:

1) Criteria, especially related to environmental and social issues, could be too stringent or inappropriate to local environmental and technological conditions in producing developing countries. The fear of many developing countries is that if the selected criteria are too strict or are based on the prevailing conditions in the countries setting up the certification schemes, only producers from those countries may be able to meet the criteria, thus these criteria may act as trade barriers. Recognizing this problem, the RSB is conducting pilot studies to assess the impact of such criteria for developing countries. Some view such criteria as a form of "green imperialism". As the criteria are extremely diverse, ranging from purely commercial aims to rainforest protection, there is a danger that a compromise could result in overly detailed rules that lead to compliance difficulties, or, on the other hand, in standards so general that they become meaningless. Implementing binding requirements is limited by WTO rules.

2) The second issue is the possible proliferation of different technical, environmental and social sustainability standards for biofuels production discussed above. With current developments by the European Commission, different European governments, several private sector initiatives, initiatives of round tables and NGO’s, there is a real risk that in the short term a multitude of different and partially incompatible systems will arise. If there are too many schemes in operation, each including a different set of requirements, then compliance, especially by small producers in developing countries, may become difficult. If they are not developed globally or with clear rules for mutual recognition, such a multitude of systems could potentially become a major barrier for international bioenergy trade instead of promoting the use of sustainable biofuels production. Additionally, lack of international systems may cause market distortions.

4. Logistical barriers. When setting up biomass fuel supply chains for large-scale biomass systems, logistics are a pivotal part of the system. Various studies have shown that long-distance international transport by ship is feasible in terms of energy use and transportation costs (e.g., Sikkema et al., 2010) but availability of suitable vessels and meteorological conditions (e.g., winter time in Scandinavia and Russia) need be considered. One of the problems of logistical barriers is a general lack of technically mature pre-treatment technologies in compacting biomass at low cost to facilitate transport, although technologies are developing (see Section 2.6).

5. Sanitary and phytosanitary (SPS) measures. Feedstocks for liquid biofuels may face sanitary and phytosanitary (SPS) measures or technical regulations applied at borders. SPS measures mainly affect feedstocks which, because of their biological origin, can carry pests or pathogens. One of the most common forms of SPS measure is a limit on pesticide residues. Meeting pesticide residue limits is usually not difficult, but on occasion has led to the rejection of imported shipments of crop products, especially from developing countries (Steenblik, 2007).

2.4.6 Final Remarks

The review of developments in biomass use, markets and policy shows that bioenergy has seen rapid developments over the past years. Bionergy use is growing, in particular biofuels (37% increase from 2006 to 2009). Projections from IEA, among others, but also many national targets count on biomass delivering substantially increase the share of renewable energy. International trade of biomass and biofuels has also become much more important over the recent years, with roughly 10% of all biofuels produced traded internationally and even a third of all pellet production for energy use (Junginger et al., 2010). The latter has proven to be an important facilitating factor in both increased utilisation of biomass in regions where supplies are constrained as well as mobilising resources from areas where demand is lacking. Nevertheless, many barriers remain in developing well working commodity trading of biomass and biofuels that at the same time meets sustainability criteria.

The policy context for bioenergy and in particular biofuels in many countries has changed rapidly and dramatically in recent years. The debate on food vs. fuel competition and the growing concerns about other conflicts haver resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second generation biofuel options does drive bioenergy to more sustainable directions.

Although this section did not evaluate the effectiveness of different policy strategies around bioenergy and biofuels, leading nations like Brazil, Sweden, Finland and the US, have shown that persistent policy and stable policy support is a key factor in building biomass production capacity and working markets, required infrastructure and conversion capacity that gets more competitive over time (see also section 2.7) and results in considerable economic activity.

Countries differ in their priorities, approaches, technology choices and support schemes for developing bioenergy further. Although on the one hand complex for the market, this is also a reflection of the many aspects that affect bioenergy deployment; agriculture and land-use, energy policy & security, rural development and environmental policies. Priorities, stage of development and physical potential and resource availability differ widely from country to country and for different settings.

One overall trend is though that policies surrounding bioenergy and biofuels become more holistic, taking sustainability demands as a starting point. This is true for the EU and the US, China, but also many developing countries such as Mozambique and Tanzania. This is a positive development, but by no means settled (see also section 2.5). The so far registered 70 initiatives worldwide to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels lead to a fragmentation of efforts (van Dam et al., 2010). The need for harmonization and international collaboration and dialogue (e.g., via the Global Bioenergy Partnership) is widely stressed at present.

2.5 Environmental and Social Impacts[4]

Studies have recently highlighted environmental and socio-economic positive and negative effects associated with bioenergy. Land use changes related to agriculture and forestry play a major role in determining positive or negative outcomes (IPCC, 2000; MEA, 2005). Bioenergy can exacerbate negative impacts already of conventional agriculture and forestry systems, which include soil and vegetation degradation arising from overexploitation of forests, too intensive crop residue removal, water overexploitation, food commodity price volatility, and displacement of farmers lacking legal land ownership. But bioenergy can also lead to positive effects such as the environmental benefits derived from integrating different perennial grasses and woody crops into agricultural landscapes, including enhanced biodiversity (Baum et al., 2009; Schulz et al., 2009), soil carbon increase and improved soil productivity (Tilman, 2006; Baum et al., 2009b), reduced shallow landslides and local ‘flash floods’, reduced wind and water erosion and reduced volume of sediment and nutrients transported into river systems (Börjesson and Berndes, 2006). Forest residue harvesting improves forest site conditions for replanting, and thinning generally improves the growth and productivity of the remaining stand and can reduce wildfire risk. (Dymond et al., 2010).

Few universal conclusions of the socio-economic and environmental implications of bioenergy can currently be drawn, given the multitude of existing and rapidly evolving bioenergy sources,

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[4] As bioenergy is a part of the overall agriculture, forestry, and related systems, space restrictions prevent complete literature coverage of environmental and social aspects. Examples of key references may be applicable to many places in the text.

complexities of physical, chemical, and biological conversion processes to multiple energy products, and the variability in site specific environmental conditions. Factors determining merits and associated impacts are a function of the socio-economic and institutional context of biomass feedstocks and bioenergy production and utilization; types of lands used and feedstock types; the scale of bioenergy programs and production practices; conversion processes used including process energy; and the rate of implementation (see, for instance, The Royal Society, 2008; Firbank, 2008; Convention on Biodiversity, 2008; Gallagher, 2008; Howarth et al., 2009; Kartha, 2006; Purdon et al., 2009; Rowe et al., 2008; OECD, 2008; Pacca and Moreira, 2009).

Bioenergy system impact assessments (IAs) must be compared to the IAs of replaced systems – usually based on fossil fuels, but could be based on other primary energy sources (see Table 2.5.1). Methodologies for the assessments of environmental (Sections 2.5.2 and 2.5.3) and socio-economic (Section 2.5.4) effects differ. One particular challenge for socio-economic IAs is that their boundaries are difficult to quantify and are a complex composite of numerous, sometimes unknown, directly or indirectly interrelated factors, many of which are poorly understood. Social processes have feedbacks difficult to clearly recognize and project with an acceptable level of confidence. Environmental IAs manage many quantifiable impact categories but face lack of data and uncertainty in many areas. The outcome of environmental IAs depends on methodological choices – which are not yet standardized and uniformly applied throughout the world.

Table 2.5.1: Environmental and socio-economic impacts: example areas of concern with selected impact categories

Example areas of concern	**Examples of Impact categories**
Economic and occupational status	Displacement of population or relocation in response to employment opportunities; property values, distribution patterns of services
Social pattern or life style	Resettlement; rural depopulation; population density changes; food and material goods, housing; rural-urban; nomadic-settled
Social amenities and relationships including psychological features	Family life styles; schools; hospitals; transportation; participation-alienation; stability-disruption; freedom of choice; involvement; frustrations; commitment; local/national pride-regret
Physical amenities including. biodiversity and aesthetic features	Wildlife and national parks; aesthetic values of landscape; wilderness; vegetation and soil quality; local/regional air quality; water availability and quality; cultural buildings; sentimental values
Global/regional (off site) effects	Greenhouse gases; black carbon; albedo; acidification; eutrophication; hydrological changes
Health	Human Health changes; medical standard
Cultural, religion, traditional beliefs	Values and value changes; taboos; heritage; religious and traditional rites
Technology	Hazards; emissions; congestion; safety; genetically modified organisms, plants
Political and legal	Authority and structure of decision making; administrative management; level and degree of involvement; resource allocation; local/minority interests; priorities; public policy

2.5.1 Environmental effects

2.5.1.1 Methodologies for assessing environmental effects

Studies of environmental effects usually employ methodologies generally in line with the ISO 14040:2006 and 14044:2006 standards for Life Cycle Assessments (LCA) that underpin the principles, framework, requirements and guidelines for conducting an LCA study. LCA quantifies general environmental effects rather than for a specific bioenergy project, but LCAs can also be suitable for evaluating multiple technologies using the same feedstocks, for evaluating technology development (Wang, 2007), and for project impact statements (e.g., DOE, 2010). The conventional methodology for the assessment of the effects of bioenergy systems compared to their substitutes is attributional while consequential LCA requires auxiliary tools such as economic, biophysical, and land-use models to evaluate the consequences of bioenergy options. These model couplings involve higher uncertainties. Complementary insights into climate benefits can be obtained from energy system models – with or without linked land-use models – where the mitigation benefit is evaluated from a total energy system perspective considering a range of fossil as well as competing renewable energy options. In addition to comprehensive LCAs, there are studies with a bifurcated focus on energy balances and GHG emissions balances (e.g., Fleming et al., 2006; Larson, 2006, von Blottnitz and Curran, 2006; Zah, 2007; OECD, 2008; Rowe et al., 2008; Menichetti and Otto, 2009). A specific methodology for assessing GHG balances of biomass and bioenergy systems has also been developed since the late 90s (Schlamadinger et al., 1997).

Assessment results need to be analyzed in the context of specific locations considering natural conditions and industrial/institutional capacity. Water use is one such instance. In some locations with scarce water availability, production processes that consume large volumes of water can be problematic; other locations with plenty of water this is less of an issue; and often these results are compared with fossil energy production water consumption (Berndes, 2002; Wu et al., 2009; Fingerman et al., 2010, Rost et al., 2009). Technical solutions for effluent management are available but are under used because of lax environmental regulation or limited law enforcement capacity. Major reduction in sugarcane ethanol plants' effluent discharge into rivers in Brazil is illustrates the importance of institutions in determining impacts of bioenergy projects (Peres et al., 2007).

Most assumptions and data used in LCA studies are related to conditions in Europe or USA, but studies are becoming available for other countries such as Brazil and China (see Table 2.3.2 and 2.6.3). Most studies have concerned biofuels for transport from conventional food/feed crops. Prospective bioenergy options (e.g., biofuels derived from lignocellulosic biomass and biomass gasification routes, albeit less studied, and their assessment via the LCA process involves projections of performance of developing technologies that are at various stages of development and have greater uncertainties (see Figure 2.3.1). Despite following ISO standards, a wide range of results has been reported for the same fuel pathway, even holding temporal and spatial considerations constant (Fava, 2005). The variations may be attributed to actual differences in the systems being modeled but are also due to differences in method interpretation, assumptions, and data. Emissions performance technology is dated by the time of publication, and learning has occurred in process energy efficiency and feedstock productivity with rapid industry expansion, as illustrated in Table 2.5.2 for corn and sugarcane ethanol and in Table 2.3.5 for a variety of countries and systems and Table 2.6.3 for developing technologies, when available.

Key issues in bioenergy LCAs are system definition including spatial and dynamic system boundary, definition of functional unit, reference flows and indicators, and the selection of allocation methods for energy and material flows over the system boundary (Soimakallio et al., 2009a). Differences in co-products treatments has impacted LCA study results, although harmonized data have much less uncertainty. The handling of uncertainties and sensitivities related to data for parameter sets used may have significant impact on the results (see, e.g., Kim and Dale, 2002; Farrell et al., 2006; Larson, 2006; von Blottnitz and Curran, 2006; OECD, 2008; Rowe et al., 2008; Börjesson, 2009; Soimakallio et al., 2009b; Wang et al., 2010).

Many biofuel production processes create multiple products. Bioenergy systems can be part of biomass cascading cycles in which co-products and biomaterial itself are used for energy after their useful life. This process introduces significant data and methodological challenges, including consideration of space and time aspects since environmental effects can be distributed over decades and different geographical locations (Mann and Spath, 1997; Cherubini and Jungmaier, 2009). Studies combining several LCA models and/or Monte Carlo analysis can provide quantification with information about confidence information on some bioenergy options or indicate what most important parameters are for minimization and optimization of developing processes (e.g., Soimakallio et al., 2009; Hsu et al., 2010).

2.5.1.2 Environmental effects related to climate change

Production and use of bioenergy influences global warming through (i) emissions from the bioenergy chain including non-CO2 GHG and fossil CO2 emissions from auxiliary energy use in the biofuel chain; (ii) GHG emissions related to changes in biospheric carbon stocks often – but not always – caused by associated LUC; (iii) other non-GHG related climatic forcers including changes in surface albedo; particulate and black carbon emissions from small-scale bioenergy use; and aerosol emissions associated with forests. The net effect is the difference between the influence of the bioenergy system and of the – often fossil based – energy system that is replaced. LUC and biospheric carbon stock changes are to a greater extent linked to bioenergy because of its close association with agriculture and forestry. However, current fossil energy chains and evolving non-conventional sources have land-use impacts detailed by Gorissen et al. (2010) including indirect impacts, such as for ensuring Middle Eastern petroleum flow (Liska and Perrin, 2009)

Different limiting resources may define the extent to which land management and biomass fuels can mitigate GHG emissions, making different indicators relevant in different contexts, two examples of which are shown in Figure 2.5.1 as GHG reductions per output bioenergy delivered either as heat or electricity, or in combined form. For transportation applications, the more appropriate metric is a distance driven per bioenergy delivered. Schlamadinger et al. (2005) proposed indicators to maximize GHG emission reductions when biomass, demand for bioenergy, and available land are the limiting factors. Useful indicators are the fossil Ceq emission displacement factor, which favors most efficient use of biomass and it allows external fossil inputs if they enhance biomass use efficiency. It can compare between outputs (electrity, heat, transport fuel, material substitution. The emission savings indicator favors biomass conversion processes with low GHG emissions but ignores the amount of biomass or land required. It cannot compare between different outputs (e.g., electricity and transport fuel). The emission savings per amount of land favors biomass yield and conversion efficiency. Greater GHG emissions from production may be acceptable if that increases biomass yield. It can compare different outputs. Another commonly used indicator is a function of how much primary fossil energy is used in the process per unit of biofuel energy output, but often, if the bioenergy chain coproduces electricity, the renewable credit is subtracted from the input. Indicators commonly lack consideration of the temporal dimension of biosphere carbon stocks changes: sustainable biomass production systems can temporarily involve substantial decreases in biosphere carbon stocks, long-rotation forestry being an illustrative example.

The above indicators are being used, for instance, to evaluate the individual technology options of two commercial ethanol cases production systems from sugarcane and from corn in Brazil and North America, showing substantial performance improvement ((S&T)2 Consultants Inc., 2009; Macedo et al., 2004, Macedo and Seabra, 2008; Seabra et al., 2010). These studies have provided substantive information on alternative functions for biorefinery development with time. Now it is necessary to complement the information with a more comprehensive analyses using integrated energy/industry/land use cover models for specific location studies (see, e.g., Leemans et al., 1996; Johansson and Azar, 2007; Van Vuuren, et al., 2007; Wise et al., 2009; Melillo et al., 2009). These can give insights into how an expanding bioenergy sector interacts with others in society, including land use and management of biospheric carbon stocks, and evaluate the importance of up-front emissions in the context of global climate targets and development pathways towards complying with such targets.

2.5.2 Climate change effects of modern bioenergy excluding the effects of land use change

Many studies have assessed the climate change effects of bioenergy and produce widely varying estimates of GHG emissions for biofuels (e.g., IEA, 2008; Menichetti and Otto, 2009) rapidly evolving bioenergy sources, complexities of physical, chemical, and biological conversion processes, feedstock diversity and variability in site specific environmental conditions – together with inconsistent use of methodology – complicate meta-analysis to produce valid quantification of the influence of bioenergy systems on climate. A recent meta-analysis explain some of the variability and compares a very wide range of production and utilization chains for many commercial and developing biofuels (Hoefnagels et al., 2010).

Efficient fertilizer strategies (minimizing N2O emissions) and the minimization of GHG emissions from the conversion process are essential for improving GHG savings. Process integration and the use of biomass fuels (e.g., bagasse, straw, wood chips), surplus heat from nearby energy or industrial plants can lead to low net GHG emissions from the conversion process. When evaluated using LCA, process fuel shifts from fossil fuels to using biomass or surplus heat can be attractive (Wang et al., 2007), but the marginal benefit of shifting depends on local economic circumstances and on how this surplus heat and biomass would otherwise have been used. Also, the GHG reduction per unit biomass used can be rather low when biomass is used as process fuel.

Crutzen et al (2007) proposed that N2O emissions from fresh anthropogenic N are considerably higher than what is obtained based on the IPCC's recommended tier 1 methodology and that N2O emissions from biofuels consequently have been underestimated by a factor of two to three. However, differences between IPCC tier 1 and Crutzen et al (2007) arise due to use of different accounting approaches. It is estimated that about one-third of agricultural N2O emissions are due to newly-fixed N fertilizer (Mosier et al. 1998). About two-third takes place as N is recycled internally in animal production or by using plant residues as fertilizer. Using the emission factors proposed by Crutzen et al. (2007) to calculate N2O emissions from N fertilization of a specific bioenergy plantation makes this bioenergy production responsible for all N2O emissions taking place subsequently, for part of the applied N is recirculated into other agriculture systems where it substitutes for other N input. Nevertheless, N2O emissions can have an important impact on the overall GHG balance of biofuels (Smeets et al., 2008; Soimakallio et al., 2009), though there are large uncertainties.

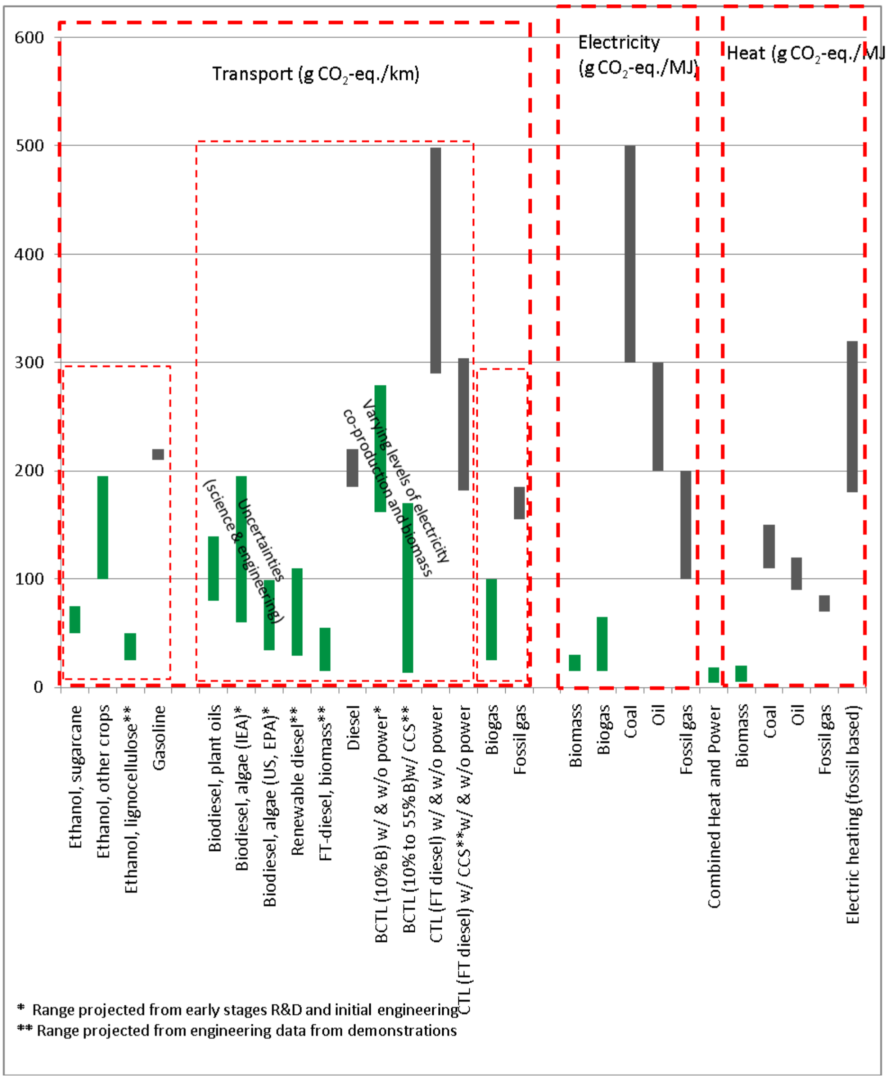

Figure 2.5.1. Ranges of emissions from major modern bioenergy chains compared to conventional and selected advanced fossil fuel energy systems. Commercial and developing systems for biomass and fossil technologies are illustrated. Data sources: Cherubini 2010; EPA 2010; Kalnes et al. 2009; Kreutz et al. 2008; van Vliet et al., 2009; Daugherty 2001.

2.5.3 Climate change effects of modern bioenergy including the effects of land use change

Conversion of natural ecosystems to biomass production systems and changes in land use can lead to changes in biospheric carbon stocks. Examples are change in production, for instance, from food to biofuel crops, or in management practice, such as reduced forest rotation periods and increased forest residue extraction. Such changes can also arise indirectly, e.g., when conversion of pastures to biofuel plantations in one place leads to conversion of natural ecosystems to new pastures elsewhere to compensate for the lost meat/dairy production. An opposite example is when degraded pastureland is moved into biofuel production and pasture management is improved so that the same area can sustain a higher density of cattle. The use of agriculture/forest residues, post-consumer waste and agriculture/forest industry by-flows can avoid land-use change, although it can occur if earlier users of these biomass sources switch to using primary biomass. Also, if left untouched (e.g., as residues in the forest), some of these biomass sources would keep organic carbon away from the atmosphere for a longer time than if used for energy.

The dynamics of terrestrial carbon stocks in LUC and long-rotation forestry leads to GHG mitigation trade-offs between biomass extraction and use for energy and the alternative to leave the biomass as a carbon store that could further sequester more carbon over time (Marland and Schlamadinger, 1997). The cultivation of biofuel crops on previous cropland taken out of production can lead to foregone carbon sequestration if the alternative would be natural or assisted conversion to grasslands or forests. Forests that are in stages of net carbon accumulation naturally lose this sink capacity if it is converted to another land cover type. Observations indicate that also very old forests can be net carbon sinks (Luyssaert et al. 2008, Lewis et al. 2009). The CO2 fertilization effect – elevated CO2 levels in the ambient air stimulate plant growth – is one possible explanation. Climate-C cycle models indicate that the CO2 fertilization effect can become weaker in the future and that the terrestrial biosphere may even become a carbon source in the final decades of the 21st century if atmospheric CO2 levels increase radically (Sitch et al. 2008).

The relative merits of the principal options, extraction for bioenergy vs. carbon storage, depend on (i) efficiency with which bioenergy can substitute for fossil fuels described by the displacement factor this efficiency is high if biomass is produced and converted efficiently, the replaced fossil fuel would have been used with low efficiency, and a carbon intensive fossil fuel is replaced; (ii) time period of consideration – the longer the timeframe of the analysis the more attractive is the bioenergy option, for only limited amounts of carbon can be stored on land but bioenergy can be produced repeatedly; (iii) growth rate of the site – the higher the growth rate, the sooner the saturation constraints of carbon sequestration will be reached, and (iv) prior use of the land (and thus its current carbon content)

Ambitious climate targets such as the 2°C degree stabilization with global GHG emissions peak within one decade (IPCC 2007, p. 15, Table SPM5) suggest use of fossil alternatives can provide near-term net GHG reductions. Many studies (for instance, Leemans 1996, Pacca and Moreira 2009) have demonstrated the significance of LUC and the care needed in the selection of specific sites of bioenergy projects to obtain near-term carbon mitigation benefits while contributing effectively on the longer term. Upfront emissions arising from the conversion of land to bioenergy production has been attention with indicators such as Carbon Debt (Fargione et al., 2008) which estimate the number of years until a net GHG reduction is obtained from a bioenergy initiative under specific conditions. The Ecosystem Carbon Payback Time (Gibbs et al. 2008 illustrates this concept graphically on Figure 2.5.2 – in one case, the scenario reflected global yields typical of the year 2000 agricultural system. From the initial land conversion to plantation significantly higher amount of time is required to reach net GHG reduction than if the global agricultural productivity increased 10% major crops. The biggest effects are for maize and castor; sugarcane, soybeans and oil palm were already high yielding and show a smaller impact. The figure does not include GHG savings from fossil fuel replacement that can improve the situation further. Of particular importance is the starred points that represent oil palm conversion onto peatlands with payback times of nearly a thousand years that are halved with an increase in plant productivity of 10%.

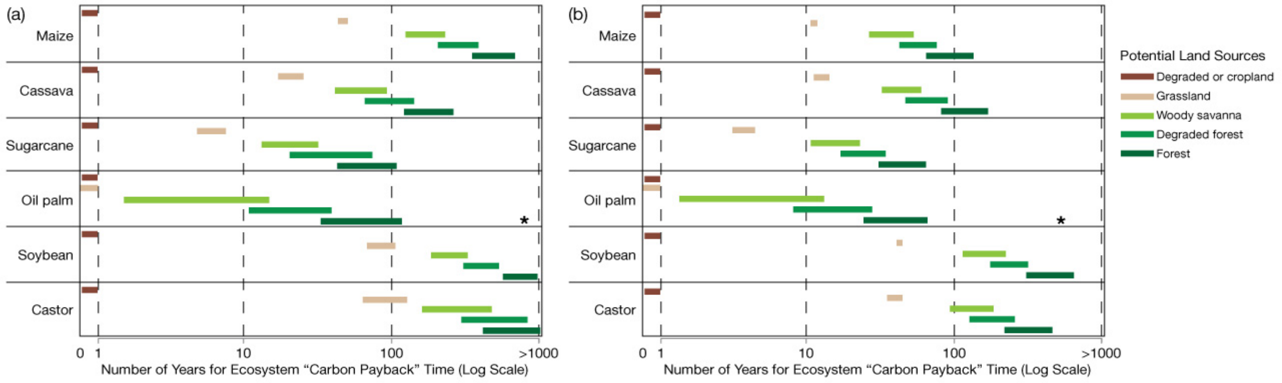

Figure 2.5.2. The ecosystem carbon payback time for potential biofuel crop expansion pathways across the tropics comparing the year 2000 agricultural system (a) with a scenario of 10% global crop increases (b).The “*” points represent oil palm crops grown in peatlands of more than 900-year payback time if oil palm expansion into peat forests of year 2000 productivity compared to 600 years for a 10% higher crop productivity (Gibbs et al., 2008)

The effects of LUC are complex and difficult to quantify with precision in relation to a specific bioenergy project because the causes of LUC are often multiple, complex, interlinked and time variable. The IPCC provides default values to consider effects of dLUC in LCA studies as well as a methodology to produce specific site estimates (IPCC 2006). However, it is preferable to use site specific data instead of general numbers for quantifying effects of dLUC in a specific case. Significant data need to be generated for such land conversions to obtain more precise dLUC values. The inclusion of iLUC in quantifications of LUC emissions adds an additional challenge. Hypotheses about indirect links between distant activities include: (i) deforestation in the Amazon region and sugarcane ethanol expansion far away in the SE of Brazil (Sparovek et al. 2009; Zuurbier and van de Vooren, 2008); (ii) increased biodiesel production from rape seed cultivated on the present cropland in Europe and increased deforestation for Palm oil in SE Asia (WWF 2007; RSPO, 2009, Reinhardt, 1991; BABCO, 2000); (iii) shift from soy to corn cultivation in USA and deforesting soy expansion in Brazil (Laurance, 2007); (iv) wheat based ethanol production in Europe reducing Amazonian deforestation by producing process by-products that substitutes imported soy feed (BABCO, 2000). Data obtained in the past three years have shed more light and did not substantiate all of the hypothesis above. The particulars of assumed scenarios need to be better founded on empirical evidence.

Presumably the faster the growth in the use of biomass for energy the higher the risk that bioenergy options will have high LUC emissions, unless mitigating measures becomes established or marginal lands are used. The extraction of temperate and boreal forest biomass can lead to near-term forest carbon stock reduction on stand level. Seen over larger areas and over longer time periods, the net carbon stock effects of increasing the use of forest bioenergy depends on how forest management evolves in response to increased bioenergy demand and other past and current pressures on forest conversion. Conclusions depend on systems definition and baseline assumptions in analyses – e.g., whether the temporal dimension includes a period before the actual biomass extraction to consider effects of different forest management regimes. A scenario involving increased forest bioenergy use and management regimes increasing forest stand growth (including growth of early thinning wood) can have higher net GHG benefit than a scenario where forest bioenergy demand is lower and management less.

The following summary of methodology and results illustrates strengths and weaknesses of assessment methodologies

2.5.3.1 Methodologies for Land Use Change Modeling

Methods used to estimate the global land use impacts of bioenergy utilization are under continuous development to address discovered weaknesses. Field measurements and model validation are needed to reduce uncertainties of analyses and models, and scenario development requires better documentation, analysis and inclusion of integrated production systems (Kline et al. 2009) (Dale et al. 2010). Existing methods for determining iLUC (often grouped with LUC) can be divided into two methods employing macro-economic/econometric and/or biophysical models and deterministic methods allocating global land-use change to respective fuels/feedstocks grown in a few specified land types (Fehrenbach et al., 2009). If specified land types were altered or key types absent, different carbon stock values (above and below ground) would be obtained over time (Amaral et al., 2009). Some recent research papers and reports that evaluate LUC or iLUC employing original methods (or significant variations) are listed in Tables 2.5.3

Results shown in first six rows of Table 2.5.3 use a combination of macro-economic/econometric models and/or biophysical models/data. Implementation of the use of these modelling systems generally proceeds in two phases. Global land use changes are calculated comparing results from scenarios with and without policy-induced increases in bioenergy. Then the impacts of iLUC are attributed to the appropriate fuel/feedstock as linked to via the economic system. Macroeconomic/econometric models combined with biophysical models/data are complex and resource intensive; they can be viewed as lacking transparency to non-modelers. Two studies utilizing these methodologies have conducted significant uncertainty analysis (EPA, 2010; Hertel et al., 2010).

Implementation of the use of these modelling systems generally proceeds in two phases. Global land use change estimates are derived from scenarios with and without policy-induced increases in bioenergy. Then the impacts of iLUC are attributed to the appropriate fuel/feedstock as linked to *via* the economic system. Macroeconomic/econometric models combined with biophysical models/data are complex and resource intensive; they can be viewed as lacking transparency to non-modelers. Two studies utilizing these methodologies have conducted significant uncertainty analysis (EPA, 2010; Hertel et al., 2010).

The recently released EPA results (2010) (see Table 2.5.3) resulted from a series of peer reviews and comments on initial modelling data (a similar review process is underway with CARB for ILUC determinations) (CARB 2010b). Among improvements EPA updated the Brazilian land use data, considering information provided by the Brazilian Land Use Model (BLUM, Nassar et al., 2009) combining remote sensing data, field data, and micro-regional modeling for inputs into a partial equilibrium model (FAPRI). With these inclusions changes in the elasticities of multiple crops across several land types were obtained for a series of larger regions for a more detailed picture of the dynamics of land use within Brazil. The major land-use change has been pasture intensification with use of degraded pastureland for biofuels derived from soya and sugarcane; also modelled are crop substitutions in the Cerrado and other regions (Nassar et al., 2009). Earlier modelling exploring the land-use consequences of increased use of U.S. corn for ethanol production used lower spatial resolution and did not include pastureland among land types covered, resulting in the conversion of forests to cropland for food and fuel production (Searchinger et al., 2008). As can be seen in Table 2.5.3, LUC estimates vary depending on model and scenario assumptions. Corn LUC results are converging with improvements in the models and their input data. Similarly, the high initial LUC values for sugarcane with low spatial resolution data (CARB) have decreased by factors of two to three (EPA and IFPRI) with improved land-use dynamics data in Brazil.

Some studies only proceed with the 1st portion of this analysis to focus on global or regional impacts and do not separate dLUC and iLUC (see, e.g., Fischer et al., 2009; Melillo et al., 2009; Wise et al., 2009)..

Papers and reports using the deterministic method for estimating iLUC are described in rows seven through nine of Table 2.5.2. This method assumes that additional biomass production will inherently lead to an increase in land use change, performs a calculation of total LUC impact using census/spatial data/measurements, and then allocates iLUC impacts among energy feedstocks/fuels. iLUC can be divided over a period of time and converted to various functional units to determine the impact of a feedstock or fuel on iLUC. Example approaches include Fritsche et al. (2009) and Tipper et al. (2009). The benefits of these deterministic methods are that they are simpler and more transparent to potential users. However, the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.

The models have the potential but have not been used, so far, to provide information about how much iLUC could decrease further as a result of (i) large increases in investments to enhance agriculture productivity growth and (ii) implementation of policies to protect C rich ecosystems.

Despite the differences between the method categories, specific methodologies, and remaining uncertainty surrounding estimates, there is a general convergence and trend towards lower estimates of LUC in more recent data, and an understanding of iLUC estimates from different models, although the extent of causal relationship biofuels and iLUC is still uncertain.

2.5.3.2 Climate change effects of traditional bioenergy

Traditional open fires and simple low efficiency stoves have a low combustion efficiency, producing large amounts of incomplete combustion products (CO, CH4, particle matter (PM), non-methane volatile organic compounds (NMVOCs), and others), with negative consequences for local air pollution and climate change (Smith et al. 2000). When biomass is harvested renewably— e.g., from standing tree stocks or agricultural residues - –most of the former CO2 emissions are sequestered as biomass re-growth. Worldwide, estimates are that household-fuel combustion causes approximately 30% of warming due to black carbon and carbon monoxide emissions from human sources, about a 15% of ozone-forming chemicals, and a few percent of methane and CO2 emissions (Wilkinson et al., 2009).

ICS GHG emissions are difficult to determine because of the wide range of fuel types, stove designs, cooking practices, and environmental conditions across the world but small-scale gasifier stoves and biogas stoves dramatically reduce short-lived GHG production up to 90% reletive to traditional stoves (Jetter and Kariher, 2009). Patsari improved stoves in rural Mexico saved between 3 and 9 tCO2-equivalent per stove-year relative to open fires, depending with or without renewable biomass harvesting conditions, respectively (Johnson et al., 2009). Wilkinson et al. (2009) estimated that advanced stove use, the dissemination of 150 million houses in a 10-yr program in India (a dissemination pace similar to that achieved in China in early 90s) may result in a mitigation of 0.5- 1 GtonCO2e, only from non-CO2 GHG.

Worldwide, using a unit GHG mitigation of 1-4 tonCO2e/stove/yr compared to the traditional open fires, the global mitigation potential of the advanced ICS was estimated at between 0.6-2.4 GtonCO2e/yr, without considering the effect of the potential reduction in black carbon emissions (GEA, 2010). Actual figures depend on biomass fuel renewability, stove and fuel characteristics, and the actual adoption and sustained used of the cookstoves.

Table 2.5.2. Summary of recent papers estimating iLUC by employing macroeconomic/ econometric and/or biophysical models/data for global and feedstock LUC estimates**.**

Reference	***LUC (d+i) Source Models/Methodology***	***Scenario Description***	***Land Conversion Types***	***LUC (d+i) Geographic Resolution***
U.S. Environmental Protection Agency (EPA) 2010 analysis of Renewable Fuel Standard 2 (RFS2) as required by the Energy Independence and Security Act (EISA) of 2007	**DAYCENT/CENTURY, FAPRI-CARD 2010, FASOM, GREET 1.8c, MODIS v5, and MOVES 2010** (Partial Equilibrium) FAPRI and GTAP v.6 models were compared with the same data (and sensitivity analysis). Results were consistent with the methodological differences between the models. FAPRI and FASOM provide higher resolution on crop expansion; GTAP total area. Projected impacts calculated for lignocellulosic biofuels technologies under development.	The "business as usual" volume of fuel is based on what would likely occur in 2022 without EISA. The control case assumed the EISA fuel mandate for 2022. For each individual biofuel, the incremental impact was analyzed while holding volumes of other fuels constant. Assumed levels of biofuels production of all countries at mandate levels at the time of analysis (2009). Studied US production and imports to meet legal requirements.	forest, grasslands, shrublands, savanna, natural and mixed, wetlands, barren	Algeria, Argentina, Australia, Bangladesh, Brazil: Amazon Biome, Brazil: Central-West Cerrados, Brazil: Northeast Coast, Brazil: North-Northeast Cerrados, Brazil: South, Brazil: Southeast, Canada, China, New Zealand, Colombia, Cuba, Egypt, EU, Guatemala, India, Indonesia, Iran, Iraq, Ivory Coast, Japan , Malaysia, Mexico, Morocco, Myanmar, Nigeria, Other Africa, Other Asia, Other CIS, Other Eastern Europe, Other Latin America, Other Middle East, Pakistan, Paraguay, Peru, Philippines, Rest of World, Russia, South Africa, South Korea, Taiwan, Thailand, Tunisia, Turkey, Ukraine, Uruguay, US, Uzbekistan, Venezuela, Vietnam, Western Africa
U.S. California Air Resources Board (CARB 2010) Analysis of Low Carbon Fuel Standard, LCFS regulation	**GTAP-SOY** (General Equilibrium) New sectors/commodities added to the model to represent production, consumption and trade of key commodities for biodiesel analyses	Two scenarios showing the change in biofuel production expected to occur in response to federal energy legislation and GHG emission regulations such as the LCFS over the time period from 2001 to 2040.	forest, grassland, crop	111 world regions
International Food Policy Institute (IFPRI 2010) study for EU Biofuels Mandate	**MIRAGE 2007, GTAP v.7 Database, Biophysical Data** (General Equilibrium)	A baseline scenario excluding EU biofuels. A scenario of first-generation land-using biofuels share of 5.6%. A final scenarios on a change in the EU biofuels trade policy regime, with an elimination of import tariffs	forest, grassland, crop	Brazil, Central America and Caribbean countries, China, East Europe, EU27, Indonesia and Malaysia, Other Latin American countries, Rest of the OECD, Rest of the World, US, Sub-Saharan Africa
Hertel et al. 2010 Comprehensive Analysis of CARB's LCFS regulation	**GTAP-BIO** (General Equilibrium)	Modeled the expansion of US maize ethanol use from 2001 levels to the 2015 mandated level of 56.7 gigaliters (GL) per year.	forest, grassland, crop	Europe; developed Pacific; former Soviet Union; North Africa/Middle East; Canada; United States; Latin America; South and South East Asia; Africa; India, China, Pakistan; and the rest of the world (ROW)
Searchinger et al. 2008 Preliminary Analysis	**FAPRI-CARD of 2007, GREET 1.7** (Partial Equilibrium, non-spatial, econometric market models)	Two scenarios comparing the LUC impact of US biofuel projected levels relative to 56 GL above that level by 2015.	forest, grassland, crop	Developed Pacific, North Africa/Middle East, Canada, US, Latin America, Africa, South and Southeast Asia, China and Pakistan and India
Lywood 2008	**Econometric Model and LUC data based on (or modified from) Fehrenbach et al. 2009 (see below).**	N/A	forest, pasture, crop	Global
Tipper et al. 2009	**Spatial Measurements Using Census Data** (Attribution of Responsibility)	Starts with an estimate of total GHG emissions from LUC from 2000 – 2005, which is mostly based on FAO's estimate of 7.3 Mha forest lost per year during this period and IPCC carbon stock factors.	N/A	Global
Fritsche et al. 2008	**Spatial Measurements Using Census Data** (Risk Adder/iLUC Factor)	The maximum land potentially involved in LUC is derived from the shares of agricultural products globally traded in the reference year 2005, that can be theoretically "displaced" by additional biomass cultivation is combined with IPCC carbon stock factors for those regions.	grassland, savanna, tropical rainforest, degraded land	EU, Indonesia, Brazil, US
Fehrenback et al. 2009	**Spatial Measurements Using Census Data** (Risk Adder/iLUC Factor)	(see Fritsche for description, but uses alternate data for a recalculation)	grassland, savanna, tropical rainforest, degraded land	EU, Indonesia, Brazil, US

N/A = not applicable; BAU=business as usual

Table 2.5.2. Summary of recent papers estimating iLUC by employing macroeconomic/ econometric and/or biophysical models/data for global and feedstock LUC estimates

Reference	***Feedstocks and Biofuels***	***Corn LUC (d+i) Value in g/MJ***	***Sugarcane LUC (d+i) Value in g/MJ***	***Rapeseed LUC (d+i) Value in g/MJ***	***Soya LUC (d+i) Value in g/MJ***	***Clarifying Comments on Paper Results and Methodology***
EPA	**Ethanol**: maize, maize stover, sugarcane, switchgrass **Biodiesel and Renewable Diesel**: soya, microalgae **FT-Diesel**: switchgrass, maize stover **Butanol**: maize Other annual and perennial crops	**Volumes** 2017: 1.3 EJ 2022: 1.3 EJ **2017 Results** Median 54 Low 36 High 76 **2022 Results** Median 30 Low 20 High 43 *30 Year Accounting Time Frame*	**Volumes** 2017: 1.1 EJ 2022: 1.4 EJ **2017 Results** Median 9 Low -8 High 22 **2022 Results** Median 5 Low -5 High 14 *30 Year Accounting Time Frame*	N/A	**Volumes** 2017: 0.08 EJ 2022: 0.08 EJ **2017 Results** Median 59 Low 30 High 95 **2022 Results** Median 40 Low 14 High 72 *30 Year Accounting Time Frame*	Key parameters: elasticities of crop yields, harvested acreage response, and transformation across cropland, pasture, and forest land. Incorporates Brazilian land use data (Nassar e. al. 2009). Thresholds of GHG with LUC of modeled technologies established (vs. 2005 US fossil fuels) are: **20%** for corn starch ethanol produced from corn starch at a new natural gas, biomass, or biogas fired facility using advanced efficient technologies or butanol; **50%** for ethanol from sugarcane; biodiesel and renewable diesel from soy oil or waste oils, fats, and greases; algal oil derived biodiesel and renewable diesel should they reach commercial production. **60%** for cellulosic ethanol/ diesel pathways modeled (for feedstock and production technology) (EPA 2010).
CARB	**Ethanol**: maize, sugarcane **Biodiesel**: soya	32 *30 Year Accounting Time*	46 *30 Year Accounting Time*	N/A	62 *30 Year Accounting Time*	Limited land use types and geographic resolution. A Sustainability Working Group is refining LUC methodology for absolute carbon intensities required by the State of California.
IFPRI	**Ethanol**: maize, wheat, sugar beets, sugarcane **Biodiesel**: palm, rape, soya, sunflower	**2020 Results** 54 (BAU) 79 (Trade Liberalization) *20 Year Accounting Time*	**2020 Results** 18 (BAU) 19 (Trade Liberalization) *20 Year Accounting Time*	**2020 Results** 53 (BAU) 51 (Trade Liberalization) *20 Year Accounting Time*	**2020 Results** 24 (BAU) 19 (Trade Liberalization) *20 Year Accounting Time*	Limited set of EU imports used. Limited land use types.
Hertel et al.	**Ethanol**: maize	**iLUC Attributable** Median: 27 Lower : 14 Upper : 90 *30 Year Accounting Time*	N/A	N/A	N/A	Comprehensive market-mediated model obtained 1/4 of the figure of Searchinger et al. (2008). Conducted sensitivity analysis and Gaussian quadrature analysis of uncertainties. Methodology used continues to undergo developed and refinement.
Searchinger et al.	**Ethanol**: maize, biomass	104 *30 Year Accounting Time*	N/A	N/A	N/A	Limited land use types (i.e., natural vegetation only; no pastures) and limited geographic resolution.
Lywood	**Ethanol**: maize, wheat, sugarcane **Biodiesel**: soya, rapeseed, palm	-92 *30 Year Accounting Time*	48 *30 Year Accounting Time*	-149 *30 Year Accounting Time*	146 *30 Year Accounting Time*	Results largely determined by linkage of soya meal to LUC in Brazil. Maize, rape, and wheat reduce GHGs through co-products substituting for soy meal. Limited land use type and geographic resolution.
Tipper et al.	**Ethanol**: wheat, sugar beet, maize, sugarcane **Biodiesel**: rapeseed, soya, palm	21 *25 Year Accounting Time*	45 *25 Year Accounting Time*	*10* *25 Year Accounting Time*	N/A	Methods is less resource intensive, but the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.
Fritsche et al.	**Ethanol**: maize, wheat, sugarcane, switchgrass, poplar **Biodiesel**: jatropha, rape, palm,	**LUC Risk Value** 48 (25%) 79.5 (50%) 111.5 (75%) dLUC: 16.5 *20 Year Accounting Time*	**LUC Risk Values** 6.5 (25%) 14 (50%) 29 (75%) dLUC: -1 *20 Year Accounting Time*	**LUC Risk Value** 91 (25%) 150.5 (50%) 210 (75%) dLUC: 31.5 *20 Year Accounting Time*	N/A	Methods is less resource intensive, but the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.
Fehrenback et al.	**Ethanol**: maize, wheat, sugarcane **Biodiesel**: rape, palm	**iLUC Risk Value** 36 (25%) 72 (50%) 108 (75%) *20 Year Accounting Time*	**iLUC Risk Values** 53 (25%) 106 (50%) 159 (75%) *20 Year Accounting Time*	**iLUC Risk Value** 60 (25%) 120 (50%) 180 (75%) *20 Year Accounting Time*	N/A	Methods is less resource intensive, but the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.

2.5.3.3 Environmental impacts other than GHG emissions

Impacts on air quality and water resources

Pollutant emissions to the air depend on combustion technology, fuel properties, combustion process conditions and emission reduction technologies installed. Compared to coal and oil combustion stationary applications, SO2 and NOx emissions are generally lower than coal and oil combustion in stationary applications. When biofuels replaces gasoline and diesel in the transport sector SO2 emissions are reduced but changes in NOx emissions depend on substitution pattern and technology applied. The effects of ethanol and biodiesel replacing petrol depend on engine features. Biodiesel can have higher NOx emissions than petroleum diesel in traditional direct-injected diesel engines that are not equipped with NOx control catalysts. (e.g., Verhaeven et al., 2005; Yanovitz and McCormick, 2009)

Bioenergy production can have positive and negative effects on water resources. The impacts are highly dependent on the supply chain element under consideration. Feedstock cultivation can lead to leaching and emission of nutrients resulting in increased eutrophication of aquatic ecosystems (Millennium Ecosystem Assessment, 2005; SCBD 2006). Pesticide emissions to water bodies may also negatively impact aquatic life. Perennial herbaceous crops and short rotation woody crops generally require less agronomic input – resulting in less impacts – and can also mitigate impacts if integrated in agricultural landscapes as vegetation filters intended to capture nutrients in passing water (Börjesson and Berndes, 2006).

The subsequent processing of the feedstock into solid/liquid/gaseous biofuels and electricity can lead to negative impacts due to potential chemical and thermal pollution loading to aquatic systems from refinery effluents and fate of waste or co-products (Martinelli and Filoso 2008, Simpson et al. 2008). These environmental impacts can be reduced if suitable equipment is installed (Wilkie et al. 2000; BNDES/CGEE 2008) but this may not happen in regions with lax environmental regulations or limited law enforcement capacity.

Most water is lost to the atmosphere in plant evapotranspiration (ET) in the production of cultivated feedstock (Berndes, 2002). Feedstock processing into fuels and electricity requires much less water (Aden et al. 2002; Berndes 2002; Keeny and Muller 2006; Pate et al. 2007; Phillips et al. 2007; Wang et al., 2010), but water needs to be extracted from lakes, rivers and other water bodies. Bioenergy processing can reduce its water demand substantially by means of process changes and recycling (Keeney and Muller, 2006; BNDES/CGEE, 2008).

Strategies that shift demand to alternative – mainly lignocellulosic – feedstock bioenergy expansion can lead to decreased water competition. Given that several types of energy crops are perennials in arable fields, being used temporarily as a pasture for grazing animals, and woody crops grown in multi-year rotations, the increasing bioenergy demand may actually become a driver for land use shifts towards land use systems with substantially higher water productivity. A prolonged growing season may facilitate a redirection of unproductive soil evaporation and runoff to plant transpiration, and crops that provide a continuous cover over the year can also conserve soil by diminishing the erosion from precipitation and runoff outside the growing season of annual crops (Berndes, 2008). Since a number of crops that are suitable for bioenergy production can be grown on a wider spectrum of land types, marginal lands, pastures and grasslands, which are not suitable for conventional food/feed crops, could become available for feedstock production under sustainable management practices (if downstream water impacts can be avoided)).

Habitat Loss

Habitat loss is one of the major causes of biodiversity decline globally and is expected to be the major driver of biodiversity loss and decline over the next 50 years (Convention on Biodiversity, 2008; Sala et al, 2009). While bioenergy can reduce global warming – which is expected to be a major driver behind habitat loss with resulting biodiversity decline – it can also in itself impact biodiversity through conversion of natural ecosystems into bioenergy plantations or changed forest management to increase biomass output for bioenergy. Biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere.

To the extent that bioenergy systems are based on conventional food and feed crops, biodiversity impacts due from pesticide and nutrient loading can be an expected outcome of bioenergy expansion. On the other hand, bioenergy expansion can lead to positive outcomes for biodiversity. Establishment of perennial herbaceous plants of short rotation woody crops in agricultural landscapes has been found to be positive for biodiversity (Semere et al., 2007; The Royal Society 2008; Lindemeyer, Nix 1993).

Bioenergy plantations that are cultivated as vegetation filters capturing nutrients in passing water can contribute positively to biodiversity by reducing the nutrient load and eutrophication in water bodies (Borjesson and Berndes, 2006; Foley et al. 2005) and provide varied landscape.

Bioenergy plantations can be located in the agricultural landscape so as to provide ecological corridors that provide a route through which plants and animals can move between different spatially separated natural and semi-natural ecosystems. This way they can reduce the barrier effect of agricultural lands. For example, a larger component of willow in the cultivated supports cervids, foxes, hares, and wild fowl.

Properly located biomass plantations can also protect biodiversity by reducing the pressure on nearby natural forests. A study from Orissa, India, showed that with the introduction of village plantations biomass consumption increased (as a consequence of increased availability) and the pressure on the surrounding natural forests decreased (Köhling, Ostwald 2001; Edinger et al. 2005).

When crops are grown on degraded or abandoned land, such as previously deforested areas or degraded crop- and grasslands, the production of feedstocks for biofuels could potentially have positive impacts on biodiversity by restoring or conserving soils, habitats and ecosystem functions. For instance, several experiments with selected trees and intensive management on severely degraded Indian wastelands (such as alkaline, sodic, or salt affected lands) showed increases of soil carbon, nitrogen and available phosphorous after three to 13 years.

Increasing demand for oilseed has put pressure on areas designated for conservation in some OECD member countries begun (Steenblik, 2007). Similarly, the rising demand for palm oil has contributed to extensive deforestation in parts of South-East Asia (UNEP, 2008). Since biomass feedstocks can generally be produced most efficiently in tropical regions, there are strong economic incentives to replace tropical natural ecosystems – many of which host high biodiversity values. (Doornbosch and Steenblik, 2007). However forest clearing is most influenced by local social, economic, technological, biophysical, political and demographic forces (Kline and Dale 2008).

2.5.3.3.1 Impacts on soil resources

Increased biofuel production based on conventional annual crops may result in changed rates of soil erosion, soil carbon oxidation and nutrient leaching owing to the increased need for tillage depending on the crop used and replaced (UNEP 2008). For instance, wheat, rapeseed and corn require significant tillage compared to oil palm and switchgrass (FAO 2008b; United Nations 2007). Excess removal of harvest residues such as straw may lead to similar types of soil degradation.

If energy crop plantations are established on abandoned agricultural or degraded land, levels of soil erosion could be decreased because of increased soil cover. This would be especially true with perennial species. For example, Jatropha can stabilize soils and store moisture while it grows (Dufey 2006). Other potential benefits of planting feedstocks on degraded or marginal lands include reduced nutrient leaching, increased soil productivity and increased carbon content (Berndes 2002).

2.5.4 Environmental health and safety implications

2.5.4.1 Feedstock Issues

Currently, the crops used in fuel ethanol manufacturing are the same as those used as traditional feed sources (e.g. corn, soy, canola and wheat). However, there is considerable in new crops, with characteristics that either enhance fuel ethanol production (e.g. high-starch corn), or are not traditional food or feed crops (e.g., switchgrass). These crops, developed for industrial processing, may necessitate a pre-market assessment of their acceptability in feed prior to their use in fuel ethanol production, if the resultant distillers' grains (DGs) are to be used as livestock feeds, or if the new crop could inadvertently end up in livestock feeds (Hemakanthi et al., 2010).

As with any genetically modified or enhanced organism, the energy-designed crop may raise concerns related to cross-pollination, hybridisation, and other potential environmental impacts such as pest resistance and disruption of ecosystem functions (FAO, 2004).

The first assessment of the impact of genetically engineered (GE) crops in the U.S., which have been in use since 1996 has now been published by the National Academy of Sciences (NAS, 2010). GE crops are currently responsible for 80 percent of corn, soya, and cotton, production and represent nearly 35 percent of the entire cropped area of the USA. Some highlights are: (i)Benefits to the farmer, including increased worker safety, flexibility in farm management, and lower cost of production due to a decline in the use of insecticides. (ii) Anticipation that water quality improvements will prove to be the largest benefit of GE crops. (iii) Acknowledgement that that more work needs to be done, particularly as it relates to installing infrastructure to measure water quality impacts, developing weed management practices, and addressing the needs of farmers whose markets depend on an absence of GE traits.

Several grasses and woody species which are potential candidates for future biofuel production also have traits which are commonly found in invasive species (Howard and Ziller, 2008). These traits include rapid growth, high water-use efficiency, and long canopy duration. It is feared that should such crops be introduced they could become invasive and displace indigenous species and result in a decrease in biodiversity. For example *Jatropha curcas*, a potential feedstock for biofuels, is considered weedy in several countries, including India and many South American states (Low and Booth, 2007). Warnings have been raised about species of Miscanthus and switchgrass (*Panicum virgatum*). Biofuel crops such as Sorghum halepense (Johnson grass), Arundo donax (giant reed), Phalaris arundinacea (reed canary grass) are known to be invasive in the United States. A number of protocols have evolved that allow for a more systematic assessment and evaluation of inherent risk associated with species introductionn.

2.5.4.2 Biofuels Production Issues

Most biofuels produced globally use conventional production technologies (see Section 2.3) that have been used in many industries for many years (Abassi, Abassi 2010; Gunderson, 2008). Hazards associated with most of these technologies have been well characterized, and it is possible to control risks to very low levels by applying existing knowledge and standards which are also applied to other fuels technologies (see, for instance, Williams et al., 2009; Astbury 2008; Hollebone, Yang, 2009; Marlay et al., 2009) and their typology is under development (Rivère, Marlair, 2009 and 2010).

As new technologies (see Section 2.6) are developed the literature highlights areas for further evaluation (e.g., Gunderson, 2008; Hill et al., 2009; Madsen, 2006; Madsen et al., 2004; Martens, Böhm, 2009; McLeod et al., 2008; Moral et al. 2009; Narayanan et al., 2008; Perry, 2009; Sumner, Layde 2009; Vinneraas et al.. 2006). Examples of areas: (i) Health risk to workers using engineered micro-organisms in biofuel production, or their metabolites. (ii) Potential ecosystem effects from the release of engineered micro-organisms. (iii) Impact to workers, biofuel consumers, or the environment of pesticides and mycotoxins accumulation in processing intermediates, residues, or products (e.g., spent grains, spent oil seeds). (iv) Risks to biofuel workers of infectious agents that can contaminate feedstocks in production facilities. (v) Exposure to toxic substances particularly workers at biomass thermochemical processing facilities different than those routes practiced by the current fossil fuels industry (vi) Fugitive air emissions and site run-off impacts on public health, air quality, water quality, and ecosystems exposure to toxic substances particularly if such production facilities became as commonplace as landfill sites or natural gas-fired electricity generating stations. (vii) Estimate the cumulative environmental impacts accruing from the siting of multiple biofuel / bioenergy production facilities in the same air and/or water shed.

2.5.5 Socioeconomic Aspects

The large-scale development of bioenergy at the global level will be associated with a complex set of socio-economic issues and trade-offs, ranging from local income and employment generation, improvements in health conditions near and far away, potential changes in agrarian structure, land-tenure, land-use competition, and strengthening of regional economies, to national issues such as food and energy security and balance of trade. The degree to which these impacts are mostly positive depends on the extent to which sustainability criteria are clearly incorporated in project design and implementation. Participation of local stake-holders, in particular small-farmers and poor households, is key to assure socio-economic benefits from bioenergy projects.

Up to now, the large perceived socio-economic benefits of bioenergy use –such as regional employment and economic gains- can clearly be identified as a significant driver for increased bioenergy production. Other “big issues” such as mitigating carbon emissions, ensuring wider environmental protection, and providing a secure energy supply are an added bonus for local communities. Benefits will result in increased social cohesion and conditions for greater social stability.

On the other hand, substantial opposition has been raised against the large-scale deployment of bioenergy, particularly regarding projects aimed at producing liquid fuels from mainly food crops with potential negative impact on food security, the extent to which current strategies and policies will actually benefit poor farmers, the potential disruption of local production systems and concentration of land and other social effects.

2.5.5.1 Socio-economic impact studies and sustainability criteria for bioenergy systems

Analyzing the socio-economic impacts of bioenergy, dependent on many exogenous factors affected by scale, is daunting ex ante or ex post. Typically, economic indicators such as employment and financial gain measure impacts. In effect, the analysis relates to a number of other aspects such as cultural and social issues. These elements are not always amenable to quantitative analysis and, therefore, have been excluded from the majority of previous impact assessments, even though they may be somewhat significant. The complex nature of biomass and possible routes for conversion make this topic a complex subject, with many potential outcomes. To overcome these problems methods for projecting social dimension accounting using a semi-quantitative approaches based on stakeholder involvement to assess social criteria such as societal product benefit and social dialogue[5] (Von Geibler et al 2006). Obtaining extensive feedback from local stakeholders, usually through the organisation of several workshops, roundtables and other similar meetings through the various project implementation stages is crucial, because basic economic information is often not available from national statistical agencies..

Most commonly reported economic criteria are private production costs over the value-chain, assuming a fixed set of prices for basic commodities (e.g., for fossil fuels and fertilizers). The bioenergy costs are usually compared to alternatives already on the market (fossil based), to judge the potential competitiveness. Externalities (environmental or societal) are seldom quantified in cost/benefit analyses, since they are difficult to value (Costanza et al., 1997). Policy instruments might already be in place to address these externalities, such as environmental regulations or emission-trading schemes. Bioenergy systems are mostly analysed at a micro-economic level, although interactions with other sectors cannot be ignored because of the competition for land and other resources. Opportunity costs may be calculated from food commodity prices and gross margins to take food-bioenergy interactions into account. Social impact indicators include consequences on local employment, although they are difficult to assess because of possible offsets between fossil and bioenergy chains. At a macro-economic level, other impacts include the social costs incurred by the society because of fiscal measures (e.g., tax exemptions) to support bioenergy chains, or additional road traffic resulting from biomass transportation (Delucchi, 2005). Symmetrically, fossil energy negative externalities need to be assessed (Bickel and Friedrich, 2005).

Diverse sustainability criteria and indicators have been proposed as a way to better assess the socio-economic implications of bioenergy projects (Bauen et al., 2009a; WBGU, 2009; see Section 2.4). These criteria relate to: (i) Human rights, including gender issues; (ii) Working and wage conditions, including health and safety issues; (iii) Local food security, and (iv)Rural and social development, with special regards to poverty reduction. These criteria also address issues of cost-effectiveness and financial sustainability (Table 2.5.4)

Table 2.5.4. Selected Socio-economic Sustainability Criteria for Bioenergy Systems

Criteria	Issues Addressed
Rural and Social Development	Improved access to basic services and livelihoods; Creation or displacement of jobs, Creation of infrastructure
Human Rights and Working Conditions	Freedom of association, Access to Social Security, Average Wages, Discrimination.
Health and Safety	Health Improvements or Impacts on Workers and Users; Safety Conditions at Work
Gender	Changes in Power or Access to resources or decision making

Socio-economic impacts of bioenergy systems are addressed in household applications (small-scale) and larger scale systems for industry, electricity generation, and transport.

2.5.5.2 Socio economic impacts of small-scale systems

The inefficient use of biomass in traditional devices such as open fires leads to significant social and economic impacts related to: the resources devoted to fuel collection, the monetary cost of satisfying cooking needs, gender issues, and significant health impacts of high levels of indoor air

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[5] Multi Criteria Analysis (MCA) methods have been applied in the bioenergy field during the past 15 years (Buchholz at al., 2008).

pollution, which affects in particular women and children during cooking. The inefficient use of biomass in traditional devices such as open fires leads to significant social and economic impacts including drudgery for getting the fuel, cost of satisfying cooking needs, and significant health impacts associated to very high levels of indoor air pollution, which affects in particular women and children during cooking (Biran et al., 2004; Romieu et al., 2009; Masera et al., 1997; Bruce et al., 2006).

Four billion people suffer from continuous exposure to high levels of indoor air pollution by cooking food over open wood burning fires (Pimentel et al, 2001). The pollutants include respirable particles, carbon monoxide, oxides of nitrogen and sulfur, benzene, formaldehyde, 1, 3-butadiene, and polyaromatic compounds, such as benzo(a)pyrene (Smith 1987). Human health effects from wood-smoke exposure have contributed towards an increased burden of respiratory symptoms and problems (Boman et al, 2006; Mishra et al., 2004; Schei et al., 2004; Thorn et al., 2001). Exposures experienced by household members, particularly women and young children who spend a large proportion of their time indoors, have been measured to be many times higher than World Health Organization (WHO) guidelines and national standards (Bruce et al., 2006; Smith, 1987). More than 200 studies in the past two decades have assessed levels of indoor air pollutants in households using solid fuels. The burden from relateddiseases was estimated at 1.6 million excess deaths/year including 900,000 children under five, and the loss of 38.6 million DALY (Disability Adjusted Life Year)/yr (Smith and Haigler, 2008). This is similar in magnitude to the burden of disease from malaria and tuberculosis (Ezzati et al., 2002).

The new generation of improved cookstoves and their dissemination described in section 2.4 have shown that properly designed and implemented ICS projects can lead to health improvements (Ezzati et al., 2004;von Schirnding et al., 2001). Figure 2.5.7 shows high and low estimates of cost effectiveness for treatment options related to eight major risk factors accounting for 40 percent of the global burden of disease (DCPP, 2006).

ICS health benefits include a 70%-90% reduction in indoor air pollution, and 50% reduction in human exposure as well as reductions in respiratory and other illnesses (Armendariz et al. 2008; Romieu et al, 2009). In India, it is estimated that an intensive program to introduce advanced biomass stoves in 87% of households would achieve in 10 yrs, 240,000 averted premature deaths from acute lower respiratory infections in children aged younger than 5 years, and more than 1.8 million averted premature adult deaths from ischaemic heart disease and chronic obstructive pulmonary disease (COPD) (Wilkinson et al. 2009)

Increased use of ICS frees up more time for women to engage in income generating activities. Reduced fuel collection times and savings in cooking time can also translate to increased time for education of rural children especially the girl-child (Karekezi et al. 2002). ICS use fosters improvements in local living conditions, kitchens and homes, and quality of life (Masera et al, 2000). The manufacture and dissemination of ICS represents also an important source of income and employment for thousands of local small-businesses around the world (Masera et al, 2005). Similar impacts were found for small scale biogas plants with the added benefits of lighting of individual households and villages, increasing the quality of life.

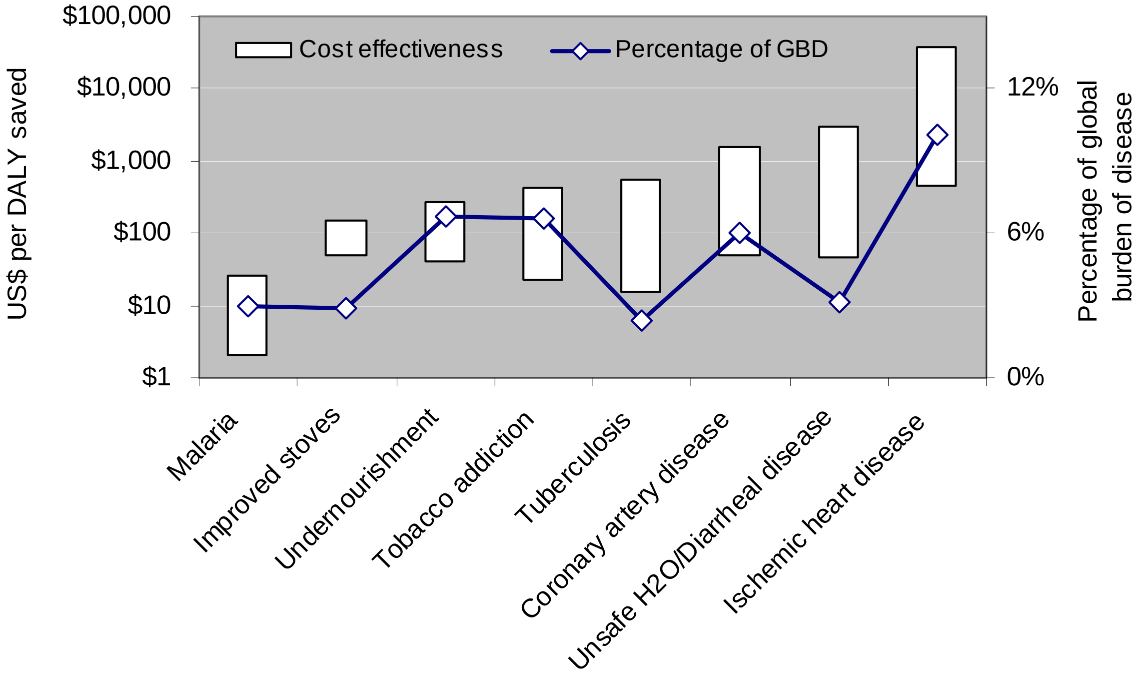

Figure 2.5.4.: Cost effectiveness of interventions expressed in dollars per Disability Adjusted Life Year (DALY) saved (DCPP, 2006) in the left scale (logarithmic scale) and contributions to the global burden of disease from eight major risk factors and diseases (in %, right scale). Source: Bailis et al., 2009.

Overall ICS and other small-scale biomass systems represent a very cost-effective intervention B/C (benefits to cost) ratio of 5.6 to 1, 20:1, and 13:1 were found in Malawi, Uganda and Mexico (Frapolli et al., 2010).

2.5.5.3 Socioeconomic aspects of large-scale bioenergy systems

Large scale bioenergy systems raise several important socioeconomic issues, and have sparked a heated controversy around food security, income generation, rural development and land tenure. The controversy makes clear that there are both advantages and disadvantages to the further development of large scale bio-energy systems.

Impacts on job and income generation

In general, bionergy generates more jobs per energy delivered than other energy sources, largely due to production of feedstocks which offers income-generating opportunities in developing countries, especially in rural areas. The extent of benefits are greater if the feedstock crop is more labor-intensive than the crop that was previously grown on the same land, because wage income is a key part of livelihoods for many poor rural dwellers.

The number of jobs created is very location specific, and varies considerably with plant size and the degree of feedstock production mechanization (Berndes and Hansson, 2007). Estimates of the employment creation potential of bioenergy options differ substantially, but liquid biofuels based on traditional agricultural crops seem to be best especially when the biofuel conversion plants are small (Berndes and Hansson, 2007). Even within liquid biofuels, the use of different crops introduces wide differences. For example, employment generation ranges from 1 to 5 direct jobs/Mlit-yr (or 45 to 220 direct and indirect jobs/PJ-yr) of ethanol using corn and sugarcane, respectively, to 3.5 to 73 direct jobs/Mlit-yr (or 100 to 2000 direct and indirect jobs/PJ-yr) biodiesel for soybean and oil palm, respectively (APEC, 2010). For electricity production, mid-scale power plants in developing countries assuming a low-mechanized system (25 MW) are estimated to generate 8 full jobs/MWe and approximately a total of 400 jobs/plant, of which 94% are in the production and harvesting of feedstocks. In developed countries the number of jobs for this size plant is estimated as 35 direct and indirect jobs/PJ (EPRI, 2008). A multiplier of five was used for the indirect to direct ratio (DOE/SSEB 2005) but could vary regionally even within a country.

The net impact of bioenergy on future employment creation is generally seen as positive; but specific figures are highly dependent on displaced crops/management systems. In Europe, if the EU25 scenario is followed, Berndes and Hansson (2007) estimate that the production of biomass for energy has the potential to contribute to employment creation at a magnitude that is significant relative to total agriculture employment (up to 15% in selected countries), but small compared to the total employment in industry in a country. Analysis also shows that there are some tradeoffs – for instance, bioenergy options promoted as agricultural options oriented to liquid biofuels create more employment, but forest-based options oriented to electricity and heat production produce more climate benefits. In Brazil, the biofuel sector accounted for about 1 million jobs in rural areas in 2001, mostly for unskilled labor (Moreira, 2006). Mechanization is already ongoing in about 50% of the Center South production (90% of the country’s harvest) thus reducing unskilled labor for manual harvest after fire, and producing an environmental benefit. Worker productivity continues to grow and part of the workforce is retrained to skilled higher paying jobs for mechanized operations (Oliveira, 2009).

2.5.5.4 Risks to food security

Liquid biofuel production creates additional demand for agricultural commodities, including foodstuffs that place additional pressure on natural resources such as land and water and thus raise food commodity prices. Lignocellulosic biomass biofuels can reduce it but not eliminate competition. To the extent that domestic food markets are linked to international food markets, even countries that do not produce bioenergy will be affected by the higher prices.

The OECD-FAO Agricultural Outlook (2008) model found that if biofuel production were to be frozen at 2007 levels, coarse grains prices would be 12% lower and vegetable oil prices 15% lower in 2017 compared to expected biofuels increases. Rosegrant et al (2008) estimated that world maize prices would be 26% higher under a scenario of continued biofuel expansion according to then-existing national development plans, and more than 70% higher under a drastic biofuel expansion scenario where biofuel demand is double that under the first scenario (these scenarios are relative to a baseline of modest biofuel development where biofuel production remains constant at 2010 levels in most countries). World prices for wheat, sugar and other crops would increase with greater biofuels production, but would be less than in the case of maize and oilseeds. IFPRI (2008) estimated that 30 percent of the weighted average increase of world cereal prices was attributable to biofuels between 2000 and 2007. The eventual impact of biofuels on prices will depend on the specific technology used, the strength of government mandates for biofuel use, the nature of trade policies that can favour inefficient methods of biofuel production, and the level of oil prices.

The impact of higher prices on the welfare of the poor depends on whether the poor are net sellers of food (benefit from higher prices) or net buyers of food (harmed by higher prices). The poor are a heterogeneous group, with some being net sellers of food while others are net buyers. On balance, the evidence indicates that higher prices will adversely affect poverty and food security, even after taking account of the benefits of higher prices for farmers (Ivanic and Martin, 2008; Zezza et al., 2008). A major study of FAO on the socio-economic impacts of the expansion of liquid biofuels (FAO, 2008b) indicates that poor urban consumers and poor net food buyers in rural areas are particularly at risk. Rosegrant et al., (2008) estimate that the number of malnourished children would increase by 4.4 to 9.6 million under the two above mentioned scenarios.

Higher food prices will have negative consequences for net food-importing developing countries. Especially for the low-income food-deficit countries, higher import prices can severely strain their balance of payments. Food exporting countries will benefit from higher prices, but the number of such countries is limited and they tend to be more developed (e.g. Thailand, Brazil, and Argentina).

Very recent commodity price analysis shows that food has been kept almost constant during the period Jan 2009- Jun 2010, while industrial commodities have increased by around 80%, bringing average commodity prices some 25% higher at the end of the period (The Economist, 2010). What we learn from this information is that it is very difficult to make forecast based in price changes that occurred in a short time spam (1 to 2 years) since agricultural prices are very volatile.

A significant increase in the cultivation of crops for bio-energy implies a close coupling of the markets for energy and food (Schmidhuber, 2007). As a result, food prices may become more closely linked to the dynamics of world energy markets. Political crises that affect energy markets would thus affect food prices. For around one billion people in the world who live in absolute poverty, this situation poses additional risks to food security.

Meeting the food demands of the world’s growing population will require an increase in global food production of 70 percent by 2050 (Bruinsma, 2009). This FAO study also estimates that the increase in arable land between 2005/07 and 2050 will be just 4 percent. Given this limited increase, at global scale, competition between food and fuel may not be a serious issue. Increased biofuels production could also reduce water availability for food production (as more water is diverted to production of biofuel feedstocks). Cash crops can represent an additional incomes source and do not necessarily compete with food crops, and may contribute to improving food security (Tefft, 2010). However, there are instances of negative effects of cash crops on food security (Binswanger and von Braun, 1991; von Braun, 1994).

2.5.5.5 Impacts on Rural and Social Development

Growing demand for biofuels and the resulting rise in agricultural commodity prices can present an opportunity for promoting agricultural growth and rural development in developing countries. The development potential critically depends on whether it is economically sustainable without government subsidies. If long-term subsidies are required, there will be fewer government funds available for investment in a wide range of public goods that are essential for economic and social development, such as agricultural research, rural roads, and education. Even short-term subsidies need to be considered very carefully, as once subsidies are implemented they can be difficult to remove. Experience from Latin America shows that governments that utilize agricultural budgets for investment in public goods instead of subsidies experience faster growth, more rapid poverty alleviation, and less environmental degradation (Lopez and Galinato, 2007).

Bioenergy may reduce dependence on fossil fuel imports and increase energy supply security, although the benefits are not likely to be large (FAO, 2008b). Case studies for several Caribbean countries have been completed and indicate large potential benefits (see Section 2.4.6.8). Recent analyses of The use of indigenous resources implies that much of the expenditure on energy provision is retained locally and re-circulated within the local/regional economy, but there are trade-offs to consider. For example the increased use of biomass for electricity production and the corresponding increase in demand for some types of biomass (e.g., pellets) could cause distortions leading to the temporary lack of supply of biomass during periods of high demand. Households are particularly vulnerable in this regard.

The technology and institutions used for biofuels production will also be an important determinant of rural development outcomes. For example, private investors in some instances will look to the establishment of biofuel plantations to ensure security of supply. If plantations are established on non-productive land without harming the environment, then there should be benefits to the economy. It is essential not to overlook the uses of land that is important to the poor. Governments need to establish clear criteria for determining marginal or productive land, and criteria must aim to protect vulnerable communities and female farmers who may have less secure land rights (FAO, 2008b). Research in Mozambique (Arndt et al 2008) shows that an outgrower approach to producing biofuels is more pro-poor, due to the greater use of unskilled labor and accrual of land rents to smallholders in this system, compared with a more capital-intensive plantation approach.

Increased investment in rural areas will be crucial for making biofuels a positive development force. If governments rely exclusively on short-term farm-level supply response, the negative effects of higher food prices will predominate. If higher prices motivate greater investment in agriculture (e.g. rural roads and education, research and development) from public and private sectors, there is tremendous potential for sparking medium and long term rural development. As one example, proposed biofuel investments in Mozambique could increase annual economic growth by 0.6 percentage points and reduce the incidence of poverty by about six percentage points over a 12-year period (Arndt et al, 2008).

The increased use of residues for some feedstocks -such as pellets or used cooking oil- require careful analysis. While residues are presently inexpensive, as the market expands or as other uses are found, the price could change dramatically. For example, used cooking oil in Europe went from a waste product to a valuable commodity. One must also assess the long-term supply picture. For example, beetle-killed timber in British Columbia, Canada is a large source material for pellet manufacture for the European market, but it is not clear for how long will it be available.

2.5.5.6 Trade-offs between social and environmental aspects

Some important trade-offs between environmental and social criteria exist and need to be considered in the future bioenergy development. In the case of sugarcane, the environmental sustainability criteria promoted by certification frameworks (such as the Roundtable for Sustainable Biofuels) favor the mechanization of harvesting due to the emissions from burning the cane in manual systems. Several working organizations are concerned about the fate of the large number of workers that will be displaced by the new systems (Huerta et al, 2010). Also, the mechanized model tends to favor further land ownership concentration in the sector, with the resulting potential exclusion of small/medium scale farmers and reduced employment opportunities for rural workers.

Strategies for addressing such concerns can include (i) support for small/medium size stakeholders lacking own capacity to manage all challenges of meeting the requirements in the certification systems and/or (ii) support aiming at mitigating possible negative socioeconomic effects of outcomes that are found to be unavoidable consequences of the transformation process. For example, there is already an established time plan for the phase out of manual harvesting in the State of São Paulo, which considers the need to develop alternative income possibilities for the seasonal workers that presently earn a substantial part of their annual income based on cutting sugarcane. Implementation of sustainability certification may need to consider that a shift to mechanised harvesting cannot be made too rapidly (Huerta et al. 2010; Oliveira, 2009).

2.5.6 Summary

The effects of bioenergy on social and environmental issues – ranging from health and poverty to biodiversity and water quality – may be positive or negative depending upon local conditions, how criteria and the alternative scenario are defined, and how actual projects are designed and implemented, among other variables.

Climate change and biomass production can be influenced by interactions and feedbacks among land use, energy and climate in scales that range from micro through macro (see Figure 2.5.5).

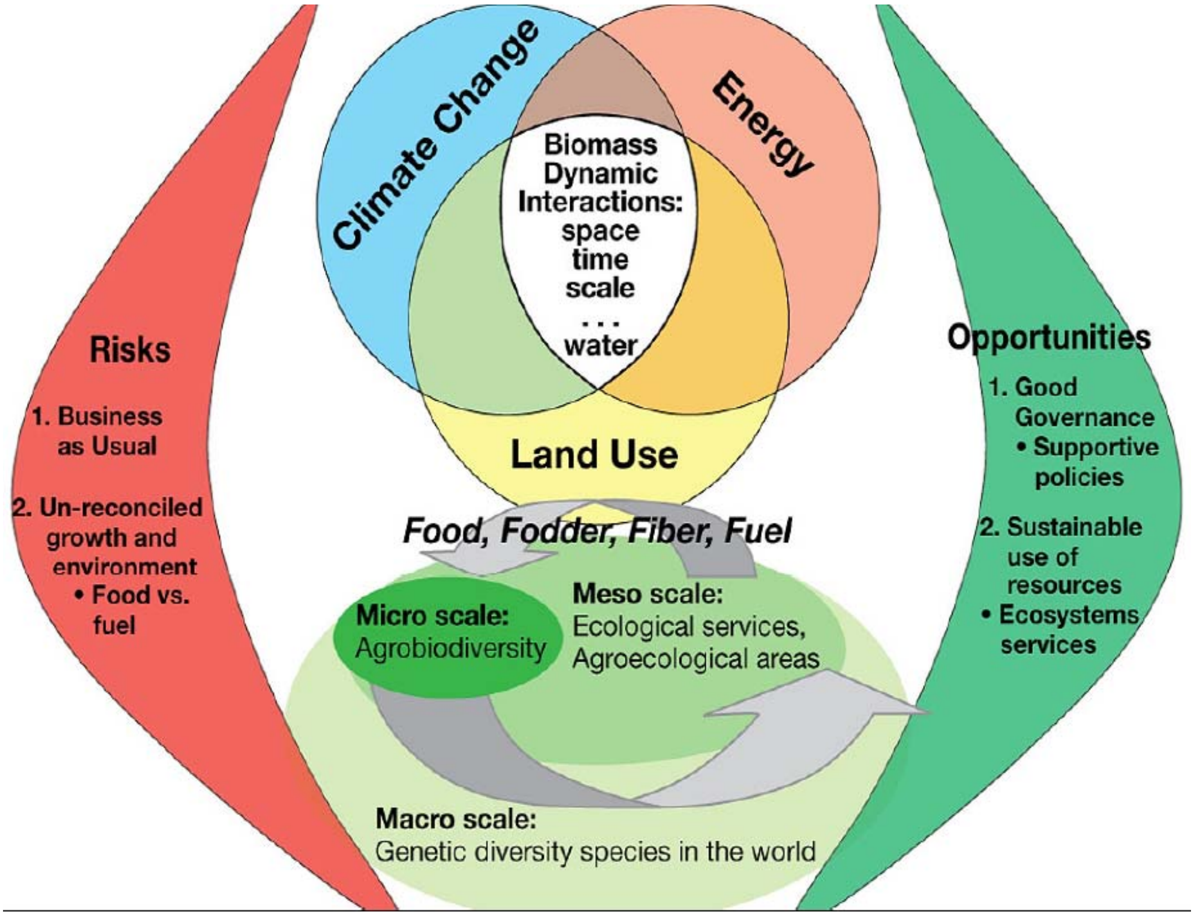

Figure 2.5.5.: Climate Change-Land Use-Energy Nexus. Adapted from Dale et al., submitted and van Dam et al. 2009.

Bioenergy is a part of complex interlinked system whose sustainability is being evaluated, in part, through Lifecycle Assessment (LCA) methodologies analyzing inputs and outputs of the system. In our review of the literature, we found that the attributional LCA analysis of GHGs emissions for several bioenergy systems is known fairly in depth, and is convergent for ethanol and biodiesel in many parts of the world, when consistent boundaries and methodologies such as those for coproduct allocation are employed. The biofuel LCA is compared with the LCA of the fossil (or other) energy system it replaces. Although many studies provide data on GHG emissions savings compared to the fossil system replaced, to the renewable energy produced, and some level of characterization of the amount of renewable energy provided relative to fossil energy employed in the biofuel production, few studies comprehensively analyze the whole chain from feedstock to final energy use. When such studies are available, it was possible to measure bioenergy GHG emissions per unit land area used, a very important measure of land use. Initial studies also report water use throughout the feedstock to final energy use chain. The description of the specific biofuel production (and use) with many functionalities is important. With this information, environmental impact assessments more broadly quantify environmental, ecological, health impacts, landscape habitat and response, and obtain an economic analysis of benefits and impacts.

From this perspective we illustrate improvements in the production of ethanol from sugarcane with time based, show emissions reductions' data, even more as both fuels and electricity are products, in addition to sugar, confirming that a rain fed semi-perennial plant in appropriate climates, produced under mechanized conditions, with an infrastructure and distribution that minimizes losses, achieves substantial GHG reductions – and can make much more contributions in the future. Progress is reported as well in relation to a landscaped environment around rivers to minimize effluent discharges. Similarly, the ethanol production from grains in the Americas and Europe has improved over time through energy efficiency and increased crop productivity, although being annual plants does not enable as good a performance in GHG emissions reductions as perennial plants as sugarcane managed with multi-year ratoons. The bulk of the ethanol production from grain uses natural gas (some biomass) for process heat and some cogeneration. Electricity generation from biomass produces consistently high GHG emissions reductions, even more in cases where methane emissions would otherwise occur. This agreement is for the directly attributional part of the LCA analysis.

As bioenergy production grew more rapidly in the past ten years, in concert with rapidly rising oil and food prices for a period, the consequences of its development throughout the world in terms or land use and impacts on the global economic system were questioned. The initial LCA tool was then coupled to a variety of macroeconomic/econometric models and to biophysical models or actual specific satellite/statistical data to assess the consequences of fuel levels proposed by legislation in several countries to the economic system of agriculture, forestry, and related sectors. We show that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation than necessary as the models did not have other kinds of lands such as pastures in Brazil that could be used. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel producing countries is now producing results that are converging to lower overall land use change impacts for ethanol production. Examples from Finnish forestry highlights the need to include the dynamics forest stocks. Indeed, the approach that EPA took is, so far, the most complete modeling effort that includes such dynamic aspects. Models and data need to improve and be validated.

Estimates of LUC effects require value judgments on the temporal scale of analysis, on land use under the assumed "no action" scenario, on expected uses in the longer term, and on allocation of impacts among different uses over time. Regardless, a system that ensures consistent and accurate inventory and reporting on carbon stocks is considered an important first step toward LUC carbon accounting.

Bioenergy is a component of the much larger agriculture and forestry systems of the world, and that land and water resources need to be properly managed in concert with the type of bioenergy most suited to the specific region and its natural resources and economic development situation. Bioenergy has the opportunity to contribute to climate mitigation, energy security and diversity goals, and economic development in developed and developing countries alike but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, how actual projects are designed and implemented, among many other factors.

2.6 Prospects for technology improvement, innovation and integration

This section provides an overview of potential performance of biomass-based energy in the future (within 2030) due to progress on technology.

2.6.1 Feedstock production

2.6.1.1 Yield gains

Increasing land productivity is a crucial prerequisite for realizing large scale future bioenergy potentials, provided land becomes available as discussed in section 2.2. Much of the increase in agricultural productivity over the past 50 years came about through plant breeding and improved agricultural management including irrigation, fertilizer and pesticide use. The adoption of these techniques in the developing world is most advanced in Asia, where it entailed a strong productivity growth during the past 50 years, and also in Brazil with sugar-cane. Considerable potential exists for extending the same kind of gains to other regions, particularly Sub-Saharan Africa, Latin America, Eastern Europe and Central Asia where adoption of these techniques was slower (FAO, 2008b). A recent long-term foresight by the FAO expects global agricultural production to rise by 1.5 percent a year for the next three decades, still significantly faster than projected population growth (World Bank, 2009). For the major food staple crops, maximum attainable yields may increase by more than 30% by switching from rain-fed to irrigated and optimal rainwater use production (Rost et al., 2009), while moving from intermediate to high input technology may result in 50% increases in tropical regions and 40% in subtropical and temperate regions. The yield increase when moving from low input to intermediate input levels can reach 100% for wheat, 50% for rice and 60% for maize (Table 2.6.1), due to better control of pests and adequate supply of nutrients. However, one should note that important environmental tradeoffs may be involved under strong agricultural intensification, and that avenues for more sustainable management practices should be explored and adopted (IAASTD, 2009).

Table 2.6.1: Long-term (15-25 years) prospects for yield improvements relative to current levels (given in Table 2.3.1).

Feedstock type	Region	Yield trend (%/yr)	Potential yield increase (2030)	Improvement routes	Ref.
DEDICATED CROPS					
Wheat	Europe	0.7	50%	New energy-orientated varieties	1
	Subtropics		100%	Higher input rates, irrigation.	
Maize	N America	0.7	35%	Genotype optimization, GMOs, higher plantation density, reduced tillage. Higher input rates, irrigation.	
	Subtropics		60%		
	Tropics		50%		
Soybean	USA	0.7	35%	Breeding	2,3
	Brazil	1.0	60%		
Oil palm	World	1.0	30%	Breeding, mechanization	3
Sugar cane	Brazil	1.5	40%	Breeding, GMOs, irrigation inputs	2,3,8
SR Willow	Temperate	-	50%	Breeding, GMOs.	3
SR Poplar	Temperate	-	45%		

Miscanthus	World	-	100%	Breeding for minimal input requirements, improved management	
Switchgrass	Temperate	-	100%	Genetic manipulation	
Planted forest	Europe	1.0	30%	Traditional breeding techniques (selection for volume and stem straightness)	4
PRIMARY RESIDUES					
Cereal straw	World	-	15%	Improved collection equipment; breeding for higher residue-to-grain ratios (soybean).	5,6
Soybean straw	N America	-	50%		
Forest residues	Europe	1.0	25%	Ash recycling.	4,7

References: 1: Fischer, 2001a; 2: IEA Bioenergy, 2009; 3: WWI, 2006; 4: Dupouey et al., 2006; 5: Paustian et al., 2006; 6: Perlack et al., 2005; 7: EEA, 2007; 8: Matsuoka et al., 2009.

These increases reflect present knowledge and technology (Fischer, 2001b; Duvick and Cassman, 1999), and vary across the regions of the world (FAO, 2008b), being more limited in developed countries where cropping systems are already highly input-intensive. Also, projections do not always account for the strong environmental limitations that are present in many regions, such as water or temperature. Biotechnologies or conventional plant breeding could contribute to improve biomass production by focusing on traits relevant to energy production. The plant varieties currently being used for first-generation biofuels worldwide have been genetically selected for agronomic characteristics relevant to food and/or feed production and not for bioconversion to energy. Varieties could be selected with increased biomass per hectare, increased oil or fermentable sugar yields, or characteristics that facilitate their conversion to biofuels. Considerable genetic improvement is still possible including for draught tolerant plants (Nelson et al., 2007; Castiglioni et al., 2008;FAO, 2008d). Doubling the current yields of perennial grasses appears achievable through genetic manipulation such as marker-assisted breeding (Eaton et al., 2008; Turhollow, 1994). Shifts to sustainable farming practices and large improvements in crop and residue yield could increase the outputs of residues from arable crops (Paustian et al., 2006).

Shifts to sustainable farming practices and large improvements in crop and residue yield could increase the outputs of residues from arable crops (Paustian et al., 2006).

2.6.1.2 Aquatic biomass

The general term “algae” can refer to both microalgae and macroalgae (i.e., seaweeds). Together with cyanobacteria (also called “blue-green algae”) these organisms dominate the world’s ocean, contributing to the estimated 350-500 billion metric tons of aquatic biomass produced annually (Garrison, 2008). Of these, oleaginous microalgae have garnered the most attention as the preferred feedstock for a new generation of advanced biofuels. Lipids from microalgae, such as triacylglycerides and free fatty acids, can be converted to fungible, high energy-density biofuels via existing petrorefinery processes (Tran et al., 2010). Certain algal species, such as Schizochytrium and Nannochloropsis, reportedly can accumulate lipids at greater than 50% of their dry cell weight (Chisti, 2007). A realistic yield of unrefined algal oil from algal biomass with a 50% oil content located on the equator was estimated to be 40,470-53,200 L ha-1year-1 which is significantly higher than most terrestrial crops (Weyer et al., 2009). Cyanobacteria have long been cultivated commercially for nutraceuticals (Colla et al., 2007; Lee, 1997) however, the accumulation of substantial amounts of triacylglycerides has not been reported in naturally occurring cyanobacterial strains (Hu et al., 2008). It is likely, though, that biofuels from cyanobacteria, will likely face the same scale-up challenges as eukaryotic microalgae as well as having to deal with an unclear regulatory landscape. Macroalgae also do not accumulate lipids like many microalgal species. Macroalgae synthesize complex polysaccharides from which various fuels could be made.

Microalgae can be cultivated in open ponds and closed photobioreactors (PBRs) located on currently unproductive land (Sheehan et al., 1998; van Iersel et al., 2009). Despite these potential advantages, scaling up of algal biofuels production is not without substantial challenges, both from a feedstock logistics viewpoint (Molina Grima et al., 2003), as well as the cost to produce the biomass itself (Borowitzka, 1999). Closed photobioreactor systems at this point in time are cost prohibitive for large-scale production of algal biomass. While the costs associated with cultivating algae in open pond systems is typically less than that of closed systems, the costs of operating open ponds must also be reduced. Macroalgae are typically grown in offshore cultivation systems (van Iersel et al., 2009). Over a million metric tons of macroalgae are cultivated and harvested every year for human dietary consumption (Zemke-White and Ohno, 1999). A few investigations into the use of seaweed for biofuels production have recently been reported (Ross et al., 2008; Aresta et al., 2005), and cultivation optimization strategies are being explored (Kraan and Barrington, 2005). However, it is unclear how large-scale production of macroalgae for bioenergy will impact marine eco-systems and competing uses for fisheries and leisure, posing zoning and regulatory hurdles at a minimum.

Productivity could reach up to several hundreds of EJ for microalgae and up to several thousands of EJ for macro-algae (Sheehan et al., 1998; van Iersel et al., 2009). Given the large number of algal species in the world, the challenge from the biological side will be to select a starting strain with the appropriate growth and production characteristics. In addition to identifying and isolating appropriate production strains required for large scale cultivation, the engineering of cost effective harvesting and extraction technologies as well as determining the appropriate use of the remaining algae components (proteins and carbohydrates) in the overall process will contribute to lower production costs. It is still difficult to assess the sustainability and economic competitiveness of algal biofuels options. While Figure 2.5.2 shows broad ranges, preliminary technoeconomic estimates and lifecycle assessment, both with large uncertainties, indicate that these fuels could offer the same range of emissions reductions or better, compared to seed oil biodiesel, with successful science and engineering and commercialization (EPA, 2010)..

Some general, but important conclusions taken from the IEA Bioenergy report and the DOE Roadmap work (DOE, 2009 microalgae) are as follows: (i) Microalgae can offer productivity levels above those possible with terrestrial plants. (ii) There are currently several significant barriers to widespread deployment and many information gaps, but there is still significant room for improvement and breakthroughs. (iii) Many different options are still being considered and this is likely to continue with different systems suited to different types of algal organisms, climatic conditions, and ranges of products. Much of the basic information related to genomics, industrial design, and performance is not yet defined. (iv) Cost estimates for algal biofuels production vary widely, but the best estimates are promising at this early stage of the technology development. (v) The cost of producing algae is still too expensive for fuel production alone. The use of algae to produce a range of products for the food, feed and fuel markets via a ‘biorefinery approach’ is likely to prove to be an attractive strategy offering better chances for economic operation than systems aimed at solely producing biofuels. (vi) Lifecycle Assessments (LCA) are inevitably difficult to do at this stage in the development of the technology. However these studies indicate that careful design of systems will be required to ensure that there is a positive energy and carbon balance associated with algae production. Excessive energy requirements for pumping, concentration, and drying must be avoided, along with efficient use of residues and any waste heat generated.

2.6.1.3 Vulnerability and adaptation to climate change

Climate change is expected to have significant impacts on biomass production, causing yields to increase or decrease by up to 20% relative to current levels at 550 ppm CO2, depending on world regions (Easterling et al., 2007). Biomass feedstocks will be affected through either a change of the agro-ecological zones suitable for them or, for those plantations already established, increased environmental stresses and higher risks of yield losses. Since some candidate feedstocks are perennial species with cultivation cycles of 20 or more years, climate impacts should be anticipated for these particular systems, and are likely to be stronger than for annual crops (Easterling et al., 2007). However, there is currently limited knowledge on the impacts of climate change on energy feedstocks.

The largest ecophysiological uncertainty in future production changes is the magnitude of the CO2 fertilisation effect on plant growth, which can cause an enhancement of net primary production of around 20% under doubled free air CO2 concentration, under controlled experimental conditions (Easterling et al., 2007). Most current biogeochemical models assume a strong CO2 fertilisation effect with a levelling off at large atmospheric concentrations, due to .enhanced growth and increased water use efficiency. Indirect effects of climate change such as increased fire risk or the spread of pests cannot be quantified but may also come into play (Easterling et al., 2007).

2.6.1.4 Future outlook and costs

While area expansion for feedstock production is likely to play a significant role in satisfying an increased demand for biomass over the next decades, the intensification of land use through improved technologies and management practices will have to complement this option, especially if production is to be sustained in the long term. Crop yield increases have historically been more significant in densely populated Asia than in sub-Saharan Africa and Latin America and more so for rice and wheat than for maize and sugar cane. Actual yields are still below their potential in most regions (FAO, 2008b). Evenson and Gollin (2003) documented a significant lag in the adoption of modern high-yielding crop varieties, particularly in Africa. Just as increased demand for bioenergy feedstock induces direct and indirect changes in land use, it can also be expected to trigger changes in yields, directly in the production of energy crops and indirectly in the production of other crops – provided appropriate investments are made to improve infrastructure, technology and access to information, knowledge and markets. A number of analytical studies are beginning to assess the changes in land use to be expected from increased bioenergy demand. Even without genetic improvements in sugar cane in Brazil, yields could increases 20 percent over the next ten years simply through improved management in the production chain (Squizato, 2008).

Projections of future costs for biomass production are scant because of their connections with food markets (which are, as all commodities, volatile and uncertain), and the fact that many candidate feedstock types are still in the research and development phase. Costs figures for growing these species in commercial farms are little known yet, but will likely reduce over time as farmers ascend the learning curves, as past experience has shown for instance in Brazil (Wall-Blake et al., 2009). Under temperate conditions, the expenses related to the farm- or forest-gate supply of lignocellulosic biomass from perennial grasses or short rotation coppice is expected to fall under 2.5 US$/GJ by 2020 (WWI, 2006), from a 3-16 US$/GJ range today (see Table 2.3.1). However, another study in Northern Europe reports much higher projections, in a 3.7-7.5 US$/GJ range (Ericsson et al., 2009). These marginal expenses will obviously depend on the overall demand in biomass, increasing for higher demand levels due to the growing competition for land with other markets (hence the notion of supply curves, addressed in section 2.7; see Figure 2.2.5). For perennial species, the transaction costs required to secure a supply of energy feedstock from farmers may increase the production costs by 15% (Ericsson et al., 2009).

2.6.2 Improvements in biomass Logistics and supply chains

Optimization of supply chains includes the role of economies of scale in transport pre-treatment as well as in conversion technologies. Relevant factors include spatial distribution and seasonal supply patterns of the biomass resources, transportation, storage, handling and pre-treatment costs, scale economy of central plants (Nagatomi et al, 2008, Dornburg & Faaij, 2001). Smart combinations of biomass resources over time can help to gain economies of scale and year round supplies of biomass and thus efficient utilization of equipment (Nishii et al, 2005, Junginger et al., 2001, Hamelinck et al., 2005):

Advanced pre-treatment technologies

Torrefied wood is manufactured by heating wood in a process similar to charcoal production. At temperatures up to 160 ºC, wood loses water and little else. Most of its physical and mechanical properties remain intact, particularly its ability to absorb moisture. Torrefied wood typically contains 70% of its initial weight and 90% of the original energy content (Bradley et al, 2009). The moisture uptake of torrefied wood is very limited, varying from 1% to 6% (Uslu et al 2008 Torrefaction serves as a pre-conditioning process, producing uniform quality feedstock which eliminates inefficient and expensive methods to handle feedstock variations and thus make conversion and use of biomass feedstocks more efficient (Anon, 2000). Torrefaction technology is however not yet commercially available, but outlook studies suggest that the overall costs of producing torrefied biomass pellets results in lower production costs of pellets compared to conventional wood pellets, and lower energy costs. Overall energy efficiency of converting wood to torrefied wood pellets may amount over 90% for fully commercial systems.

Advanced pyrolysis processes converts solid biomass to liquid bio-oil, a complex mixture of oxidized hydrocarbons. Although toxic in nature and stabilization of the oil is needed for longer term storage, this liquid product is relatively easy to transport. Although pyrolysis oil production is more expensive and less efficient per unit of energy delivered compared to torrefied wood pellets pyrolysis offers specific advantages, compared with liquid fuels it has an estimated production cost of US$6.5/GJ, when using char and gases for process heat (Bain, 2007). The process allows for separation of a solid fraction (biochar) that contains the bulk of the nutrients of the biomass. With proper handling, such biochars can be used locally to improve soil quality, recycle nutrients and possibly store additional carbon in the soil for longer periods of time while at the same time improving soil properties and fertility. The economic prospects of this route are at the moment however poorly understood and the technology and biochar application need further research and optimization (Laird et al. 2009).

Learning and optimization in the past 1-2 decades in regions as Europe (Scandinavia and the Baltic in particular), North America, Brazil, but also in various developing countries have shown steady progress in market development and lowering costs of biomass supplies (see e.g. Junginger et al. 2006). Well working international biomass markets and substantial investments in logistic capacity are key prerequisites to achieve this (see also section 2.4).

It should however also be noted that while over time the lower costs biomass residues resources are increasingly utilized, more expensive (e.g., cultivated) biomass needs to cover growing demand. This may in some case off-set part of the lower supply costs due to learning and optimization as (E4tech, 2010) concludes that heat generation from pellets in the UK may be more costlier in future (2020) than today due to a shift from local to imported feedstocks. Similar (although limited) effects are found in (Londo et al., 2010) for scenario's of large scale deployment of biofuels in Europe.

2.6.3 Conversion technologies & bioenergy systems

As shown on Table 2.6.2, recent research and development emphasis is focused on producing hydrocarbon fuels from biomass. Among the drivers is the fact that jet fuels require nearly double the energy density of the most common commercial biofuel, ethanol, and more than ten percent higher energy density of biodiesel. In addition, fuels for military applications are also being developed from biomass, which also demand high energy density and strict specifications. Biofuel aviation tests are already ongoing both for commercial and military operations even though the technologies are not cost competitive yet (see, for instance, E4tech, 2009; DOE, 2009 microalgae; DOE, 2009).

There is significant room for research breakthroughs in this area generated by increased scientific understanding of biomass conversion with the increased ability to understand the chemistry, the biology, and the biochemistry at the molecular level with complex biomass materials. Biomass conversion have a broader range of conditions compared with those of conventional petrochemical processes. The presence of many carbon-oxygen bonds enables lower temperature processing leading to the exploration of a variety of conditions for chemical reactions such as mild conditions of aqueous phase reforming, molecular rearrangements such as isomerization and condensation reactions leading to molecular building in the appropriate molecular sizes and properties, as well as exploration of higher reactivity of biomass in vapor phase catalytic reactions (NSF, 2008).

An evolving emerging field is synthetic biology where microorganisms are engineered to produce biofuels – bringing scientific advances and tools from the medical field and high value drug production to the design of high volume fuels and chemicals (Keasling and Chou, 2008). Synthetic biology aims to bring engineering principles of modularization and componentization to the manipulation of genetic circuitry in microorganisms, so that engineering an organism for fuel production is as easy as assembling a computer (Lee et al., 2008). The U.S. Department of Energy (DOE, 2009) is fostering this field from its basic science to nurturing startup companies and partnerships toward development and commercialization.

Table 2.6.3 displays information on relevant bioenergy systems and chains, in various stages of development, which were illustrated in Figure 2.3.1. Where publicly available from the literature cost information is also provided. The technologies from Table 2.6.2 and Table 2.6.3 could be in commercial operation at global level by 2020 to 2030, depending on investments in support of continued research, development, demonstration, and results of first-of-a-kind plants under construction. For each end use of a bioenergy product, Table 2.6.3 presents information about the feedstock, processing technology, examples of country or region developing these technologies, and the estimated production cost, when available, projected usually from the performance of nth plants. Additional information about relevant technology development needs, and general comments, are also provided.

Table 2.6.2 Developing **Biofuels as Direct Replacement of Conventional Hydrocarbon Fuels (Source: E4tech, 2009; IEA ExCo, 2009). See Table 2.6.3 for available cost information.**

Renewable Fuel for Jet Fuel, Diesel, or Gasoline	Feedstock(s)	Conversion process	Development needed
Biomass to liquids (BTL)	Lignocellulosic materials (energy crops, forestry residues, wastes)	Gasification and Fischer Tropsch synthesis	Demonstration of plants at commercial scale
HRJ (Hydrotreated renewable jet) or Renewable Diesel	Conventional oil crops (soy, palm, rapeseed)	Oil extraction and hydrotreating	Deployment of conversion plants
	New oil crops under development: algae, carmelina, jatropha, saltwater farming (halophytes)	Oil extraction and hydrotreating. Whole algae solution could undergo catalytic liquefaction	RD&D on yield improvements, agronomy, and algal systems
'Synthetic hydrocarbons' also called drop-in hydrocarbons[1,2,3]	Nearer term: Sugars from sugar-rich crops like sugarcane or hydrolysis of starch from grains Longer term: Lignocellulosic materials after pretreatment and hydrolysis to mixtures of sugars	Biological syntheses to, e.g., isoprenoids[4,5]	RD&D to prove routes pilot stage
		Chemical catalytic routes for alkanes from aqueous phase reforming that combine hydrogenation and carbon-carbon condensation[6,7]	RD&D to prove routes at the pilot stage[8]
		Fermentation with engineered organisms to Butanol to Butene catalytic conversion to hydrocarbons	RD&D to prove routes at the pilot stage
Pyrolysis derived fuels	Lignocellulosic materials (energy crops, forestry residues, wastes)	Pyrolysis and upgrading through hydrotreating that could be done in an oil refinery[9]. Fossil fuel blendstocks as products[10]	RD&D on upgrading processes
Algal biomass derived fuels -- biodiesel, renewable diesel, HRJ and others	Whole algae, or the residues remaining after algal oil extraction	Routes above such as gasification, pyrolysis; from lipid fraction through esterification biodiesel or renewable diesel by hydrotreatment.	RD&D on production of feedstocks and conversion technologies. Multiple products possible
Biodiesel or Renewable Diesel	Sugars sugar crops or hydrolysis of starch (later lignocellulosic)	Dark fermentation using microalgae to triacyl-glycerides; extraction and esterification or hydro-treating to renewable diesel	RD&D to prove routes at the pilot stage

NSF, 2008; 2. DOE, 2009; 3. Tang, Zhao, 2009;4.Fortman et al., 2008; 5. Renninger and McPhee, 2008; 6. Huber et al., 2005; 7. Gurbuz et al. 2010; 8. Blommel and Cortright, 2008; 9. Holmgren, J. 2009; 10. Brandvold, 2009.

Table 2.6.3. **Table summarizing the state of the art of the main chains for future production of end use biofuels.**

Energy Product and End Use	**Processing**	**Feed-stock**	**Site**	**Efficiency and process economics Eff. = Energy Product Energy/Biomass Energy**	**% GHG reduction from fossil reference**	**Technical Advances**	**Production Cost by 2030 (US$/GJ)**	**Industrial Development**
Ethanol/ Transport	Separate Hydrolysis/ Fermentation	Ligno-cellulosic Barley straw	USA Finland	Eff. = 0.49 for wood and 0.42 for straw; includes integrated electricity production of unprocessed components[1]. Barley straw steam explosion followed by hydrolysis and fermentation estimated current production cost at $30/GJ [9]	NA	Efficient C5 conversion[2-4] Significant amount of investment in R&D[5] Engineering of enzymes using advanced biotechnologies[6]	8.5 to 10.5[1]	Many demonstration and pilots on various parts of the processes under way. Key are enzyme costs and pretreatment
	Simultaneous Saccharification &Fermentation						30[9] (Finland barley straw)	
	Consolidated Bioprocessing					lignin dissolution to produce a cellulose-rich residue[7]	13.5 to 16 [8] benchscale	
	Simultaneous Saccharification and Fermentation	Ligno-cellulosic	USA	Process efficiencies in kg/gallon for poplar, miscanthus, switchgrass, corn stover and wheat are: 14, 12, 10, 10, and 9, respectively. Plant sizes 1500 to 1000 tonnes/day. Raw material about 50% of total cost.[10]	83-88 Depending on co-product credit method[25]	Process integration - capital costs per installed liter of product range from $0.9 to $1.3 for plants of 150 to 380 million liters per annum. (2020 estimates)	18-22[10] (U.S. costs for wheat straw to poplar) Costs from pilot data	Several pilots and 1st commercial plants under way
		Bagasse	Brazil	Standalone plant[35] 370 L/t dry (ethanol) + 0.56 kWh/L EtOH (electricity)	86[36]	Improvements in mechanical harvest of sugarcane residues (already occurring)	6[35] w/o feed cost 15[35] w/ feed cost	
Hydro-carbons: gasoline/ diesel/jet fuel/waxes Transport	Gasification followed by Fischer-Tropsh process - Biomass to Liquids	Ligno-cellulosic	USA		91 [26]	BCCS for CO2 from processing	24 to 30[11]	One first commercial plant (wood) under way. Many worldwide demonstration & pilots processes under way.
			US	Eff.= 0.52 w/o CCS and 0.5 w/CCS with electricity coproduction of 35 and 24 MWe. 4000 tons/day of switchgrass. Plant cost ~$650 million		Gas clean up costs and scale. 2020 cost projections; could decrease with increased volume	25[10] (w/o BCCS)[10] 30[10] (w/ BCCS)	
	Fischer-Tropsh	Ligno-cellulosic	EU	via biomass gasification and subsequent syngas processing	90 [27]	Diesel without BCCS	14 to 18[5]	
Alcohols or bioplastics	Gasification followed by bioprocessing	Ligno-cellulosic	US/EU/ Canada	Syngas fermentation to ethanol or other alcohol; polyalkanoates from syngas by bacterial or other systems	NA	NA	NA	Exploratory phase to pilot (ethanol)

Energy Product and End Use	Processing	Feed-stock	Site	Efficiency and process economics Eff. = Energy Product Energy/Biomass Energy	% GHG reduction from fossil reference	Technical Advances	Production Cost by 2030 (US$/GJ)	Industrial Development
Renew-able Diesel/Jet Fuel Transport	Hydrogenation	Large variety of plant oils, animal fats	Many countries	Technology well known. Cost of feedstock is the barrier. Lower cost animal fats' processing under way	63-130 Depending on co-product credit method[26]	Feedstock costs drive this process. Process is standard in petrochemical operations	15-17[12] 17-18[34] Feed cost most important	Demonstrations and product tests in U.S., Brazil, EU. A few flights on biojet fuel from various plant oils conducted[33]
Fuel/ Power	Gasification/ Synthesis	Ligno-cellulosic	USA/ EU	Combined fuel and power production possible. Power at $0.07/kWh (2008) in Finland[13]	NA	BCCS for CO2 from processing	7 to 9.5[11]	NA
Bio-Butanol Transport	Fermentation; product compatible with gasoline infrastructure	sugar/ starch	USA/ EU	The development of an integrated system for biobutanol production and removal may have a significant impact on commercialization of this process using the solvent producing *Clostridia*[14] - initial acetone, butanol ethanol (ABE) fermentation is costly.	5-31% Depending on co-product credit method[29]	Recent developments [15, 16] lead to higher selectivity to butanol: e.g., mutated strain of *Clostridium beijernekei* BA101, or protein engineering in E. coli to increase selectivity and downstream processing of biobutanol. Alternatively a dual fermentation process to buryric acid and reduction to ethanol (Dual). Estimated production costs include return on capital[17]	Nearer term production costs from 29 for ABE to 22 for mutated Clostridia and 22 for Dual process[17] 18[18]	Large and small companies and ventures pursuing different routes. Gasoline additive and also jet fuel applications are being pursued.
	Gasification	Ligno-cellulosic	USA/ EU	Catalytic process for synthesis of predominantly butanols	NA	Estimated production costs include return on capital [17]	12-15 [17]	
Ethanol primarily Transport	Gasification/ Synthesis	Ligno-cellulosic	USA	Gasification followed by catalytic synthesis of ethanol and smaller amounts of propanol and butanol. Catalyst development and syngas cleaning issues	88 [30]	170 Million l per year plant (Ref 12 varies size).	12[12] to 15[18]	
Hydrogen Transport	Gasification/ Syngas processing	Ligno-cellulosic	USA/ EU	Combined fuel and power production possible	88 [30]	Research in gasification as basis for hydrogen production for fuel cells[19]	6 to 9.5 [19]	R&D stage
							6[20] to 12[12]	
Methane Heat, Power or Transport	Gasification/ Methanation	Ligno cellulosic	EU/ UK	Combined fuel and power production possible	98 [27]	RD&D on gas clean up and methanation catalysts	15.5 [21]	RD&D stage

Energy Product and End Use	**Processing**	**Feed-stock**	**Site**	**Efficiency and process economics Eff. = Energy Product Energy/Biomass Energy**	**% GHG reduction from fossil reference**	**Technical Advances**	**Production Cost by 2030 (US$/GJ)**	**Industrial Development**
Methanol	Gasification/ Synthesis	Ligno-cellulosic	US/ EU	Combined fuel and power production possible	90 [27]	Methanol and dimethylether production possible in various configurations that coproduce power	12 to 18 [11]	RD&D stage
CHP	Integrated Gasification Combined Cycle	Ligno-cellulosic	World-wide	In district heat production, the power-to-heat ratio of this concept is 0.8 – 1.2, the power production efficiency 40-45 % and the total efficiency 85 to 90 %. Investment 1200$/kWh*th*. Feedstocks wood residues in Finland[22]	96 [31]	Gas cleaning, increased efficiency cycles, cost reductions	8 to 11[11]	Actively pursued with many demonstrations worldwide
Algal Biodiesel or Renew-able Diesel	Lipid production, extraction, and conversion to biofuel. Remainder of algal mass can also be converted to fuels through other processes	Micro-algae	USA/EU/ Israel	Assuming biomass production capacity of 10,000 t/yr, cost of production per kg is $0.47 and $0.60 for photobioreactors and raceways, respectively.[23]	68-89 Scenarios for open pond and bio-reactor[32]	Assuming[32] biomass contains 30% oil by weight, cost of biomass for providing a liter of oil would be $1 to $3 and $1.5- to $5 for algae of Low Productivity =2.5 g/m^2/day or High Productivity=10 g/m^2/day in open ponds or photobiological reactors (PBR)	Preliminary Results 95 or more[23] 30-80[32] for open ponds 50-140[32]for PBR going from low to high productivity	R&D actively pursued by companies small and large including pilots pursuing jet and diesel fuel substitutes.

1UK DFT, 2008; 2Jeffries, 2006; 3Jeffries et al., 2007; 4Balat et al, 2008; 5Sims et al, 2008; 6 Bom and Ferrara, 2007; 7 Tuskan, 2007; 8Kumar et al, 2008; 9 von Weyman, 2007; 10 NRC, 2009; 11 IEA Bioenergy: ExCo,2007; 12 Bain 2007; 13 McKeough et al. 2008; 14 Wu et al., 2007;15 Ezeji et al., 2007a;16 Ezeji et al., 2007b; 17 Cascone 2008; 18 Tao and Aden 2009; 19Riegelhaupt et al., 2009; 20 Hoogwijk, 2004; 21 Sustainable Transport Solutions 2006; 22 Helynen et al. 2002; 23 Chisti, 2007; 24Pienkos, Darzins 2009; 25. Wang, 2010; 26. Kalnes et al., 2009; 27. Edwards et al., 2008; 28. Huo et al., 2009; 29. Wu et al., 2007; 30. Laser et al., 2009; 31. Daugherty, 2001; 32. IEA, 2010; 33. E4tech, 2009; 34. EPA, 2010; E4tech, 2009; 34. EPA, 2010; 35. Seabra et al., 2010; 36. Macedo and Seabra, 2008.

2.6.3.1 Liquid Fuels

Gasification of solid biomass is a promising technology for production of power and or heat based in the use of solid biomass, with high efficiency gains expected especially in the case of polygeneration with Fischer-Tropsch fuels (Williams et al., 2009).

Biotechnology can be applied to improve the conversion of biomass to liquid biofuels. Several strains of micro-organisms have been selected or genetically modified to increase the efficiency with which they produce enzymes (FAO, 2008d). Many of the current commercially available enzymes are produced using genetically modified (GM) micro-organisms where the enzymes are produced in closed fermentation tank installations (e.g., Novozymes, 2008). The final enzyme product does not contain GM micro-organisms (The Royal Society, 2008) suggesting that genetic modification is a far less contentious issue here than with GM crops.

Coupled to improved corn ethanol facilities or any other biomass processing method that releases concentrated forms of CO2, coproduct CO2 utilization is likely to continue. Most of the ethanol plants, because of the low commercial value of CO2, simply vent it into the air. CO2 capture from sugar fermentation to ethanol is possible (Mollersten, et al., 2003). The experience of ethanol manufacturers from corn of supplying CO2 for carbonated beverages, flash freezing meet, and enhanced oil recovery of depleted fields may be useful now in the biological carbon sequestration BCCS area. A few companies are demonstrating these concepts in the United States such as the Midwest Geological Sequestration Consortium will inject nearly a million tonne of CO2 from an ethanol plant over three years into the Mount Simon sandstone formation in central Illinois. An evaluation of the impact of this technology ((S&T)2 Consultants Inc., 2009) showed that it could reduce the life-cycle GHG emissions of ethanol by 70% at the expense of degrading its energy balance by only 3.5% (see Table 2.5.2 for performance in different functional units).

Internationally, there is an increased interest in the commercialization of lignocellulose to ethanol technology (a 2nd generation pathway). It involves a pre-treatment to separate and partially hydrolyze fibers, usually with acid solutions or steam explosion, to release cellulose and hemicellulose compounds. The resulting sugar stream can then be fermented, using improved methods to allow both hexose and pentose sugars to be fermented simultaneously into ethanol. Research efforts have improved yields and reduced the time to complete the process, and a total of 16 plants were under construction in the USA in 2009 (US Cellulosic, 2009). Nevertheless, attempts to economically transform cellulose in sugars date back at the start of the 20th-century. It is expected that, at least in the near to medium-term, the biofuel industry will grow only at a steady rate and encompass both 1st- and 2nd-generation technologies that meet agreed environmental, sustainability and economic policy goals. The transition to an integrated 1st- and 2nd generation biofuel landscape is therefore most likely to encompass another decade or two (Sims et al, 2008).

Regarding diesel substitution, the difficulty to reduce cost through the first generation process (see Table 2.3.3 for examples of conditions) suggests as a possible alternative the thermo-chemical route. The thermo-chemical route is largely based on existing technologies that have been in operation a number of decades. Hydrogenation technologies have already produced significant quantities of direct diesel substitutes for testing. However, their costs are also highly dependent on the plant oil cost and of the subsidies. Using lignocellulosic materials would lead to the most cost effective options. Some routes produce and upgrade liquids from fast pyrolysis processes (see Table 2.6.2) while others employ the versatile gasification of the biomass, producing a clean gas of an acceptable quality and the high intrinsic cost of the process. Gasification elements of the thermo-chemical platform for the production of biofuels are close to commercial viability today using various technologies and at a range of scales (see Table 2.6.3), although reliability of the process is still an issue for some designs. Another area where some progress may be expected is the possibility of using biomass residues from vegetable oil feedstocks as a source of energy. The utilisation of straw to produce process heat and power would make a strong contribution to the total net energy supply from crops (BABFO, 2000).

There is currently no clear commercial or technical advantage between the biochemical and thermochemical pathways for liquid biofuels, even after many years of RD&D and the development of near-commercial demonstrations (Foust et. al., 2009). Both sets of technologies remain unproven at the fully commercial scale, are under continual development and evaluation, and have significant technical and environmental barriers yet to be overcome. Given the uncertainties in the estimates, the various routes are not distinguishable in costs (McAloon et al., 2000; Hamelinck et al., 2005, Kumar et al., 2008). Alternative technologies for diesel and gasoline substitution include biomass pyrolysis oil upgrading in conjunction with hydrodeoxygenation and catalytic upgrading (de Feber and Gielen, 1999). Proof of principle exists for this route for corn stover-derived pyrolysis oils and through the examples shown on Tables 2.6.2 and 2.6.3.

2.6.3.2 Gaseous Fuels

Anaerobic digestion New technologies like fluorescence in situ hybridisation (Cirne et al., 2007) allows the development of strategies to stimulate hydrolysis further and ultimately increasing the methane production rates and yields from reactor-based digestion of these substrates (FAO, 2008d). A range of other biotechnologies are also being applied in this context, such as the use of metagenomics (i.e. isolating, sequencing and characterising DNA extracted directly from environmental samples) to study the micro-organisms involved in a biogas producing unit in order to improve its operation.[6] Recently marine algae have also been studied for biogas generation (Vergana-Fernandez, 2008). These advances could lead to significant cost reductions in the production of methane from a variety of waste streams combined, with a higher proportion of lignocellulosic materials. Control and automation technologies may make increase reliability of this technology and along with improved gas clean up and upgrading could make gas injection to natural lines (stand alone or grid) a more widespread application at small or large scales.

Microbial fuel cells using organic matter as a source of energy are being developed for direct generation of electricity, through what may be called a microbiologically mediated oxidation reaction. This implies that the overall conversion efficiencies that can be reached are potentially higher for microbial fuel cells compared to other biofuel processes. Microbial fuel cells could be applied for the treatment of liquid waste streams (Rabaey and Verstraete, 2005.

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[6](See, for instance, http://www.jgi.doe.gov/sequencing/why/99203.html)

Synthesis gas Progresses in scale-up, exploration of new and advanced applications, and efforts to improve operational reliability, have identified several hurdles to advance the state-of-the-art of biomass gasifiers. They include among others handling of mixed feed stocks, minimising tar formation in gasification, tar removal, and process scale-up (Yokoyama and Matsumura, 2008). To tackle the problem of tar content, particularly for power generation, multistage gasification systems (BMG) technologies are being designed and developed to produce Medium Calorific Value (MCV) gas (Fargernas et al., 2006).

2.6.3.3 Biomass with CO2 capture and storage (CCS): negative emissions

Biomass-CCS (Obersteiner et al., 2001; Yamashita and Barreto, 2004; Mollersten et al., 2003; Rhodes and Keith, 2007, Pacca and Moreira, 2009) could substantially change role of biomass-based mitigation. Biomass-CCS may be capable of cost-effective indirect mitigation—through emissions offsets—of emission sources that are expensive to mitigate directly (Rhodes and Keith, 2007). More generally, the most expensive emissions to abate directly could be mitigated indirectly with offsets from biomass-CCS systems deployed wherever (in the world) they are least expensive.

2.6.3.4 Biorefineries

The concept of biorefining is analogous to current petroleum refining, which leads to an array of products including liquid fuels, other energy products and chemicals (NREL, 2009; Kamm, Gruber and Kamm, 2006). Although the biofuel and associated co-products market are not fully developed, first generation operations that focus on single products (such as ethanol and biodiesel) are regarded as a starting point in the development of sustainable biorefineries, mainly the ones using sugar cane where electricity is usually generated and even exported to the grid (EPE, 2008). Advanced or second generation biorefineries are developing on the basis of more sustainably-derived biomass feedstocks, with a further essential feature being the enhanced integration of energy and material flows. These biorefineries optimize the use of biomass and resources in general (including water and nutrients), while mitigating GHG emissions (Ragauskas et al., 2006).

2.6.3.5 Bio-based products

Bio-based products are defined as non-food products derived from biomass (e.g., from plants, algae or biological waste from households). The term is typically used for new non-food products and materials such as bio-based plastics lubricants, surfactants, solvents and chemical building blocks. Traditional paper and wood products, but also biomass as an energy source are generally excluded (EU Commission Report, 2007). In today’s chemical and petrochemical industry, plastics represent 73% of the total petrochemical product mix, followed by synthetic fibres, solvents, detergents, and synthetic rubber (Gielen et al., 2008). These product categories, and in particular plastics and fibres, can therefore be expected to play a pivotal role among the bio-based products.

The four principal ways of producing polymers and other organic chemicals from biomass are: (i) Direct use of several naturally occurring polymers usually modified with some thermal treatment, chemical derivatization, or blending. (ii) Convert biomass thermochemically (e.g., pyrolysis or gasification), followed by synthesis and further processing. (iii) Convert biomass-derived sugars or other intermediates using fermentation processes (for most bulk products) or enzymatic conversions (mainly for specialty and fine chemicals). (iv) Bioproduction of polymers or precursors in genetically modified field crops such as potatoes or miscanthus.

Many bio-based plastics and other bio-based products are likely to be produced in energy self sufficient ways and could deliver additional energy using renewable biomass, thereby completely replacing fossil energy sources. As a consequence, a biorefinery could actually be carbon neutral. This is not yet the case today. However, it can be expected that the energy use and the concomitant impacts related to biomaterials production will decrease in future not only as a consequence of technical progress within these processes but also due to the use of cleaner grid power.

A study carried out in 2009 (Shen et al., 2009) estimated the worldwide production of recently emerging bio-based plastics is expected to grow from less than 0.4 million tonnes in 2007 (and expected 2.3 Mt in 2013, see above) to 3.45 Mt in 2020 (now potentially delayed). Model calculations for Europe (EU-25) for an extended timeframe until 2050 show largely diverging results: in case of disadvantageous conditions (i.e., high prices for fermentable sugar and low fossil fuel process) bio-based polymers and chemicals hardly emerge while under favourable conditions (low prices for fermentable sugar, large fossil fuel process increasing up to US$ 85/barrel and large growth of the sector) approximately 110million tonnes of (fermentation-based) could be produced in EU-25 (Dornburg et al., 2008; see also Hermann et al., 2007b). Compared to frozen efficiency this would offer savings by 2050 of up to nearly 40% for starch as feedstock and up to 67% for lignocellulosic feedstocks.

For the production of synthetic organic materials, land use typically ranges from 0.2 to 0.35 hectares/tonne, with larger land requirements for specific products (e.g., nearly to 0.5 hectares/tonne for polyethylene; Patel et al., 2006). Under the assumption producers of bio-based polymers and chemicals will minimize their resource requirements, at productivity of 0.15 hectares/tonne, an area of 75 million hectares globally around by the year 2020 or to 15-30 EJ, could lead to value added products.

Given the early stage of development, the abatement costs differ substantially. For high-value starch plastics with a large content of petrochemical compounds, GHG abatement costs may today be in the order of US$ 500/t CO_2 and even more while simple starch/polyolefin blends may be sold at lower prices than petrochemical polyolefins, resulting in negative abatement costs (win-win situation). However, the latter type of material has less attractive material properties and is therefore quite limited regarding its application potential. The current abatement costs related to polylactic acid are estimated at US$ 100 to US$ 200 per tonne of abated CO_2. Today's abatement costs related to bio-based polyethylene, if produced from sugar cane based ethanol, may be in the order of US$ 100/t CO_2 or lower.

2.6.4 Conclusions

Estimated production costs of a variety of these advanced technology products (see Table 2.6.3) could become competitive with the price of fossil derived fuels with continued RD&D. Since many of the options require a much more difficult set of pretreatment of the biomass material than the starch/sugar counterparts, overcoming this recalcitrance is of paramount importance. Ongoing science and technological developments are continuing to overcome this significant challenge. Once unlocked, these biomass derived sugars could expand the range of biomass derived products that can be made and truly become the renewable carbon "petroleum". Science and technology of the past ten years shows that chemical, catalytic, biological syntheses and biochemical routes can make ethanol, simple alcohols, as well as any carbon based fuel molecule present in today's gasoline, diesel and jet fuel. This versatility is important as there are potential substitutes for gasoline (electric vehicles or electric drives in hybrids) but there are many applications that require high energy density fuels.

Sugars are not the only intermediates from which today's set of fuels can be derived. Gasification is another route that unlocks the potential of a more developed catalytic chemistry and engineering that is already in practice today with coal and natural gas to be applied to biomass. Should the carbon capture and storage technologies under investigation to sequester fossil carbon reach commercialization, the companion biomass routes will enable renewable carbon to be added to fossil carbon sequestration (see Figure 2.5.1). Newer discoveries of transforming pyrolysis oils, which maintain most of the energy of the wood in liquid form for processing, in a centralized or distributed manner, open a route to utilizing petroleum processing facilities on biomass feedstocks. Decentralized routes can provide rural development opportunities to countries small and large.

Significant progress has been made in utilizing organic wastes from various sources as a source of biomethane. European countries are ahead in the utilization of these routes. These natural gas supplements or substitutes are important fuels where natural gas use is prevalent in the specific country matrix and for diversification of energy sources.

While the science and the technology are moving and indicating substantial potential, it will not be achieved unless the demonstration, first commercial, and follow up plants continue to be demonstrated on an integrated basis. There are many parts of the new bioenergy chains that have not been demonstrated for the types of processes discussed here. The demonstration and commercialization will enable better knowledge of production costs and decreased risk for investors in these technologies. These efforts are expensive but required for the development of broad range of biomass derived products. Industry is already taking on the development of several new biobased products because of their properties and the need to address alternative resources that could be or become less expensive than their conventional counterparts. Energy research needs to continue addressing key barriers – one of which is the integration of the overall system from seedling to the final emissions of last product use (or reuse or recycle as in cascading uses of biomass products) in conjunction with measures of overall system sustainability as discussed (see Table 2.5.2). Technology development mindful of the environmental and social aspects described in Section 2.5 can deliver sustainable bioenergy technologies for the world at large.

Table 2.7.1: Estimated geographical potential of energy crops for the year 2050, at abandoned agricultural land and rest land at various cut off costs (in U$2005) for the two extreme land-use scenarios A1 (e.g., high crop growth intensity and high trade in 2050) and A2 (e.g., low crop intensity growth and low international trade in 2050) [Hoogwijk et al., 2009]

Region	A1			A2		
	> 1 $ GJ^{-1}	> 2 $ GJ^{-1}	> 4 $ GJ^{-1}	> 1 $ GJ^{-1}	> 2 $ GJ^{-1}	> 4 $ GJ^{-1}
Canada	0	12.9	16.2	0.0	9.0	10.7
USA	0	20.2	38.5	0.0	7.8	21.2
C. America	0	7.9	14.7	0.0	2.3	3.3
S.America	0	13.3	83.3	0.0	6.0	16.8
N.Africa	0	1.0	2.3	0.0	0.8	1.5
W Africa	7.5	29.9	32.3	9.0	16.6	17.6
E. Africa	9.2	27.0	27.7	4.1	7.0	7.3
S.Africa	0	14.2	18.8	0.1	0.3	0.8
W.Europe	0	3.4	13.0	0.0	6.3	14.2
E. Europe	0	7.7	10.1	0.0	7.0	7.1
F.USSR	0	89.1	96.3	0.9	47.5	52.8
Middle East	0	0.1	3.4	0.0	0.0	1.5
South Asia	0.1	13.7	17.3	0.7	9.3	11.1
East Asia	0	18.5	72.1	0.0	0.0	6.6
S. East Asia	0	10.0	11.0	0.0	7.8	7.9
Oceania	0.8	37.9	39.9	1.8	18.8	20.4
Japan	0	0.0	0.1	0.0	0.0	0.0
Global	17.6	306.8	496.8	16.6	146.6	200.7

2.7 Cost trends

2.7.1 Determining factors

Determining the costs of production of energy (or materials) from biomass is complex because of the regional variability of the costs of feedstock production and supply and the wide variety of biomass – technology combinations that are either deployed or possible. Key factors that affect the costs of bioenergy production are:

- For crop production: the cost of land and labor, crop yields, prices of various inputs (such as fertilizer), supply of water, and the management system (e.g., mechanized versus manual harvesting).
- For the supply of biomass to a conversion facility, spatial distribution of biomass resources, transport distance, mode of transport and the deployment of pre-treatment technologies (early) in the chain are key factors. Supply chains ranges from use on-site (e.g., fuel wood or use of bagasse in the sugar industry, or biomass residues to other conversion facilities) up to international supply chains with shipping pellets or liquid fuels such as ethanol.

- For final conversion to energy carriers (or biomaterials) the scale of conversion, interest rate, load factor, production and value of co-products and costs of energy carriers (in the production facility) required for the process are key factors that vary between technology and location. Types of energy carrier used in the process influence the climate mitigation potential.

Biomass supplies are, as any commodity, subject to pricing mechanisms. Biomass supplies are strongly affected by fossil fuel prices (see, for instance, global trade models of the OECD, Global Trade Analysis Project of Purdue University) as well as agro-commodity and forest product markets. Although in an ideal situation demand and supply will balance and production and supply costs provide a good measure for actual price levels, this is not a given (see also Section 2.5.3 discussions on land use change). At present, market dynamics determines the costs of the most important feedstocks for biofuels, such as corn, rapeseed, palm oil and sugar. For wood pellets, another important fuel for modern biomass production which is internationally traded, prices have been strongly influenced by oil prices (since wood pellets partly replace heating oil) and by supportive measures to stimulate green electricity production, such as feed-in tariffs of co-firing. (see, e.g., Junginger et al., 2008 and Section 2.4). In addition, prices of solid and liquid biofuels are determined by national settings and specific policies and the market value of biomass residues is often determined by price mechanisms of other markets for which there may be alternative applications influenced by national policies (see Junginger et al., 2001).

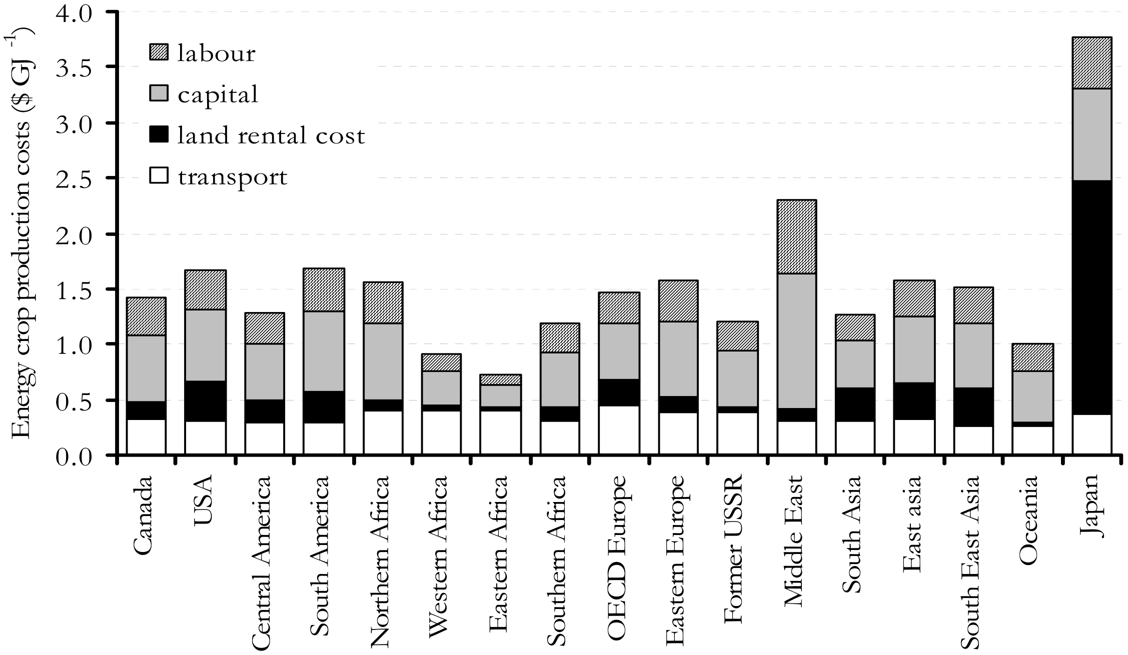


Figure 2.7.1: Cost breakdown for energy crop production costs in the grid cells with the lowest production costs within each region for the A1 scenario in year 2050 (Hoogwijk et al., 2009).

On a global scale and longer term, the analyses of Hoogwijk et al. 2009 provide a long-term outlook of potential biomass production costs (focused on perennial cropping systems) on the long term, related to the different SRES scenario's (see Table 2.7.1, and Figure 2.7.1). Land rents, although a smaller cost factor in most world regions, is made dependent on intensity of land use in the underlying scenarios. Based on these analyses, a sizeable part (100 – 300 EJ) of the technical biomass potentials on long term could lay in a cost range around U.S. $2.4/GJ.

Table 2.7.2: Generic overview of performance projections for different options to produce heat and power from different biomass resource categories on shorter (~5) and longer (>~20) years (e.g., based on: Hamelinck and Faaij, 2006; Faaij, 2006; Bauen et al., 2009b; IEA Bioenergy, 2007).

Biomass feedstock	**Heat**		**Electricity**	
	Short term; roughly stabilizing market	Longer term	Short term; strong growth market worldwide	Longer term; growth may stabilize due to competition of alternative options
Organic wastes (i.e. MSW etc.)	Undesirable for domestic purposes (emissions); industrial use attractive; in general competitive.	Especially attractive in industrial setting and CHP. (Advanced combustion and gasification for fuel gas)	<3 – 5 U$ct for state-of-the art waste incineration and co-combustion as well as digestion of wet organic wastes. Economics strongly affected by tipping fees and emission standards.	Similar range; improvements in efficiency and environmental performance, in particular through IG/CC technology at large scale.
Residues: Forestry Agriculture	Major market in developing countries (<1-5 U$/kWhth); stabilizing market in industrialized countries.	Especially attractive in industrial setting and CHP. Advanced heating systems (domestic) possible but not on global scale	4-12 U$ct/kWh (see below; major variable is supply costs of biomass); lower costs also in CHP operation and industrial setting depending on heat demand.	2-8 U$ct/kWh (see below; major variable is supply costs of biomass)
Energy crops: (perennials)	N.A.	Unlikely market due to high costs feedstock for lower value energy carrier; possible niches for pellet or charcoal production in specific contexts	6-15 U$ct/kWh High costs for small scale power generation with high quality feedstock (wood) lower costs for large scale (i.e. >100 MWth) state-of-the art combustion (wood, grasses) and co-combustion.	3-9 U$ct/kWh Low costs especially possible with advanced co-firing schemes and BIG/CC technology over 100-200 MWe.

As discussed in Sections 2.3 and 2.6, biomass energy systems are very flexible and can provide wide range of different energy and other products. The bioenergy production costs vary depending on feedstock type, conversion technology and scale, type of process energy used, and final energy carrier produced and coproducts.

Table 2.7.2 summarizes literature data for power and heat from various sources of literature for a variety of systems and scales of production in the near and longer term. In Table 2.7.3 we summarize the estimated production costs collected from various references in the literature and from a variety of countries in Sections 2.3 and 2.6. We did not perform a harmonization study on these various costs but reported them from the literature. As many of the technologies are under development in 2.6, cost knowledge only improves with demonstrations and commercial implementation.

Table 2.7.3: Global overview of current and projected select bioenergy technology estimated production costs. For technology performance data and references see Tables 2.3.3 and 2.6.3

End Use	Select Bioenergy Technology	Energy Sector (Electricity, Thermal, Transport)*	Present Estimated Production Costs (US$)	2020-2030 Estimated Production Costs (US$)
HEAT	Fuelwood and charcoal direct use (traditional)	Thermal	6.3-9.6/GJ	1-6/GJ
	Cookstoves (primitive and advanced)		0-8/GJ	N/A
	Smaller and large scale boilers		1-12.5/GJ	N/A
ELECTRICY	CHP in key industries (paper & pulp, sugar)	Electricty (some options CHP)	4.8/GJ (BR, sugarcane)	8.5-11/GJ
	Combustion (large and small), gasification (small), and co-firing based stand alone power generation		4.2-10/GJ (large) 1-4/GJ gasif.(small, India)	6-8/GJ
	Digestion (larger scale)		20-28/GJ	N/A
	Gasification based power generation (larger scale; BIG/CC)	Could be combined with fuels for Transport (CCS possible)	Not commercially available	7-9.5/GJ
FUELS	Sugar cane based ethanol production	Transport Fermentation routes (CCS possible)	10-15/GJ (BR)	9-10/GJ (BR)
	Corn based ethanol production		20-21/GJ (US)	18/GJ (US)
	Wheat based ethanol production		41/GJ (EU)	Approx. 39/GJ
	Soy, rapeseed, and palm based biodiesel production	Transport (heavy duty) and electricity in developing countries (includes raw oil)	23.5-49/GJ (US)	25-37/GJ
	Jatropha based biodiesel production		N/A	15-25/GJ (Feed 2.9/GJ)
	Plant oil or biomass pyrolysis oil derived hydrotreatment/hydrocracking to gasoline, diesel, and jet fuel (Drop in substitutes)	Multimodal Transport: Gasoline, Diesel, and Jet Fuels and a variety of coproducts (CCS possible)	Not commercially available	15-18/GJ Renewable Diesel
	Lignocellulose sugar-based ethanol, butanol, or renewable gasoline, diesel, and fuel production (can be equiped with CCS). Can also use sugarcane, corn, wheat and other crops.		Not commercially available	8.5-17/GJ (US/EU) (for lignocellulosic ethanol); 6-15 (BR) bagasse
	Lignocellulose based synfuel production (i.e., synthetic diesel, MeOH, DME, H2; and fermentation of biological routes to ethanol or plastics).		Not commercially available	12-18/GJ (US/EU) alcohols 14-30/GJ (US/EU) synth. Diesel

*Algae-based fuels and chemicals are also categories under development with higher cost uncertainties at this stage of development. Industrial products include biobased chemicals as replacements of traditional ones or new for polymers for packaging, carpets, surfactants, and other products and biobased construction materials.

2.7.2 Technological learning in bioenergy systems

Cost trends and technological learning in bioenergy systems have long been less well described than solar or wind energy technologies. Recent literature however gives more detailed insights in the experience curves and progress ratio's of various bioenergy systems. Table 2.7.4 and Figure 2.7.2 summarizes a number of analyses that have quantified learning as expressed by their progress ratio (PR) and experience curves for three commercial biomass systems: (i) sugarcane based ethanol production (Van den Wall Bake et al., 2009), (ii) corn based ethanol production (Hettinga et al., 2009), (iii) wood fuel chips and CHP in Scandinavia (Junginger et al., 2005 and a number of other sources). PR denotes the progress ratio, expressing the rate of unit cost decline with each doubling of cumulative production. For example, a PR of 0.8 implies that after one doubling of cumulative production, unit costs are reduced to 80% of the original costs or, in other words, the cost decreased by 20%. The definition of the 'unit' may vary depending on the study variable. See also absolute performance of the two major commercial ethanol systems, shown in Table 2.5.1 in terms of a variety of functional units related to climate impact and fossil energy, as a function of time.

Table 2.7.4. Overview of experience curves for biomass energy technologies / energy carriers. Cost/price data collected from various sources (books, journals, press releases, interviews) PR = Progress Ratio, R2 is the correlation coefficient of the statistical data.

Learning system	PR (%)	Time frame	Region	n	R^2
Feedstock production					
Sugarcane (tonnes sugarcane) Van den Wall Bake et al.; 2009	68±3	1975-2003	Brazil	2.9	0.81
Corn (tonnes corn) Hettinga et al, 2009	55±0.02	1975-2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden) Junginger et al., 2005	85-88	1975-2003	Sweden / Finland	9	0.87-0.93
Investment & O&M costs					
CHP plants (€/kW$_e$) Junginger et al., 2005	75-91	1983-2002	Sweden	2.3	0.17-0.18
Biogas plants (€/m^3 biogas/day) Junginger et al., 2006a	88	1984-1998		6	0.69
Ethanol production from sugarcane Van den Wall Bake et al.; 2009	81±2	1975-2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs) Hettinga et al, 2009	87±1	1983-2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane Goldemberg et al., 2004	93 / 71	1980-1995	Brazil	~6.1	n.a.
Ethanol from sugarcane Van den Wall Bake et al., 2009	80±2	1975-2003	Brazil	4.6	0.84
Ethanol from corn Hettinga et al., 2009	82±1	1983-2005	USA	6.4	0.96
Electricity from biomass CHP Junginger et al., 2006a	91-92	1990-2002	Sweden	~9	0.85-0.88
Electricity from biomass IEA, 2000	85	Unknown	EU (?)	n.a.	n.a.
Biogas, Junginger et al., 2006a	85- 100	1984-2001	Denmark	~10	0.97

n Number of doublings of cumulative production on x-axis.

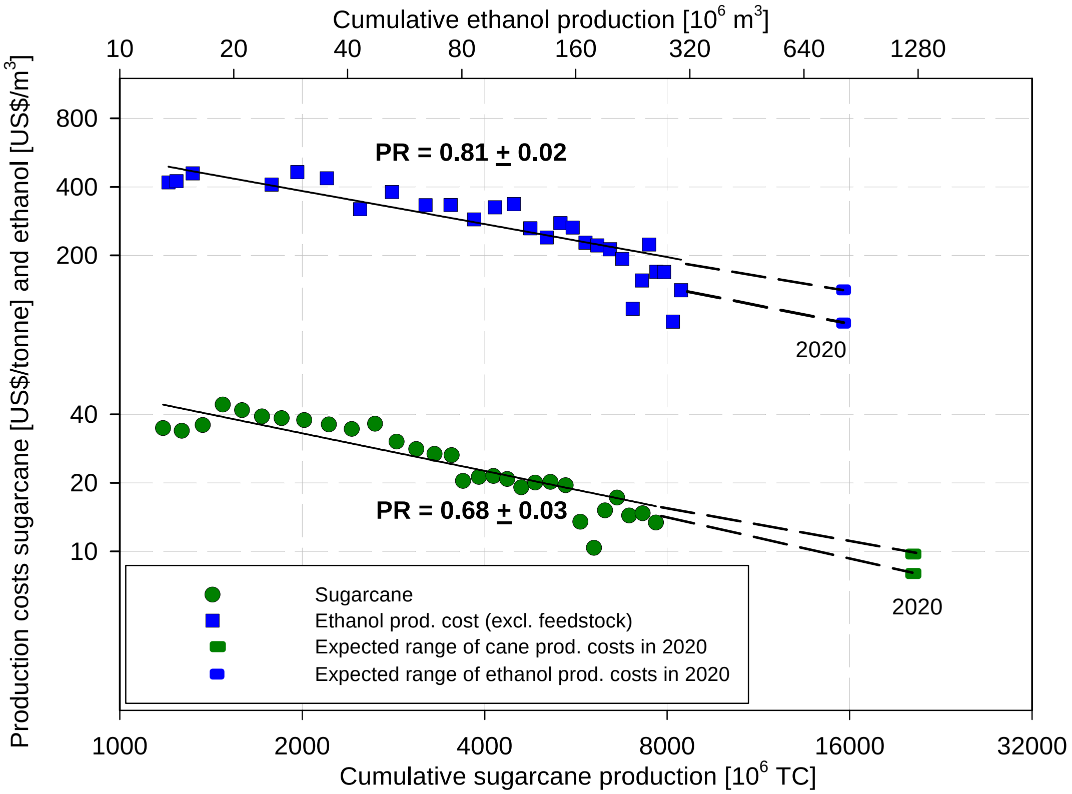


Figure 2.7.2: Experience curves for sugarcane production costs and ethanol production costs in Brazil between 1975-2005, and extrapolation to 2020 (Wall-Bake et al., 2009).

Learning and experience curves studies has accuracy limitations (Junginger et al., 2008). Yet, there are a number of general factors that drive cost reductions that can be identified:

For the production of sugar crops (sugarcane) and starch crops (corn) (as feedstock for ethanol production), increasing crop productivity yields has been the main driving force behind cost reductions. For instance, for sugarcane, varieties of sugarcane developed through R&D efforts by research institutes with increased sucrose content and thus ethanol yield; prolongation of the ratoon systems, increasingly efficient manual harvesting and the use of larger trucks for transportation reduced feedstock costs. More recently, mechanical harvesting of sugarcane is replacing manual harvest, increasing the amount of residues for electricity production (Wall Bake et al. 2009; Seabra et al., 2010; see Table 2.5.1). For the production of corn, highest cost decline occurred in costs for capital, land, and fertilizer until 2005. Main drivers behind cost reductions were increased plant sizes through cooperatives that enabled higher production volumes, efficient feedstock collection, and decreased the investment risk through government loans and the introduction of improved efficiency natural gas-fired ethanol plants, now responsible for nearly 90% of production. Higher corn yields by introducing corn hybrids genetically modified to have higher pest resistant enabled increasing adoption of no-till practices and significantly improved water quality (Hettinga et al., 2009; NAS, 2010; see Table 2.5.1). While it is difficult to quantify the effects of each of these factors, it seems clear that R&D efforts (realizing better plant varieties), technology improvements, and learning-by-doing (e.g., more efficient harvesting) played important roles.

Industrial production costs for ethanol production from both sugarcane and corn mainly decreased because of increasing scales of the ethanol plants. Cost breakdowns of the sugarcane production process showed reductions of around 60 percent within all sub processes. Ethanol production costs (excluding feedstock costs) declined by a factor of three between 1975 and 2005 (in real terms, i.e., corrected for inflation). Investment and operation and maintenance costs declined mainly due to economies of scale. Other fixed costs, such as administrative costs and taxes did not fall dramatically, but cost reduction can be ascribed to application of automated administration systems. Declined costs can mainly be ascribed to increased scales and load factors.

For ethanol from corn, ethanol processing costs (without costs for corn and capital) declined by 45% from 240 U$ per m^3 in the early 1980's to 130 U$ per m^3 in 2005. Costs for energy, labour and enzymes contributed in particular to the overall decline in costs. Key drivers behind these reductions are higher ethanol yields, the introduction of specific and automation and control technologies that require less energy and labour and lastly the upscaling of average dry grind plants (Hettinga et al, 2009).

2.7.3 Future scenarios for cost reduction potentials

Only for the production of ethanol from sugarcane and corn, future production cost scenarios based on direct experience curve analysis were found in the literature:

For ethanol from sugarcane (Wall Bake et al., 2009), total production costs at present are approximately 780 RS_{2005}/m^3 ethanol. Based on the experience curves for feedstock and industrial costs, total ethanol production costs in 2020 are estimated between 460 – 600 RS_{2005}/m^3 Values in U$ come with uncertainty, because the exchange rate of the Brazilian Real fluctuated from 2.3 RS/U$ in 2005 to 3.6RS/U$ in 2004 (while in such a short timeframe production costs did not change significantly). Production costs of ethanol expressed in $U\$_{2005}$ therefore lay in a range of 220 –340 U$/m3 (10 – 16 U$/GJ) at present and could amount 8-12 U$/GJ by 2020 following the identified improvement potential in that timeframe.

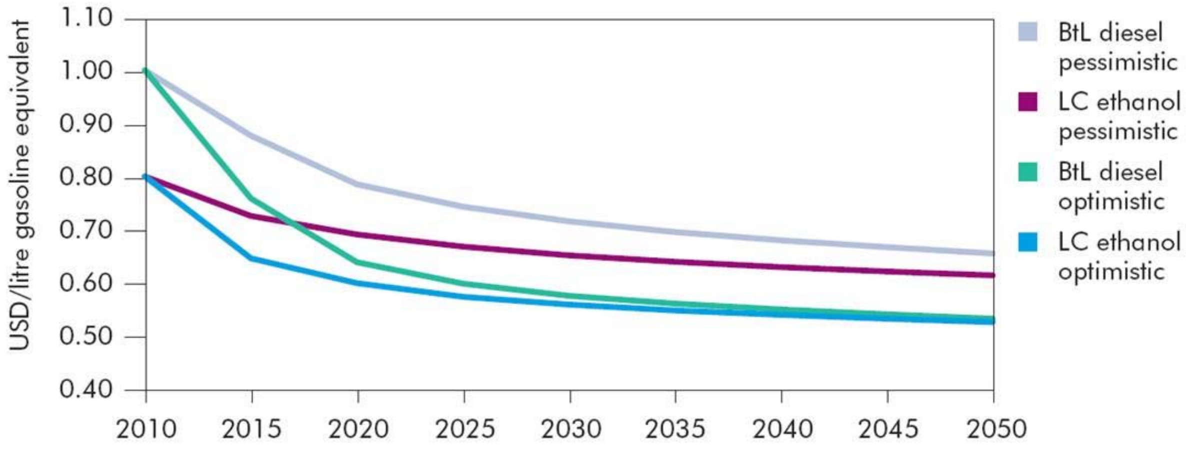
For ethanol from corn (Hettinga et al, 2009), production costs of corn are estimated to amount to 75 $US\$_{2005}$ per tonne by 2020 and ethanol processing costs could reach 60 - 77 US$/$m^3$ in 2020. Overall ethanol production costs could decline from currently 310 US$/$m^3$ to 248 US$/$m^3$ in 2020. This estimate excludes the cost of capital and the effect of probably corn prices in the future.

In the REFUEL project that focused on deployment of biofuels in Europe, (de Wit et al., 2009; Londo et al., 2009) specific attention was paid to the projections of future costs due to learning for lignocellulosic biofuels technologies. The analyses showed two key things:

- Lignocellulosic biofuels have a considerable learning potential with respect to crop production, supply systems, and the conversion technology. For conversion in particular, economies of scale are a very important element of the future cost reduction potential as specific capital costs can be reduced (partly due to improved conversion efficiency). Biomass resources may become somewhat more expensive due to a reduced share of (less costly) residues over time. It was estimated that lignocellulosic biofuel production cost could compete with gasoline and diesel from oil at 60-70 U$/barrel.

- The penetration of lignocellulosic biofuel options depends considerably on the rate of learning. Although this is a straightforward finding at first, it is more complex in policy terms, because learning is observed with increased market penetration (which allows for producing with larger production facilities).

In the IEA Energy Technology Perspectives report and IEA-WEO 2009, especially between 2020 and 2030 sees a rapid increase in production of lignocellulosic biofuels (sometimes referred to as 2nd generation fuels), accounting for all incremental biomass increase after 2020. The analysis on biofuels projects an almost complete phase out of cereal and corn based ethanol production and oilseed based biodiesel after 2030. The projected potential cost reductions for production of specific lignocellulosic biofuels investigated are shown in figure 2.7.3.



Note: BtL = Biomass-to-liquids; LC= ligno-cellulose.

Figure 2.7.3. Cost projections for lignocellulosic ethanol and BTL diesel. Source: IEA-ETP, 2008 and see also IEA (2008) for data figures.

2.7.4 Closing remarks on cost trends

Despite the complexities of determining the economic performance of bioenergy systems and regional specificities there are several key conclusions that can be drawn from available experiences and literature:

- There are several important bioenergy systems today, most notably sugar cane based ethanol and heat and power generation from residues and waste biomass that can be deployed competitively.
- Several important bioenergy systems have reduced their cost and improved environmental performance over time but require government subsidies provided usually for economic development, including poverty elimination, energy security and diversity, and other specific country reasons.
- There is clear evidence that further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring the

costs of power (and heat) generation from biomass down to attractive cost levels in many regions, especially when competing with natural gas. In case of deployment of carbon taxes of up to 50 U$/ton (or CCS), biomass can also be competitive with coal based power generation. Nevertheless, the competitive production of bio-electricity depends also on the performance of alternatives such as wind and solar energy, CCS coupled with coal, and nuclear energy.

- Bioenergy systems namely for ethanol and biopower production show technological learning and related cost reductions with progress ratios comparable to those of other renewable energy technologies. This applies to cropping systems (following progress in agricultural management when annual crops are concerned), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (ethanol production, power generation, biogas, and biodiesel).
- With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough to make them compete with oil prices of 60-70 U$/barrel. Currently available scenario analyses indicate that if shorter term R&D and market support is strong, technological progress could allow for commercialization around 2020 (depending on oil price developments and level of carbon pricing). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, since competitive production would decouple deployment from policy targets (mandates) and demand from biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift are so far poorly studied.
- Data availability is poor with respect to production of biomaterials; cost estimates for chemicals from biomass are rare in peer reviewed literature and future projections and learning rates even more so, linked, in part, to the fact that successful biobased products are entering the market place either as partial components of otherwise fossil derived products (e.g., poly(1,3)propylenetherephtalates based on 1,2-propanediol derived from sugar fermentation) or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. This is also the case for bio-CCS concepts, which are not deployed at present and cost trends are not available in literature. CO2 from ethanol fermentation is commercially sold to carbonate beverages, flash freeze meats, or enhance oil recovery, and demonstrations of bio-CCS are ongoing (see 2.3.5). Nevertheless, recent scenario analyses indicate that advanced biomaterials (and cascaded use of biomass) as well as bio-CCS may become attractive medium term mitigation options. It is therefore important to gain experience so that more detailed analyses on those options can be conducted in the future.

2.8 Potential Deployment

The expected deployment of biomass for energy on medium to longer term differs considerably between studies. A key message from the review of available insights on large scale biomass deployment is it’s role is mostly conditional: deployment strongly depends on sustainable development of the resource base and governance of land use, development of infrastructure and cost reduction of key technologies, e.g., efficient and complete use of primary biomass energy from most promising first generation feedstocks and new generation lignocellulosic biomass, and a variety of biofuels.

2.8.1 2.8.1. SRREN Chapter 10 review

The results of the review of studies with respect to bioenergy deployment under different scenarios as presented in chapter 10 of the SRREN are summarized in figures 2.8.1 and 2.8.2. For medium term (2030), estimates for primary biomass use range (rounded) between 7 to 180 EJ for the full range of results obtained. The 25-75% quantiles deliver a range of 30-117 EJ. This is combined with a total final energy delivered of 0-61 EJ. For 2050, these ranges amount for primary biomass supplies 10-305 EJ for the full range and 22-184 EJ for the 25-75% quantiles and 0 – 76 EJ (22-57 EJ for the 25-75% quantiles) for final energy delivered.

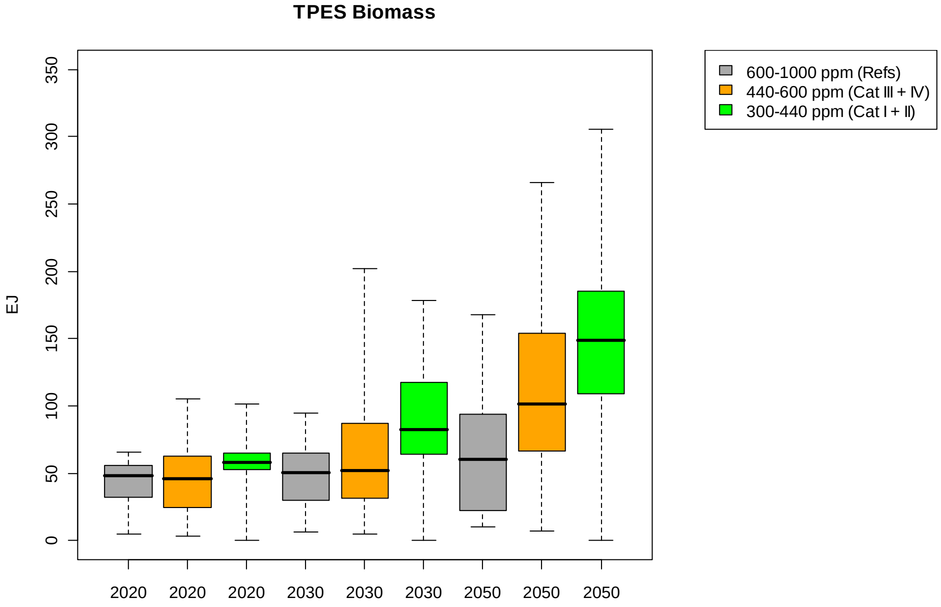


Figure 2.8.1. The Total Primary Energy Supply (TPES) biomass utilization according to the scenario review of Chapter 10, divided into projections for reference scenarios, scenarios that target 440-600 ppm and scenario's that target 330-440 ppm. The colored bars represent the 25-75% quantiles of the obtained results. The dotted bars represent the full range of estimates.

High quality data on performance prospects (and thus learning potential and rates) of energy technologies is essential to avoid neglecting potentially important contributor to the energy future and for such strategic studies. In addition, since the cost data is not static but improves as development continues, the information needs to be updated periodically and refined, as through harmonization studies that enable direct comparison of alternative uses of biomass.

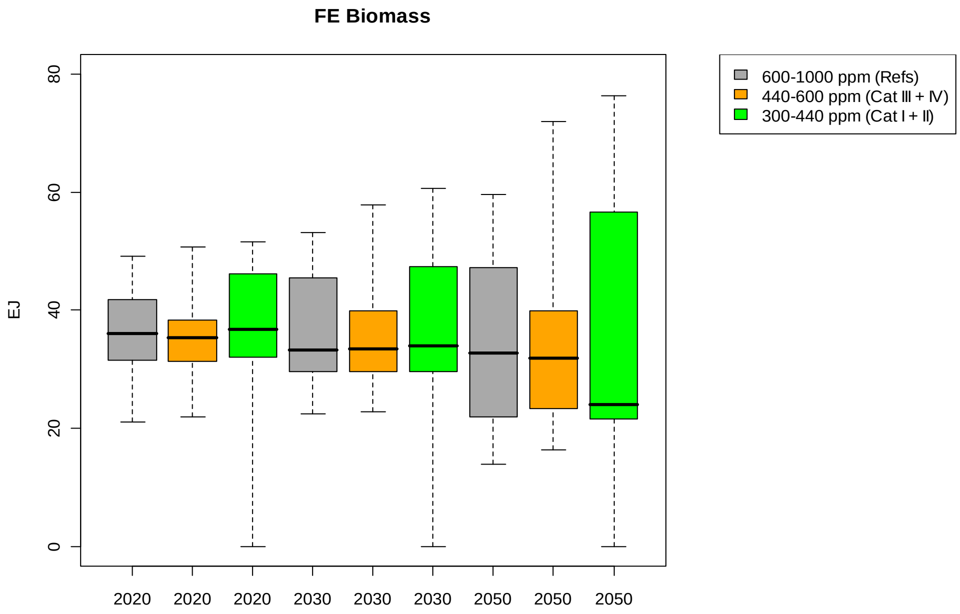


Figure 2.8.2. The Final Energy (FE) delivered via biomass utilization according to the scenario review of Chapter 10, divided into projections for reference scenarios, scenarios that target 440-600 ppm and scenarios that target 330-440 ppm. The colored bars represent the 25-75% quantiles of the obtained results. The dotted bars represent the full range of estimates.

2.8.2 Synthesis of findings from this chapter and chapter 10.

Although there is an impressive literature base on global potentials of bioenergy and potential impacts on the environment with deployment, there are very few analyses that provide a coherent and integrated picture taking key relevant relationships (see sections 2.2 and 2.5 of this chapter) into account. The focus of many recent analyses was on the possible conflicts and limitations of first generation biofuels deployment using food crops [see e.g. FAO's State of Food & Agriculture, 2008 for an overview].

Studies of the use of biomass for heat and power, lignocellulosic biofuels and biomaterials taking into account a range of biomass resources such as forestry and agriculture residues, organic wastes, and perennial plants (herbaceous and woody crops) cultivated on arable, pasture and marginal and degraded lands, provide a different outlook. There are conditions under which environmental, ecological, and socio-economic impacts of further deployment of bioenergy also enhance the environment, the development, the economy and provide independent energy sources. This is extensively discussed in section 2.5, where potential conflicts and synergies or benefits of development of biomass resources for, e.g. , biodiversity, rural development, water demand and soil quality have been identified, which depend on the implementation route at the local level, plant/crop choice, governance of land-use and management of agricultural productivity and water resources. The following key points have been made:

The effects of bioenergy on social and environmental issues – ranging from health and poverty to biodiversity and water quality – may be positive or negative depending upon local conditions, the specific feedstock production system and technology paths chosen, how criteria and the alternative scenarios are defined, and how actual projects are designed and implemented, among other variables. Perhaps most important is the overall management and governance of land-use when biomass is produced for energy purposed on top of meeting food and other demands from agricultural production (as well as livestock). In case biomass production is in balance with improvements in agricultural management undesirable (i)LUC effects can be avoided, while unmanaged, conflicts may emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land-use and water resources. Trade-offs between those dimensions exists and need to be resolved through appropriate strategies and decision making. Such strategies are currently emerging due to many efforts targeting the deployment of sustainability frameworks and certification for bioenergy production (see also section 2.4), setting standards for GHG performance (including LUC effects), addressing environmental issues and taking into consideration a number of social aspects., etc.

GHG performance evaluation of key biofuel production systems deployed today and possible 2nd generation biofuels using different calculation methods is available (see, Section 2.5 and Hoefnagels et al., 2010). Recent insights converge by concluding that well managed bioenergy production and utilization chains can deliver high GHG mitigation percentages (80-90%) compared to their fossil counterparts, especially for lignocellulosic biomass used for power generation and heat and, when the technology would be commercially available, for lignocellulosic biofuels. The use of most residues and organic wastes for energy result in such good performance. Also, most current biofuel production systems have positive GHG balances, if no iLUC effects are to be incorporated.

LUC can strongly affect those scores and when conversion of land with large carbon stocks takes place for the purpose of biofuel production, then directly emission benefits can shift to negative levels in the near term. This is most extreme for palm oil based biodiesel production where extreme carbon emissions are obtained if peatlands are drained and converted to oil palm (Wicke et al., 2008). Establishing causal relationship between biofuel development and distal land use change is still controversial. The GHG mitigation effect of biomass use for energy (and materials) therefore strongly depends on location (in particular avoidance of converting carbon rich lands to carbon poor cropping systems), feedstock choice, and avoiding iLUC (see below). In contrast, using perennial cropping systems can store large amounts of carbon and enhance sequestration on marginal and degraded soils, and fuel production replaces fossil fuels use. Governance of land-use and proper zoning and choice of biomass production systems is therefore a key to achieve good performance.

Other key environmental impacts cover use of water, biodiversity and other emissions. Just as for GHG impact, proper management determines emission levels to water, air and soil. Development of standards or criteria (and continuous improvement processes) will push bioenergy production to low emissions and higher efficiency than today’s systems.

Water is a critical issue that needs to be better analysed on regional level to understand the full impact of changes in vegetation and land-use management. Recent studies do indicate (Dornburg et al., 2008, Berndes, 2002; Wu et al., 2009; Rost, S. et al., 2009) that considerable improvements can be made in water use efficiency in conventional agriculture, as well as biomass crops and that, depending on location and climate, perennial cropping systems in particular can achieve benefits in terms of improved water retention and lowering direct evaporation from soils. Nevertheless, without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable (Fingerman et al., 2010).

Similar remarks can be made with respect to biodiversity, although for this topic, more scientific uncertainty exists due to ongoing debate on methodologies how to quantify biodiversity impacts in general. Clearly, large scale monocultures that would go at the expense of nature areas are detrimental for biodiversity (for example highlighted in CBD, 2007). However, as discussed and referenced in Section 2.5, bioenergy can also lead to positive effects such as the environmental benefits that can be derived from integrating different perennial grasses and woody crops into agricultural landscapes, including enhanced biodiversity, soil carbon increase and improved soil productivity, reduced shallow landslides and local ‘flash floods’, reduced wind and water erosion and reduced volume of sediment and nutrients transported into river systems. Forest residue harvesting improves forest site conditions for replanting and thinning generally improves the growth and productivity of the remaining stand. Removal of biomass from over dense stands can reduce wildfire risk. This is also an area that deserves considerably more research, data collection, and proper monitoring, as exemplified by ongoing activities of governments and roundtables in case or pilot studies (e.g., DOE, 2010; RSB, 2010).

With respect to iLUC, the assessment of available literature (see table 2.5.3) showed that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation than necessary as the models did not have other kinds of lands such as pastures in Brazil that could be used. While the early paper of Searchinger et al. (2008) claimed an iLUC factor of 1 (losing one hectare of forest land for each hectare of land used for bioenergy), later macro-economic coupled to biophysical model studies tuned that down to 0.3 – 0.15 and more detailed evaluations of e.g. (Lapola et al., 2010 and IFRI (Al-Fiffai et al., 2010) suggest that any iLUC effect strongly (up to fully) depends on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. This balance in development is also the basis for the recent European biomass resource potential analysis, for which expected gradual productivity increments in agriculture are the basis for possible land availability as reported in (Fischer et al, 2010 and de Wit & Faaij, 2010) and that take avoidance of competition with food (or nature) as a starting point. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel producing countries is now producing results that are converging to lower overall land use change impacts and acknowledgement that land use management at large is key. .

Social impacts from a large expansion of bioenergy are very complex and difficult to quantify. In general, bioenergy options have a much larger positive impact on job creation in rural areas than other energy sources. Also when conventional agriculture would rationalize to ‘free up land’’ for bioenergy, the total job impact and value added generated in rural regions increases when bioenergy production increases (see e.g. Wicke et al., 2009). For many developing countries, the potential bioenergy has for generating employment and economic activity in rural regions is a key driver. In addition, expenditures on fossil fuel (imports) can be (strongly) reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land-use is governed. In case (too) rapid bioenergy deployment competes with food production, increases in food prices can be significant as shown by many recent studies that focused on implications of rapid expansion of first generation biofuels produced from food crops: impacts on food prices – and more in general on food security- may be significant, particularly for poor people

The way bioenergy is developed, under what conditions and what options will have a profound influence on whether those impacts will largely be positive or negative (see for example van Dam et al., 2008 and van Dam et al., 2009) with examples of such scenarios for Argentina). Bioenergy has the opportunity to contribute to climate mitigation, energy security and diversity goals, and economic development in developed and developing countries alike but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, how actual projects are designed and implemented, among many other factors.

Based on this review, it is not possible to deliver conclusive information on *the* deployment of biomass for energy and climate change mitigation on shorter and longer term. Upon reviewing the information from the various studies conducted (see Sections 2.2 and 2.5), the IPCC group of technical experts writing this Chapter, concluded that the most likely range is between 100 and 300 EJ for penetration by 2050 (see Biomass Technical Potential 1 in Figure 2.8.3). Since 80% of the total biomass use is traditional heating, cooking, and lighting applications in the developing world, and we expect increased efficiency of biomass use that will offset increases by perhaps as much as 10 to 17 EJ (GEA, 2010; see Section 2.5.3.4,) to be offset somewhat by population increase. Taking improved traditional use of biomass energy to 25 EJ by 2050, to reach 100 to 300 EJ would require increases of factors of four to twelve in modern bioenergy. If these increases had to rely only on modern bioenergy's contribution of 10 EJ alone, it would means ten- to thirty-fold increases required by 2050.

To put numbers of 100 to 300 EJ in perspective, in the United States, a two-hundred-fold primary bioenergy increase occurred in the area of waste/residue to energy since the creation of the Environmental Protection Agency nearly 40 years ago with legislation to clean air, water, and solid emissions alongside energy legislation. A factor of 20 in 20 years was reached by ethanol primarily from corn with production incentives among other tools (see Section 2.4.6.7). Then an increase by a factor of five took place in the subsequent eight years with additional incentives for production for energy security, economic development of rural regions, and environmental reasons. This rapid growth caused significant industrial investment in new production based on legislation with more certainty of future markets (Chum and Overend, 2005). A factor of three was reached by the biopower industry in the eighties in ten years. These increases are impressive for total of 4.1 EJ (primary, 2008 estimate; biofuels consumption 1.4EJ). To implement the Energy Independence and Security Act the biofuels volume in 2022 would more than triple today's levels and require an estimated $90 billion capital investment in 12 years (EPA, 2010). These historical parameters frame the significant levels of investments and infrastructure for biomass collection and processing required to reach 75 to 300 EJ.

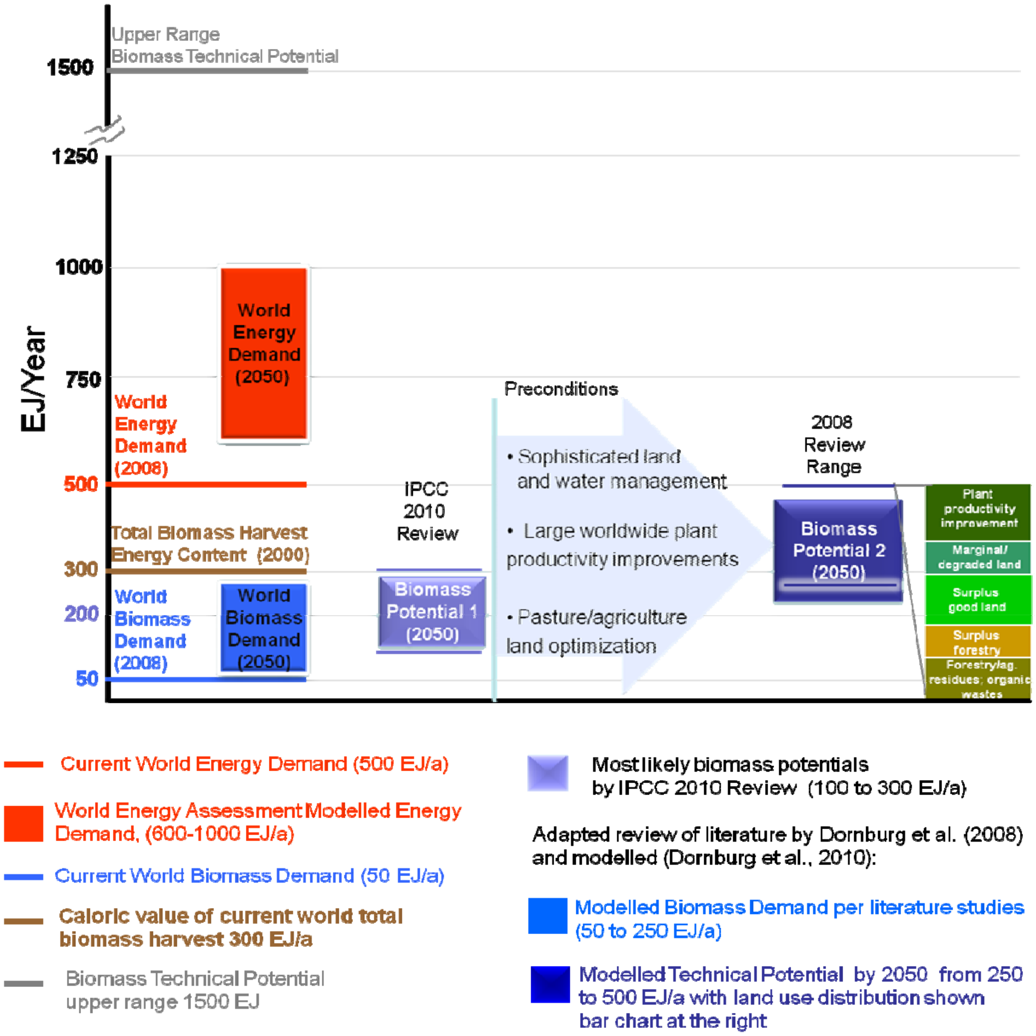


Figure 2.8.3. Upper technical biomass supply potentials, most likely biomass potential (IPCC review, this Chapter), modelled biomass potential (Dornburg et al., 2010), expected demand for biomass (primary energy) based on global energy models and expected total world primary energy demand in 2050. The Biomass Potential 2 scenario incorporates some key limitations and criteria with respect to biodiversity protection, water limitations, soil degradation, and considers developments in agricultural management between A2 versus A1/B1 scenario conditions. The breakdown consist of: (i) Residues: Agricultural and forestry residues; (ii) Forestry: surplus forest material (net annual increment minus current harvest); (iii) Exclusion of areas: potential from energy crops, leaving out areas with moderately degraded soils and/or moderate water scarcity; (iv) No exclusion: additional potential from energy crops in areas with moderately degraded soils and/or moderate water scarcity; (v) Learning in agricultural technology: additional potential when agricultural productivity increases faster than historic trend. Adapted from Dornburg et al. (2008) and Dornburg et al. (2010) based on several review studies

Based on the current state-of-the-art analyses that took into consideration key sustainability criteria as of 2007-2008 literature, the upper bound of the biomass resource potential halfway this century can amount over 400 EJ (see Biomass Potential 2 of figure 2.8.3). This could be roughly in line with the conditions sketched in the IPCC SRES A1 and B1 storylines, assuming sustainability and policy frameworks to secure good governance of land-use and improvements in agricultural and livestock management (see also van Vuuren et al., 2009). These findings are summarized in (Biomass Potential 2) based on an extensive assessment of recent literature and additional studies with the IMAGE-TIMER modeling framework that include known and projected future water limitations, biodiversity protection, soil degradation and competition with food (Dornburg et al., 2008; Dornburg et al., 2010).

As shown above, narrowing down the biomass resource potential to distinct numbers is not possible. But it is clear that several hundred EJ per year can be provided for energy in the future, given favourable developments. This can be compared with the present biomass use for energy at about 50 EJ per year. It can also be concluded that:

- The size of the future biomass supply potential is dependent on a number of factors that are inherently uncertain and will continue to make long term biomass supply potentials unclear (Hoogwijk et al. 2003, 2005, Smeets et al. 2007, WBGU 2009). Important factors are (i) population and economic/technology development and how these translate into fibre, food and fodder demand (including diets), and development in agriculture and forestry; (ii)climate change impacts on future land use including its adaptation capability (Schneider et al 2007, Lobell et al 2008, Fischer 2009); (iii) and restrictions set by land degradation, water scarcity, and biodiversity and nature conservation requirements (WBGU 2009, Molden 2007, Bai et al. 2008, Berndes 2008).
- Studies point that residue flows in agriculture and forestry and unused (or extensively used, marginal/degraded) agriculture land are important sources for expansion of biomass production for energy, both on the near term and on the longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set limits on residue extraction in agriculture and forestry (Lal 2008, Blanco-Canqui and Lal 2009, WBGU 2009)
- The cultivation of suitable plants crops can allow for higher potentials by making it possible to produce bioenergy on lands where conventional food crops are less suited – also due to that the cultivation of conventional crops would lead to large soil carbon emissions. Landscape approaches integrating bioenergy production into agriculture and forestry systems to produce multi-functional land use systems could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and helps restore/maintain soil productivity and healthy ecosystems. (Hoogwijk et al. 2005, Berndes et al. 2008, Folke et al. 2009, IAASTD 2009, Malezieux et al. 2009)
- Water constraints may limit production in regions experiencing water scarcity. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable energy crops that are drought tolerant can help adaptation in water scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing use (Jacksson et al. 2005, Zomer 2006, Berndes et al. 2008, De Fraiture and Berndes).

The energy potential ranges for different biomass resources summarized below are derived from the assessment combined with modelling efforts of the Dornburg review. These are compared in figure 2.8.3 with the expert review made for this report. For the latter, no new modelling efforts were carried out, but they incorporate the quantitative results from Dornburg as well as a wide range of other studies and viewpoints reviewed in sections 2.2 and 2.5.

- Residues from forestry and agriculture and organic wastes (including the organic fraction of MSW, dung, various process residues, etc.), which in total represent between 40 - 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the potential biomass supplies is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range.
- Surplus forestry, i.e. apart from forestry residues an additional amount about 60-100 EJ/yr of surplus forest growth may be made available.
- Biomass produced via cropping systems:
    - A lower estimate for energy crop production *on possible surplus good quality agricultural and pasture lands*, including far reaching corrections for water scarcity, land degradation and new land claims for nature reserves represents an estimated 120 EJ/yr.
    - The potential contribution of *water scarce, marginal and degraded lands* for energy crop production, could amount up to an additional 70 EJ/yr. This would comprise a large area where water scarcity provides limitations and soil degradation is more severe and excludes current nature protection areas from biomass production.
    - Learning in agricultural technology assumes that improvements in agricultural and livestock management or more optimistic than in the baseline projection (i.e. comparable to conditions sketched in the SRES A1 and B1 scenarios) would add some 140 EJ/yr to the above mentioned potentials of energy cropping.

The three categories added together lead to a biomass supply *potential* of up to about 500 EJ, represented in the right hand stacked bar of figure 2.8.3.

Energy demand models calculating the amount of biomass used if energy demands are supplied cost-efficiently at different carbon tax regimes, estimate that in 2050 about 50-250 EJ/yr of biomass are used. This is roughly in line with the projections given in chapter 10 and figure 2.8.3. At the same time, scenario analyses project a global primary energy use of about 600 – 1040 EJ/yr in 2050. Thus, up to 2050, biomass has the potential to meet a substantial share of the worlds energy demand; the average of the range given in figure 2.8.3 results in potential a contribution bioenergy of some 30% to total primary energy demand with the possibility of impacting rural and industrial development in developing and developed regions.

However, if the sketched conditions are not met, the biomass resource base may be largely constrained to a share of the biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands and some regions where biomass is evidently a cheaper energy supply option compared to the main reference options (which is the case for sugarcane based ethanol production). Biomass supplies may than remain limited to an estimated 100 EJ in

2050. Also this is discussed in, for example, van Vuuren et al. (2009) and WBGU (2009) and confirmed by the scenario review in chapter 10 of the SRREN.

2.8.3 Limitations in available literature and analyses

The demand for bioenergy will, as argued earlier, depend on the relative competitive position of bioenergy options in the energy system compared to main alternatives. Available analyses indicate that on the longer term, biomass will be especially attractive for production of transport fuels and feedstock for industry and that the use of biomass for electricity may become relatively less attractive in the longer run.

Innovations in biofuel production and biorefining technologies however, combined with high oil prices as projected in IEA's World Energy Outlook and in addition CO2 pricing, are likely to result in competitive biofuel production in many parts on the globe on medium term and may lead to an acceleration of biomass use and production compared to available projections. This mechanism is basically projected in the 2020-2030 timeframe of the 450 ppm scenario in the 2009 World Energy Outlook (IEA-WEO, 2009). In such a scenario, the sustainable development of the biomass resource base may become the limiting factor, especially after 2030.

Also poorly investigated so far is the possible role of biomass with Carbon Capture & Storage, an option that may become very important under stringent mitigation scenarios (i.e., aiming for a 350 ppm scenario in 2050) where negative emissions are required to meet set targets. The use of biomass becomes absolutely essential to achieve the set targets and demand may further increase.

It is also still poorly understood what the impact of electric vehicles and drive chains in transport may be on the potential demand for biofuels. Electric drive chains in passenger vehicles have good potential to increase energy efficiency of vehicles. IEA (WEO, 2009) projects a limited inroad of fully electric vehicles for the coming decades and rapid introduction of hybrid vehicles of which energy use will be partly (in case of plug-in hybrids) or fully be covered by liquid fuels. In addition, on long term (and rapidly growing) demand of liquid fuels from aviation, shipping and truck transport (for which full electric driving is not feasible) remain responsible for some 60% of the (growing) global demand for transport fuels.

The costs of biomass supplies in turn are influenced by the degree of land-use competition, availability of (different) land (classes) and optimisation (learning and planning with sustainability in mind) in cropping and supply systems. The latter is still relatively poorly studied and incorporated in scenarios and (energy and economic) models, which can be improved. The variability of biomass production costs seems far less than that of oil or natural gas, so uncertainties in this respect are relatively limited.

Given the relatively small number of comprehensive scenario studies available to date, it is fair to characterize the role of biomass role in long-term stabilization (beyond 2030) as very significant but with relatively large uncertainties. One additional model that supports this importance is shown on Figure 2.5.4: an agricultural intensification scenario reflecting the actual rate of land use change observed since the year 2000 is investigated projecting biofuels expansion mostly through agriculture intensification. Climate mitigation is initially negative (20 years) but then increases (Melillo et al. 2009) to a biofuel energy contribution of 320 EJ by 2100. Further research is required to better characterize the potential; for regional conditions and over time. A number of key factors have been identified in this last section and throughout the report.

Given that there is a lack of studies on how biomass resources may be distributed over various demand sectors, no detailed allocation of the different biomass supplies for various applications is suggested here. Furthermore, the net avoidance costs per tonne of CO2 of biomass usage depends on a large variety of factors, including the biomass resource and supply (logistics) costs, conversion costs (which in turn depends on availability of improved or advanced technologies) and fossil fuel prices, most notably of oil.

2.8.4 Key messages and policy

Table 2.8.1 describes key preconditions and impacts for two possible extreme biomass scenarios.

Table 2.8.1: Two opposing storylines and impacts for bioenergy on long term.

Storyline	**Key preconditions**	**Key impacts**
- High biomass scenario		
Largely follows A1/B1 SRES scenario conditions,	Assumes: - well working sustainability frameworks and strong policies - well developed bioenergy markets - progressive technology development (biorefineries, new generation biofuels and multiple products - successful deployment of degraded lands. - Developing countries successfully transition to higher efficiency technologies and implement biorefineries with scales compatible with the resources available. Satellite processing emerges	- Energy price (notably oil) development is moderated due to strong increase supply of biomass and biofuels. - Some 300 EJ of bioenergy delivered before 2050; 35% residues and wastes, 25% from marginal/degraded lands (500 Mha), 40% from arable and pasture lands 300 Mha). - Conflicts between food and fuel largely avoided due to strong land-use planning and aligning of bioenergy production capacity with efficiency increases in agriculture and livestock management. - Positive impacts with respect to soil quality and soil carbon, negative biodiversity impacts minimised due to diverse and mixed cropping systems.
Low biomass scenario		
Largely follows A2 SRES scenario conditions, assuming limited policies, slow technological progress in both the energy sector and agriculture, profound differences in development remain between OECD and DC's.	- High fossil fuel prices expected due to high demand and limited innovation, which pushes demand for biofuels for energy security perspective - Increased biomass demand directly affects food markets	- Increased biomass demand partly covered by residues and wastes, partly by annual crops. - Total contribution of bioenergy about 100 EJ before 2050. - Additional crop demand leads to significant iLUC effects and impacts on biodiversity. - Overall increased food prices linked to high oil prices. - Limited net GHG benefits. - Socio-economic benefits sub-optimal.

2.8.5 Key messages and policy recommendations from the chapter 2

- The biomass resource potential, also when key sustainability concerns are incorporated, is significant (up to 30% of the world's primary energy demand in 2050) but also conditional. The larger part of the potential biomass resource base is interlinked with improvements in agricultural and forestry management, investment in infrastructure, good governance of land and smart land use and introduction of effective sustainability frameworks and land-use monitoring.
- If the right policy frameworks are *not* introduced, further expansion of biomass use can lead to significant conflicts in different regions with respect to food supplies, water resources and biodiversity. However, such conflicts can also be avoided and synergies with better management of land and other natural resources (e.g., soil carbon enhancement and restoration, water quality improvements) and especially agriculture and livestock management and contributing to rural development are possible. Logically, such synergies should explicitly be targeted in comprehensive policy frameworks.
- Bioenergy at large has a significant GHG mitigation potential, provided resources are developed sustainably and provided the right bioenergy systems are applied. Perennial cropping systems and biomass residues and wastes are in particular able to deliver good GHG performance in the range of 80-90% GHG reduction compared to the fossil energy baseline.
- Optimal use and performance of biomass production and use is regionally and site specific. Policies therefore need to take regionally specific conditions into account and need to incorporate the agricultural and livestock sector as part of good governance of land-use and rural development interlinked with developing bioenergy.
- The recently and rapidly changed policy context in many countries, in particular the development of sustainability criteria and frameworks and the support for advanced biorefinery and lignocellulosic biofuel options drives bioenergy to more sustainable directions.
- Technology for lignocellulose based biofuels and other advanced bioelectricity options, biomass conversion combined with Carbon Capture and Storage, advanced biorefinery concepts, can offer fully competitive deployment of bioenergy on medium term (beyond 2020). Several short term options can deliver and provide important synergy with longer term options, such as co-firing, CHP and heat production and sugarcane based ethanol production. Development of working bioenergy markets and facilitation of international bioenergy trade is another important facilitating factor to achieve such synergies.

Biomass potentials are influenced by and interact with climate change impacts but the detailed impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g. soil protection, water retention and modernization of agriculture) with production of biomass resources.

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Chapter 3

Direct Solar Energy

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(Sub)Section:	All	
Author(s):	CLAs:	Dan Arvizu; Palani Balaya
	LAs:	Luisa F. Cabeza, Terry Hollands, Arnulf Jäger-Waldau, Michio Kondo, Charles Konseibo, Valentin Meleshko, Wes Stein, Yutaka Tamaura, Honghua Xu, Roberto Zilles
	CAs:	Armin Aberle, Andreas Athienitis, Shannon Cowlin, Don Gwinner, Thomas Huld, Ted James, Lawrence Kazmerski, Margaret Mann, Koji Matsubara, Anton Meier, Ed Morofsky, Arun Mujumdar, Takashi Oozeki, Oumar Sanogo, Matheos Santamouris, Michael Sterner, Paul Weyers
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Turquoise highlighted – inserted comment text from Authors or TSU i.e. [AUTHORS/TSU]

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Chapter 3 has been allocated 68 pages in the SRREN. The actual chapter length (excluding references & cover page) is 84 pages: a total of 16 pages over the allocated page number. Expert reviewers are therefore kindly asked to indicate where the Chapter could be shortened by up to 16 pages in terms of text and/or figures and tables to reach the allocated length.

All monetary values provided in this document will need to be adjusted for inflation/deflation and converted to US$ for the base year 2005.

Some values for 2008 or 2009 are not yet available, but should be by later this year: changes will be made then to Fig. 3.9, Sec. 3.4.1 (active solar heating; below Table 3.3), Sec. 3.4.2 (active solar heating and cooling).

Chapter 3: Direct Solar Energy

CONTENTS

EXECUTIVE SUMMARY

This Chapter summarizes the current status of the direct use of solar energy as a means to mitigate climate change. Drawing on references from the most recent literature, we review solar energy's resource potential, describe the technology and its current status, look at the current trends in its adoption, and provide predictions of its future role. We summarize here the important findings of the Chapter.

Solar energy is the most abundant of all energy resources. Indeed, the rate at which solar energy is intercepted by the Earth is about 10,000 times greater than the rate at which all energy is used on this planet. In a more practical example, with today's solar power technology, the world's energy requirements for electricity and for other needs could be met by operating solar power stations on only about 4% of the surface area of the Sahara Desert. Although not all countries are equally endowed with solar energy, almost every country receives sufficient direct solar energy that can contribute significantly to its energy mix.

Solar technology embraces a family of technologies capable of being integrated amongst themselves, as well as with other renewable energy technologies. The solar technologies can deliver heat, cooling, electricity, lighting, and fuels for a host of applications. Conversion of solar energy to *heat* (i.e., thermal conversion) is comparatively straightforward, because any material object placed in the sun will absorb thermal energy. However, maximizing and maintaining that absorbed energy can take specialized techniques and devices such as vacuums, phase-change materials, optical coatings, and mirrors. Which technique will be used depends on the application and temperature at which the heat is to be delivered, and this can range from 25°C (e.g., for swimming pool heating) to 1000°C (e.g., for dish/Stirling solar thermal electrical power)—and even up to 3000°C in solar furnaces. Generation of *electricity* can be achieved in either of two ways. In the first, solar energy is converted directly into electricity in a solid-state semiconductor device called a photovoltaic (PV) cell. In the second, solar thermal energy is used in a concentrating solar power (CSP) plant to produce high-temperature heat, which is then converted to electricity via a heat engine and generator. Both approaches are currently in use. The use of solar energy for lighting requires no conversion per se; solar lighting occurs naturally in buildings through windows, but maximizing the effect requires careful engineering and architectural design. In addition to these applications, passive solar heating is a technique for maintaining buildings at comfortable conditions by exploiting the sun's rays incident on the buildings' exterior, without using pumps and fans. Solar *cooling* for buildings can also be achieved, for example, by using solar-derived heat to drive a special thermodynamic cycle called absorption refrigeration. Furthermore, solar devices can deliver process heat and cooling, and other solar technologies are being developed that will deliver fuels such as hydrogen or hydrocarbons.

The various solar technologies have differing maturities, and their viability depends on local conditions and government policies to support their adoption. Some technologies are already viable in certain locations, and the overall viability of solar technologies in general is improving. Solar thermal can be used for a wide variety of applications, such as for domestic hot water, comfort heating of buildings, and industrial process heat. It is significant that many countries spend up to one-third of their annual energy usage as heat. Service hot-water heating for domestic and commercial buildings is now a mature technology growing at a rate of about 16% per year and employed in most countries of the world. The world installed capacity of thermal power from these devices is estimated to be 200 GW_{th}, with a capacity factor of about 10%. The production of electricity from PV panels is also a worldwide phenomenon. Assisted by supportive pricing policies, PV production is growing at a rate of about 40% per year—making it one of the fastest-growing energy technologies. Currently, it claims an installed capacity power production of about 22 GW_e, with a capacity factor of about 11%. Most of these installations are roof-mounted and grid-connected. Energy from PV panels and solar domestic water heaters can be especially valuable because the energy production often occurs at times of peak loads on the grid, as in cases where there is a large load associated with air conditioning. For example, a cost savings can be incurred by photovoltaics when it offsets the expensive peak-load electricity generated by conventional technologies. PV and solar domestic water heaters also fit well with the needs of many countries because they are modular, quick to install, and can delay the need for a large national grid. The production of electricity from CSP installations has seen a huge increase in planned capacity in just the last few years and has now reached a cumulative installed capacity within a few countries of about 0.7 GW_e, with capacity factors expected to be in the range of 35 to 40%. At the same time, passive solar and solar daylighting are conserving energy in buildings at a highly significant rate, but the actual amount is difficult to quantify. The use of passive solar has been found to decrease the comfort heating requirements by about 15% for existing buildings and about 40% for well-designed new buildings. The remaining solar technologies, such as fuel production and provision of industrial process heat, are still being developed and/or are waiting for higher conventional energy prices and for market barriers to be removed before they can be deployed in a significant way. In total, it is estimated that direct solar technologies are currently preventing about 6,000,000 tonnes of CO_2 per year from entering the atmosphere.

Over the last 30 years, solar technologies have seen very substantial reductions in cost through learning or experience. And so, looking to the future, we can expect that further technological improvements and cost reductions will be achieved. For example, much work is ongoing to improve the efficiency and reduce the materials requirements of PV cells. Judging from the more than 30 years track record of learning curves in semiconductor devices of 20% cost reduction with each doubling of production volume, one can expect that the steep learning curve will continue into the future. But the learning curves of solar technologies depend on production volume, not on the mere passage of time, and so they will only continue if market volumes for the respective technologies increase in parallel. Without rapidly increasing production volumes, the learning curves will slow, limiting the application of solar technologies in the future. Private capital is flowing into all the technologies, but government support and stable political conditions are needed to lessen the risk of private investment and to boost the assurance of faster development.

3.1 Introduction

Solar energy is an abundant energy resource. Indeed, in just one hour, the solar energy intercepted by the Earth exceeds the world's energy consumption for the entire year. Solar energy's potential to mitigate climate change is equally impressive. Except the modest amount of CO_2 emissions produced in the manufacture of conversion devices—recently estimated at 18 to 76 g per kWh for PV conversion (Fthenakis and Kim, 2010) and about 14 g per kWh for CSP conversion (Trieb, 2005; European Commission, 2007)—the direct use of solar energy produces essentially no greenhouse gases, and it has the potential to displace large quantities of fossil fuels.

The aim of this chapter is to provide a synopsis of the state-of-the-art and possible future scenarios of the full realization of this potential for climate change mitigation. It establishes the resource base, describes the various technologies (which are many and varied), appraises the current market development, outlines some methods for integrating solar into other energy systems, addresses its environmental and social impacts, and finally, evaluates the prospects for future developments.

Some of the solar energy absorbed by the Earth appears later in the form of wind, wave, ocean thermal, hydro power, and excess biomass energies. The scope of this chapter, however, does not include these other indirect forms. Rather, it deals with the *direct* use of solar energy.

3.1.1 Brief History

That history started when early civilizations discovered that buildings with openings facing the sun were warmer and brighter, even in cold weather. During the late 1800s, solar collectors for heating water and other fluids were invented and put into practical use for domestic water heating. Later, attempts were made to use mirrors to boost the available fluid temperature, so that heat engines driven by the sun could develop motive power, and thence, electrical power. Also, the late 1800s brought the discovery of a device for converting sunlight directly into electricity. Called the photovoltaic (PV) cell, this device bypassed the need for a heat engine. The modern solar cell, attributed to Russell Ohl working at AT&T's Bell Labs, was discovered in around 1940.

The modern age of solar research began in the 1950s with the establishment of the International Solar Energy Society (ISES) and increased research and development (R&D) efforts in many industries. For example, advances in the solar hot-water heater by companies such as Miromit in Israel and the efforts of Harry Tabor at the National Physical Laboratory in Jerusalem helped to make solar energy the standard method for providing hot water for homes in Israel by the early 1960s. At about the same time, national and international networks of solar radiation measurements were beginning to be established. The founders of ISES were motivated by the fact that the age of fossil fuels was limited and a sustainable replacement was needed; but it soon became clear that the mitigation of climate change was an equally important incentive for developing solar energy.

With the oil crisis of the 1970s, most countries in the world developed programs for solar energy R&D, and this involved efforts in industry, government labs, and universities. These policy support efforts, which have, for the most part, continued up to the present, have borne fruit: now one of the fastest-growing renewable energy technologies, solar energy is poised to play a vital and environmentally friendly role on the world energy stage.

3.1.2 Theoretical Potential and Nature of the Resource

A nuclear fusion reactor in the sun's core drives an enormous release of energy at its surface. In fact, the energy release at the sun's surface is so great that even the small fraction intercepted by the Earth—1.53×10^9 TWh or 5.5×10^6 EJ per year—dwarfs the rate at which the world consumes energy, which is about 1.5×10^5 TWh or 500 EJ/year.

Every material body emits heat rays, called thermal radiation, and solar radiation is that thermal radiation emitted by the sun. Above the Earth's atmosphere, solar radiation's energy rate equals 1368 watts (W) per every square meter of surface facing the sun. With clear skies on Earth, this figure becomes roughly 1000 W/m^2 at the Earth's surface. These rays are actually electromagnetic waves—travelling fluctuations in electric and magnetic fields. With the sun's surface temperature being close to 5800 Kelvin, solar radiation is spread over short wavelengths ranging from 0.25 to 3 micrometers (µm).

The sun's high temperature, unequalled on Earth, makes solar radiation very special. For example, it embraces daylight: about 40% of solar radiation is visible light, while another 10% is ultraviolet radiation, and 50% is infrared radiation. Solar radiation can alternatively be viewed as a flux of electromagnetic bundles of energy, called photons. Because of the sun's high temperature, many of these photons are so energetic that they can generate conduction electrons in semiconductors, thereby ultimately enabling the PV conversion of sunlight into electricity.

3.1.3 Various Conversion Technologies and Applications

Solar energy is a family of technologies having a broad range of energy service applications: lighting, comfort heating, hot water for buildings and industry, high-temperature solar heat for electric power and industry, photovoltaic conversion for electrical power, and production of solar fuels, e.g., direct water-splitting with a semiconductor solar device without electricity production. This chapter will deal with all of these technologies in detail.

Several solar technologies, such as domestic hot-water heating and pool heating, are already competitive and used in locales where it offers the least-cost option. And in jurisdictions where governments have taken steps to level the energy playing field, very large solar-electricity (both PV and solar-thermal) installations, approaching 1000 MW of power, have been realized, in addition to huge numbers of rooftop installations. Other applications, such as solar fuels, require additional R&D before reaching this level of adoption.

In pursuing any of the solar technologies, there is the need to deal with the sun's variability. One option is to store excess collected energy until it is needed. This is particularly effective for handling the lack of sun at night, which is the least-challenging aspect of solar variability. For example, a 0.1-meter-thick slab of concrete in the floor of a home will store much of the solar energy absorbed during the day and release it to the room at night. When totalled over a long period of time such as one year, or over a large geographical area such as a continent, solar energy becomes much more reliable. The use of both these concepts, together with energy storage, has enabled designers to produce more reliable solar systems. But much more work is needed in the area of solar reliability.

Because of its inherent variability, solar energy is most useful when integrated with another energy source, to be used when solar energy is not available. In the past, that source has generally been a non-renewable one. But there is great potential for integrating direct solar energy with other renewable energies. When properly integrated, renewable energy can meet a large fraction of the world's energy demands.

3.1.4 Context Summary

The rest of this chapter will include the following topics. The next section (Section 3.2) summarizes the research that has gone into characterizing this solar resource and establishes the technical potential for direct solar energy. Section 3.3 describes the five different technologies and their applications: passive solar heating and lighting for buildings (Section 3.3.1), active solar heating and cooling for buildings and industry (Section 3.3.2), PV solar electricity generation (Section 3.3.3), concentrating solar power electricity generation (Section 3.3.4), and finally solar fuel production (Section 3.3.5). The next section (Section 3.4) reviews the current status of market development, including installed capacity and energy currently being generated (Section 3.4.1) and the industry capacity and supply chain (Section 3.4.2). Following this are sections on the integration of solar technologies into other energy systems (Section 3.5), the environmental and social impacts (Section 3.6), and finally, the prospects for future technology innovations (Section 3.7). The two final sections cover cost trends (Section 3.8) and the policies needed to achieve the goals for deployment (Section 3.9). Many of the sections are, like Section 3.3, segmented into subsections, one for each of the five solar technologies. Thus, the reader must be ready to jump between the technologies, because that is the nature of direct solar energy: it has many faces.

3.2 Resource Potential

3.2.1 Global Technical Resource Potential

The solar resource is inexhaustible, and it is available and able to be used in all countries and regions of the world. But to plan and design appropriate energy conversion systems, solar energy technologists must know how much radiation will fall on their collectors.

The solar energy flux at the top of the atmosphere can be evaluated with high precision because it depends essentially on astronomical parameters. At the Earth's surface, however, evaluation of the solar flux is more difficult because of its interaction with the atmosphere, which contains aerosols, water vapor, and clouds that vary both geographically and temporally. Atmospheric conditions reduce direct-beam solar radiation by about 10% on clear, dry days and by 100% on days with thick clouds, leading to lower average solar flux.

The solar radiation reaching the Earth's surface is divided into two components: direct-beam radiation, which comes directly from the sun's disk, and diffuse radiation, which comes from the whole of the sky except the sun's disk. The term "global solar radiation" refers to the sum of the direct-beam and the diffuse components. Figure 3.1 shows the average global solar flux as it varies across the Earth for two different three-month time periods.

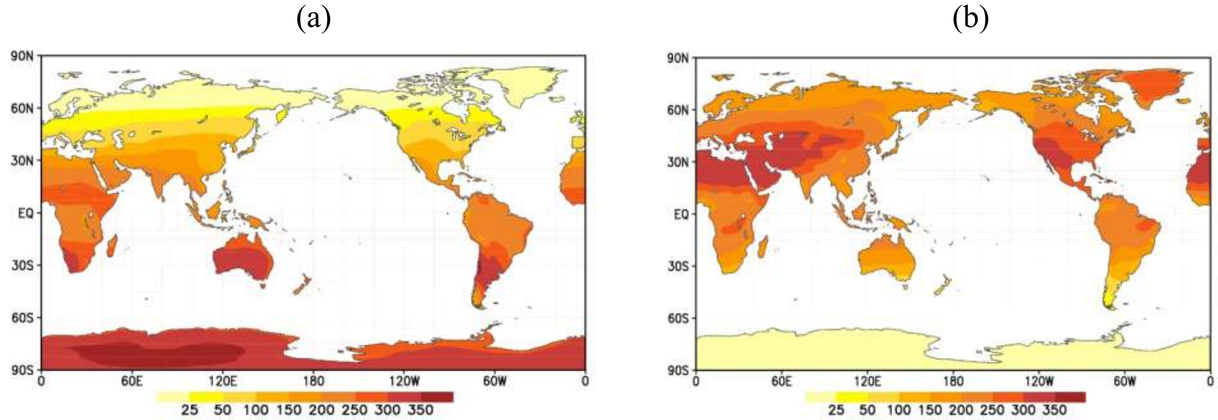


Figure 3.1: The global solar flux (in W m^{-2}) at the Earth's surface—derived from the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)—averaged over two 3-month periods: (a) December-January-February and (b) June-July-August. [TSU: please state source explicitly]

There are many different ways to assess the global potential of solar energy. The *theoretical* potential indicates the amount of radiation at the Earth's surface (land and ocean) that is theoretically available for energy purposes. It has been estimated at 3.2×10^6 EJ/year (IPCC, 2007).

The *technical* potential is a more practical estimate of how much solar radiation could be put to human use by considering the conversion efficiency of available technologies and local factors such as land availability and meteorological conditions. According to some assessments (Food and Agriculture Organization of the United Nations, 1999), the land area suitable for installation of solar collectors is about 27% of the entire land area, or about 4×10^7 km^2. Assuming that 1% of the world's unused land surface is used for solar power, the technical potential will be about 1,600 EJ/year. This amount is about three times the world energy consumption from all sources in 2008. On the other hand, the current use of solar energy is estimated as 0.5% for solar heat and 0.04% for solar photovoltaics relative to world total energy consumption (International Energy Agency, 2007).

The technical potential varies over the different regions of the Earth, as do the assessment methodologies. As described in a comparative literature study for the German Environment Agency (Umweltbundesamt, UBA) (Krewitt *et al.*, 2009), the technical potential is based on the available solar radiation, land use exclusion factors, and the future development of technology improvements. Note that this study used different assumptions for the land use factors for PV and CSP. In the first case, it is assumed that 98% of the potential comes from centralised PV power plants and that the suitable land area in the world averages 1.67%. For CSP, all land areas with high direct-normal irradiance (DNI)—with a minimum DNI of 2,000 kWh/m^2/year—were defined as suitable and just 20% of that land was excluded for other uses. The resulting technical potentials for 2050 are 1,689 EJ/year for PV and 8,043 EJ/year for CSP.

For PV, the UBA study analysed three studies (Hofman *et al.*, 2002; Hoogwijk, 2004; de Vries *et al.*, 2007) and made others assumptions, as well. The technical potential varies significantly between these three studies, ranging from 1,338 to 14,766 EJ/year. The main difference between the studies arises from the allocated land area availabilities and, to some extent, on differences in the power conversion efficiency used.

For CSP, the UBA study also analysed three studies (Hofman *et al.*, 2002; Trieb, 2005; Trieb and others, 2009). The main differences between these studies were the minimum threshold for suitable DNI, the restrictions of suitable land varying from 5% suitable (Hofman *et al.*, 2002) to 80% (Krewitt *et al.*, 2009), and different assumptions concerning future plant and storage efficiencies.

In Table 3.1, the column marked “Minimum” shows a breakdown of the global technical potential for different regions. A more optimistic assessment of the solar energy resource is also given in the table under the “Maximum” column.

Table 3.1: Annual technical potential of solar energy for various regions of the world (modified from Nakićenović *et al.*, 1998).

Regions	**Technical Potential of Solar Energy**	
	Minimum, EJ	**Maximum**, EJ
North America	181	741
Latin America and Caribbean	113	338
Western Europe	25	91
Central and Eastern Europe	4	154
Former Soviet Union	199	866
Middle East and North Africa	412	1,106
Sub-Saharan Africa	372	953
Pacific Asia	41	99
South Asia	39	134
Central Asia	116	414
Pacific OECD	73	226
TOTAL	**1,575**	**5,122**
Ratio of technical potential to primary energy consumption in 2007 = 503 EJ (IEA, 2009d, Table 9.1, p.322)	*3.1*	*10.2*

Note: Assumptions used in assessing minimum and maximum technical potential of solar energy:

- Annual minimum clear-sky irradiance relates to horizontal collector plane, and annual maximum clear-sky irradiance relates to two-axis-tracking collector plane; see Table 2.2 in World Energy Council (1994).
- Maximum and minimum annual sky clearance assumed for the relevant latitudes; see Table 2.2 in World Energy Council (1994).
- 1% of unused land is used for both maximum and minimum solar power installations; unused land data are taken from (Food and Agriculture Organization of the United Nations, 1999).
- For conversion from EJ to TWh: 278 TWh = 1 EJ.

As Table 3.1 also indicates, the worldwide technical potential of solar energy is considerably larger than the current primary energy consumption. However, the *economic* potential for applying solar energy depends on a wide variety of factors, for example, theoretical availability of solar energy in a particular region, environmental constraints (e.g., topography, climate condition), resource availability (e.g., land, water), conversion efficiency of the available technology, competition with alternative energy sources, national and local support policies for renewable power generation, coverage and structure of the electricity grid, capability of the power system to deal with power output intermittency, and last but not least, energy consumption demand and patterns in various sectors of the economy and social life. The range of technologies using solar energy is wide and the respective markets have quite different growth rates, ranging between 10% and 50% per year. Therefore, determining the resource potentials is a moving target. Whenever the cost of a specific solar technology is reduced or the cost of conventional energy increases, a new market opens up and the assessment of economic potential changes dramatically.

In determining the amount of solar energy reaching the Earth's surface, one should keep in mind that because of absorption by the atmosphere, its maximum value does not exceed 1000 W/m^2 at a perpendicular surface and for clear-sky conditions. However, due to cloud reflection and clean atmospheric conditions, the solar flux may be higher than the above value in some cases. Generally, the daily mean value of solar flux per unit area is at least three times less due to change of day and night and inclination of the sun above the horizon. During winter, the magnitude of solar flux in the middle latitudes is further reduced; thus, the available amount of energy per unit area at the Earth's surface determines the potential of solar resources. Currently, solar energy is widely used in regions where there are physical limitations in using other energy sources, in off-grid applications, and where the use of solar energy is justified economically.

Regarding the national and local policies on which the application potential also substantially depends, it is important to note that currently at least 60 countries (37 developed and transition countries and 23 developing countries) have some type of policy to promote renewable power generation, including solar energy. The most common policy is the feed-in law, which has been enacted in many countries and regions in recent years, but there are many other forms of policy support (REN21, 2009).

3.2.2 Sources of Solar Radiation Data

Technologists studying the solar impact on energy systems such as buildings and power plants require data measured at the place of the application, i.e., directly at the site of the solar installation. Knowledge of solar energy resource available at different locations strongly influences the assessment of the economics of solar investments. Therefore, it is very important to know the overall global solar energy available, as well as the relative magnitude of its three components: direct-beam irradiation, diffuse irradiation from the sky including clouds, and irradiation received by reflection from the ground surface. Also important are the patterns of seasonal availability, variability of irradiation, and daytime temperature on site. Due to significant inter-annual variability of regional climate conditions in different parts of the world, such measurements must be generated over several years for many applications to provide sufficient statistical validity. In the case of solar PV, panels mounted on roofs of buildings located in tropical regions easily reach temperatures over 70°C (158°F), thereby reducing power output by up to 20%. This is attributed to the temperature sensitivity of solar PV modules.

Solar radiation data can be used to do the following: 1) select optimum sites for large solar energy applications such as power plants, 2) estimate the performance of any solar energy system at any location, 3) design optimum solar energy systems for specific sites, and 4) estimate probable returns on investments.

Numerous empirical schemes have been developed to estimate the global radiation, mainly using conventional ground-based observation of bright sunshine duration and clear-sky solar flux for particular locations. The accuracy of these schemes has been widely studied, and some schemes have been found to reproduce the actual measurements within up to ±30 W/m^2 on a monthly basis, or roughly 3% of maximum clear-sky flux. Although not satisfactory as full-scale measurement, these data can be useful for designers. For example, they can be combined with methods for generating synthetic radiation data to achieve appropriate hourly values that can be used in simulation programs (Graham *et al.*, 1988; Graham and Hollands, 1990).

A complementary source of radiation data can be provided by remote sensing from geostationary satellites. Although such data are inherently less accurate than the ground-based measurements, they may be more suitable for generating specific data at arbitrary locations and times. The images from the satellite provide an estimate of global solar radiation on the horizontal surface with spatial resolution up to about 10 km × 10 km. However, calibration of satellite data from ground measuring stations is also needed.

It is important to note that satellites measure only the upward reflected and scattered solar radiation. Therefore, satellite conversion algorithms are generally based on semi-empirical assumptions. Information contained in these data on the atmospheric composition is then used to compute the amounts of global and diffuse radiation reaching the ground. In the case of variable conditions, satellite-estimated irradiance is representative of the ground-measured irradiance at least in some locations for a time within an hour.

Various international and national institutions provide information on the solar resource: World Radiation Data Center (WRDC, Russia), National Renewable Energy Laboratory (NREL), National Aeronautics and Space Administration (NASA), Brasilian Spatial Institute (INPE), German Aerospace Center (DLR), Bureau of Meteorology Research Center (Australia), CIEMAT (Spain), and certain commercial companies.

The World Radiation Data Centre collects and disseminates daily measurements of global and diffuse radiation, radiation balance and sunshine duration at the Earth's surface submitted by national meteorological services all over the world (Tsvetkov *et al.*, 1995). The data are available from about 1280 sites, and nearly 900 sites have periods of observation of more than 10 years (Figure 3.2). The distribution of measuring sites across the globe is rather non-uniform. Because of the scarcity of measuring sites in some parts of the world, the use of representative sites has been a common practice for engineering calculations. The simple method of estimating radiation at a given point is interpolation from neighbouring ground measuring sites. It is also the only ground-based method available when the density of ground stations is low.

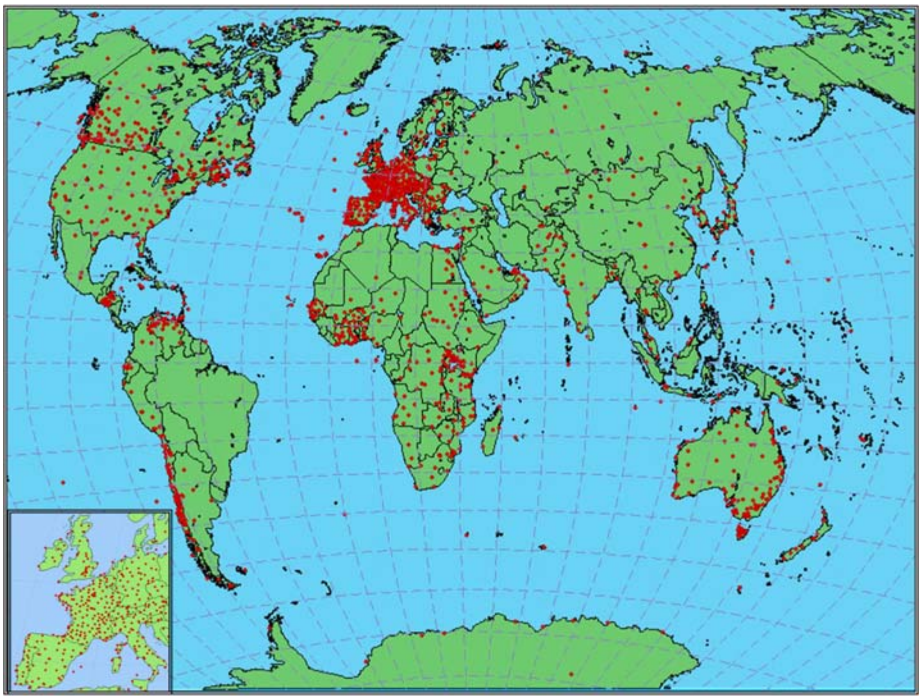


Figure 3.2: The ground-based solar radiation measuring sites from which solar data are available at the WRDC for period 1964–2009. [TSU: source missing]

For projects in the USA, NREL has recently released an updated version of the National Solar Radiation Database (NSRDB) that has 1454 ground locations for 1991 to 2005 (Arvizu, 2008). The gridded data include hourly satellite-modelled solar data for 1998 to 2005 on a 10-km grid. The data can be combined with hourly meteorological data for photovoltaic and concentrating solar power simulation. These hourly values of the solar resource components (direct beam, global horizontal, and diffuse) can be used by designers to determine the solar resource for any orientation of solar collector.

The most common data for describing the local solar climate are the Typical Meteorological Year (TMY) data, which are a collation of selected weather data for a specific location. The TMYs are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations. Because they represent typical, rather than extreme, conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location. TMY data are frequently used to assess the expected heating and cooling costs for the design of a building. They are also used by designers of solar energy systems including solar domestic hot-water systems and large-scale solar thermal power plants. The latest TMY3 collection compiled by the National Renewable Energy Laboratory is based on data for 1,020 locations and derived from a 1991–2005 period of record (Wilcox and Marion, 2008).

Another valuable source of solar energy data is the European Solar Radiation Atlas (ESRA) prepared under the auspices of the Commission of the European Communities (Scharmer and Greif, 2000a; Scharmer and Greif, 2000b). The Atlas comprises observed daily global radiation and monthly sums of sunshine duration provided from many National Weather Services and scientific institutions of the European countries. Satellite images from METEOSAT were supplied by GKSS Research Centre (Geesthacht, Germany), Deutscher Wetterdienst (Offenbach, Germany), and NASA Langley Research Center (USA).

The long-term monthly average data of ESRA were taken as the basis for developing PVGIS (Šúri *et al.*, 2005; Šúri *et al.*, 2007). In this, the ESRA data are enhanced by 3D spatial interpolation and the use of a higher-resolution (1-km) digital elevation model. The effect of shadows from terrain is also taken into account.

The Solar Radiation Atlas of Africa was prepared with support from the Non-Nuclear Energy R&D programme (SUNSAT project) of the Commission of the European Communities. It contains information on the surface radiation with a temporal detail of one month and a spatial resolution of 30 to 50 km, over all regions of Europe, Asia Minor, Africa, and most parts of the Atlantic Ocean. The data covering 1985 and 1986 were derived from measurements of upward solar radiation, which is reflected from the Earth's surface to space and was regularly measured by the geostationary satellite METEOSAT 2.

Another data set representing Africa has been developed at the Ecole des Mines de Paris, France. The data are based on images from the METEOSAT geostationary satellites that were processed with the Heliosat-2 method (Rigollier *et al.*, 2004) and covers the period 1985 to 2004. Long-term average solar radiation data from this database can be accessed using the Photovoltaic Geographical Information System (PVGIS Photovoltaic Geographic Information System, 2008) interface. To control the accuracy of this information for potential users, thorough comparisons were performed with collocated and simultaneously measured data. The ground-based measurements were made at sites in countries that were seen from METEOSAT's position. These comparisons confirmed that data on a monthly basis showed a 10% uncertainty range. Comparison between monthly averages of global radiation data derived from METEOSAT 2 data (resolution about 30 to 50 km) and collocated at the ground shows that bias could vary from 17 to 68 Wh/m^2 and the unbiased standard deviation could vary from 433 to 474 Wh/m^2. All databases primarily prepared for solar energy applications are available to potential users on request from the Institute of Physics of the GKSS Research Centre.

3.2.3 Possible Impact of Climate Change on Resource Potential

On a long timescale, climate warming due to increase of greenhouse gases in the atmosphere may influence cloud cover and turbidity, and it can impact the potential of the solar energy resource in different regions of the globe. Changes of major climate variables, including cloud cover and solar flux at the Earth's surface, have been evaluated using climate models for the 21st century (Meehl *et* *al.*, 2007; Meleshko *et al.*, 2008). It was found that the pattern variation of monthly mean global solar flux does not exceed 1% over some regions of the globe, and it varies from model to model. Validity of the pattern changes seems to be rather low, even for large-scale areas of the Earth.

3.3 Technology and Applications

This section discusses technical issues for a range of solar technologies, organized under the following categories: passive solar, active heating and cooling, photovoltaic (PV) electricity generation, concentrating solar power (CSP) electricity generation, and solar fuel production. Each section also describes applications of these technologies.

3.3.1 Passive Solar

Passive solar energy technologies absorb solar energy, store and distribute it in a natural manner without using mechanical elements, but use natural ventilation (Hernandez Gonzalvez, 1996). The term “passive solar building” is a qualitative term describing a building that makes significant use of solar gain to reduce heating and possibly cooling energy consumption based on the natural energy flows of radiation, conduction, and natural convection. The term “passive building” is often employed to emphasize use of passive energy flows in both heating and cooling, including redistribution of absorbed direct solar gains and night cooling (Athienitis and Santamouris, 2002).

The basic elements of passive solar architecture are windows, thermal mass, protection elements, and reflectors. With the combination of these basic elements, different systems are obtained: direct-gain systems (e.g., the use of windows in combination with walls able to store energy), indirect-gain systems (e.g., Trombe walls), mixed-gain systems (a combination of direct-gain and indirect-gain systems, such as greenhouses), and isolated-gain systems. Passive technologies are integrated with the building and may include the following components:

1. Near-equatorial-facing **windows** with high solar transmittance and a high thermal resistance to maximize the amount of direct solar gains into the living space while reducing heat losses through the windows in the heating season and heat gains in the cooling season. Skylights are also often used for daylighting in office buildings and in solaria/sunspaces.

2. Building-integrated **thermal storage**, commonly referred to as thermal mass, may be sensible, such as concrete or brick, or phase-change materials (Mehling and Cabeza, 2008). The most common type of thermal storage is the **direct gain** system in which thermal storage is distributed in the living space, absorbing the direct solar gains. Storage is particularly important because it performs two essential functions: storing much of the absorbed direct gains for slow release, and maintaining satisfactory thermal comfort conditions by limiting the maximum rise in operative (effective) room temperature (ASHRAE, 2009). Alternatively, a **collector-storage wall**, known as a Trombe wall, may be used, in which the thermal mass is placed directly next to the glazing, with possible air circulation between the cavity of the wall system and the room. However, this system has not gained much acceptance because it limits views to the outdoor environment through the fenestration. **Isolated thermal storage** passively coupled to a fenestration system or solarium/sunspace is another option in passive design.

3. **Airtight insulated opaque envelope** appropriate for the climatic conditions to reduce heat transfer to and from the outdoor environment. In most climates, this energy-efficiency aspect is an essential part of passive design. A solar technology that may be used with opaque envelopes is transparent insulation (Hollands *et al.*, 2001) combined with thermal mass to store solar gains in a wall, turning it into an energy-positive element.

4. **Daylighting technologies and advanced solar control systems,** such as motorized shading (internal, external) and fixed shading devices, particularly for daylighting applications in the workplace. These technologies include electrochromic and thermochromic coatings and

newer technologies such as transparent photovoltaics, which, in addition to a passive daylight transmission function, also generate electricity. Daylighting is a combination of energy conservation and passive solar design. It aims to make the most of the natural daylight that is available. Traditional techniques include the following: shallow-plan design, allowing daylight to penetrate all rooms and corridors; light wells in the centre of the buildings; roof lights; tall windows, which allow light to penetrate deep inside rooms; the use of task lighting directly over the workplace, rather than lighting the whole building interior; and deep windows that reveal and light room surfaces to cut the risk of glare (Everett, 1996).

Some basic rules for optimizing the use of passive solar heating in buildings are the following: buildings should be well insulated to reduce overall heat losses; they should have a responsive, efficient heating system; they should face toward the Equator—the glazing should be concentrated on the equatorial side, as should the main living rooms, with little-used rooms such as bathrooms on the opposite-equatorial side; they should avoid shading by other buildings to benefit from the essential mid-winter sun; and they should be “thermally massive” to avoid overheating in the summer (Everett, 1996).

Clearly, passive technologies cannot be separated from the building itself. Thus, when estimating the contribution of passive solar gains, we need to distinguish between the following: 1) buildings specifically designed to harness direct solar gains using passive systems, defined here as solar buildings, and 2) buildings that harness solar gains through near-equatorial facing windows; this orientation is more by chance than by design. Few reliable statistics are available on the adoption of passive design in residential buildings. Furthermore, the contribution of passive solar gains is missing in existing national statistics. Passive solar is reducing the demand and is not part of the supply chain, which is what is considered by the energy statistics.

The European project SOLGAIN has evaluated the effect of passive solar gain utilization in the existing residential buildings in Europe. The estimated CO_2 emission savings due to solar gains are 345 kg/person/year, or 9 kg/m^2/year. Table 3.2 summarizes the available data.

Table 3.2: Impact of passive solar gain utilization in existing residential buildings in terms of energy and emission savings (European Renewable Centres Agency, 2001) .

Country	Solar Fraction (%)	Total Solar Gains (TWh)	Total Solar Gains (x10^{-3} EJ)	Total CO_2 Reduction (Mt)
Norway	10	4.4	15.8	0.4
Finland	18	8.6	30.9	2.4
UK	15	57	205	22.5
Ireland	11	2.0	7.2	1.2
Germany	13	76	273	26
Belgium	12	13	46.8	4.4
Greece	18	8.9	32.0	3.3

The passive solar design process itself is in a period of rapid change, driven by the new technologies becoming affordable, such as the recently available highly efficient fenestration at the same prices as ordinary glazings. For example, in Canada, double-glazed low-emissivity argon-filled windows are presently the main glazing technology used; but until a few years ago, this glazing was about 20% to 40% more expensive than regular double glazing. These windows are now being used in retrofits of existing homes, as well. Many homes also add a solarium during retrofit. The new glazing technologies and solar control systems allow the design of a larger window area than in the recent past.

Assuming random and equal window distribution, one can estimate that about 25% of the window area on existing buildings is within ±45 degrees of facing the Equator. However, these window areas are typically only about 5% (Swan *et al.*, 2009) of the heated floor area in existing Canadian houses, as compared to 9% or more in the case of solar homes such as the Athienitis house (Athienitis, 2008). Solar homes receive significant useful passive solar gains and have the potential to reduce heating loads by about 20% to 30% (Balcomb, 1992)—and up to 40% in well-insulated houses according to the Passive House Standard (PassivHaus Planning Package [PHPP], 2004). However, occupants often leave curtains or blinds closed while away, which potentially reduces the useful passive solar gains by 30% to 50%.

In most climates, unless effective solar gain control is employed, there may be a need to cool the space during the summer. However, the need for mechanical cooling may often be eliminated by designing for passive cooling. Passive cooling techniques are based on the use of heat and solar protection techniques, heat storage in thermal mass, and heat-dissipation techniques. Progress on passive cooling techniques is important, and applying such techniques may decrease the cooling load of buildings up to 80%, (Santamouris and Asimakopoulos, 1996). The specific contribution of passive solar and energy conservation techniques depends strongly on the climate (United Nations Environment Programme [UNEP], 2007). Solar-gain control is particularly important during the “shoulder” seasons when some heating may be required. In adopting larger window areas—enabled by their high thermal resistance—active solar-gain control becomes important in solar buildings for both thermal and visual considerations.

The potential of passive solar cooling in reducing CO_2 emissions has been shown in two recent publications (Cabeza *et al.*, 2010; Castell *et al.*, 2010). Experimental work shows that adequate insulation can reduce by up to 50% the cooling energy demand of a building during the hot season. Moreover, including phase-change materials in the already insulated building envelop can reduce the cooling energy demand in such buildings further by up to 15%—about 1 to 1.5 kg/year/m^2 of CO_2 emissions would be saved in these buildings due to reducing the energy consumption compared to the insulated building without phase-change material.

Passive solar system applications are mainly of the direct-gain type, but they can be further subdivided into the following main application categories:

Multistory residential buildings designed to have a large equatorial-facing façade so as to provide the potential for a large solar capture area.

Two-story detached or semi-detached solar homes designed to have a large equatorial-facing façade so to provide the potential for a large solar capture area (see Figure 3.3a) (Athienitis, 2008).

Perimeter zones and their fenestration systems in office buildings designed primarily based on daylighting performance. In this application, there is usually an emphasis on reducing cooling loads, but passive heat gains may be desirable, as well, in the heating season (see Figure 3.3b for a schematic of shading devices).

In addition, residential or commercial buildings may be designed to use natural or hybrid ventilation systems and techniques for cooling or fresh-air supply, in conjunction with design for using daylight throughout the year and direct solar gains during the heating season. These buildings may profit from low summer night temperatures using night hybrid ventilation techniques (Santamouris and Asimakopoulos, 1996).

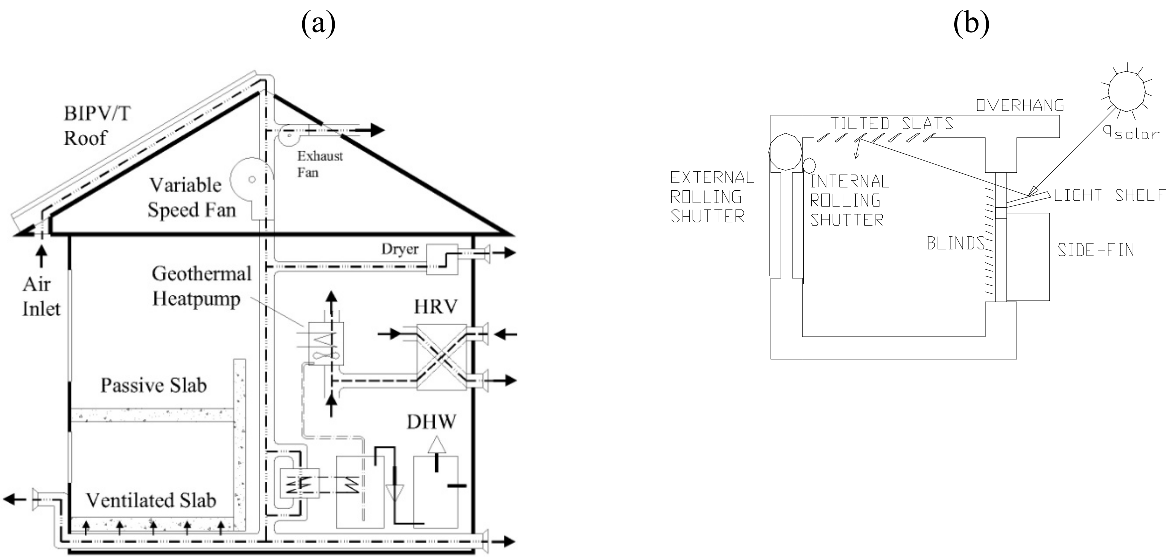


Figure 3.3: (a) Schematic of thermal mass placement and passive-active systems in EcoTerra house; (b) schematic of several daylighting concepts designed to redistribute daylight into the office interior space.[TSU: sources missing]

Currently, passive technologies play a prominent role in the design of net-zero energy solar homes—homes that produce as much electrical and thermal energy as they consume in an average year. These houses are primarily demonstration projects in several countries currently collaborating in a new IEA Task (IEA, 2009c)—SHC Task 40—ECBCS Annex 52, which focuses on net-zero energy solar buildings. In Canada, the EQuilibrium^{TM} net-zero energy home demonstration program conducted by Canada Mortgage and Housing Corporation (Canadian Mortgage and Housing Corporation [CMHC], 2008) has resulted in the construction of several near-net-zero energy solar homes in which passive solar design is used in a systematic manner. Figure 3.4 shows photos of one of these homes—the EcoTerra^{TM}—which is a prefabricated home (Chen *et al.*, 2008). The prefabricated home industry can contribute to a systematic and widespread implementation of passive technologies. Passive technologies are essential in developing affordable net-zero energy homes. Passive solar gains in both the EcoTerra and homes based on the Passive House Standard are expected to reduce the heating load by about 40%. By extension, we can expect systematic passive solar design of highly insulated buildings on a community scale, with optimal orientation and form of housing to easily result in a similar energy saving of 40%.

			
Assembly of house modules (built in the factory and delivered to the site)	Installation of building-integrated photovoltaic/thermal roof module	Family room (direct-gain area: concrete mass 15 cm thick with ceramic tiles)	Finished house: equatorial-facing triple-glazed window area is 9.1% of heated floor area

Figure 3.4: Photos from the EcoTerra^{TM} demonstration solar house assembly and the final completed house. [TSU: source missing]

Another IEA Annex—ECES IA Annex 23—was initiated in November 2009 (IEA Energy Conservation through Energy Storage). The general objective of the Annex is to ensure that energy storage techniques are properly applied in ultra-low-energy buildings and communities. Applications of these designs are foreseen in a post-Kyoto Protocol world where total CO_2 reduction is required. Proper application of energy storage is expected to increase the likelihood of sustainable building technologies.

Windows play a very important role in the energy balance of buildings because heat losses through them are 4 to 10 times higher than through the other elements of the building. In parallel, windows control daylight penetration and natural ventilation flow. Another possibility is the provision of summer shading for direct-gain windows by using photovoltaic overhangs.

Other solar passive applications are natural water heating (included in the next subsection) and natural drying. Grains and many other agricultural products have to be dried before being stored so that insects and fungi do not render them unusable. Examples include wheat, rice, coffee, copra (coconut flesh), certain fruits, and timber (Twidell and Weir, 2006). Solar energy dryers vary mainly as to the use of the solar heat and the arrangement of their major components. Solar dryers constructed from wood, metal, and glass sheets have been evaluated extensively and used quite widely to dry a full range of tropical crops (Imre, 2007).

3.3.2 Active Solar Heating and Cooling

Active solar heating and cooling technologies use the sun to provide either heating or cooling; various of these technologies are discussed here, as well as thermal storage.

In a **solar heating system** the solar collector transforms solar radiation into heat and uses a carrier fluid (e.g., water, solar fluid, or air) to transfer that heat to a well-insulated storage tank, where it can be used when needed.

The two most important factors in choosing the correct type of collector are the following: 1) the service to be provided by the solar collector, and 2) the related desired range of temperature of the heat-carrier fluid. An evacuated-tube collector (described below) is likely to be the most suitable option for producing heat for industry. An uncovered absorber is likely to be limited for low-temperature heat production. Figure 3.5 illustrates the relationship of temperature difference between the collector and ambient versus the efficiency of a collector.

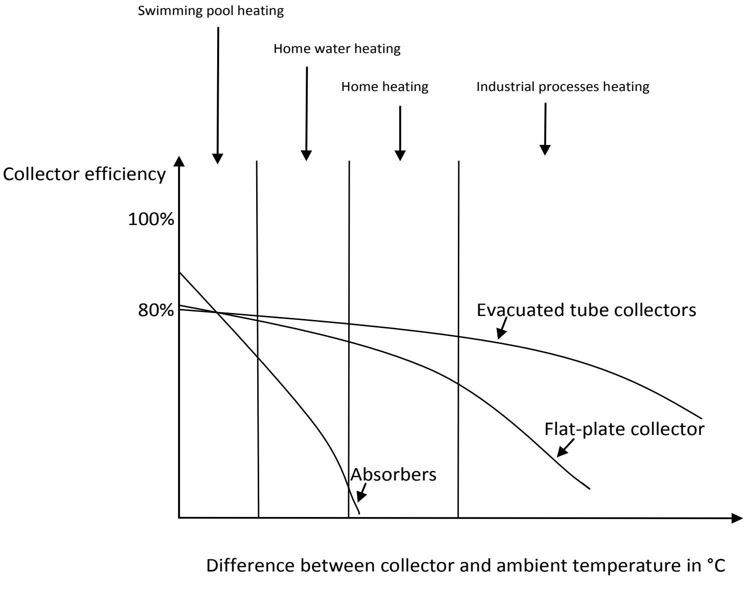


Figure 3.5: Selection of the most suitable solar collector for different applications (adapted from Duffie and Beckman, 2006). The x-axis indicates the difference in temperature between the collector and ambient, and the y-axis indicates the relative efficiency of the collector.

A **solar collector** can incorporate many different materials and be manufactured using a variety of techniques. Its design is influenced by the system in which it will operate and by the region.

Flat-plate collectors are the most widely used solar thermal collectors for residential solar water-heating and space-heating systems. A typical flat-plate collector consists of an absorber, a header and riser tube arrangement or a single serpentine tube, a transparent cover, a frame, and insulation (Figure 3.6a). For low-temperature applications, such as the heating of swimming pools, only a single plate is used as an absorber, with the fluid trickling over its surface. Flat-plate collectors demonstrate a good price/performance ratio, as well as a broad range of mounting possibilities (e.g., on the roof, in the roof itself, or unattached).

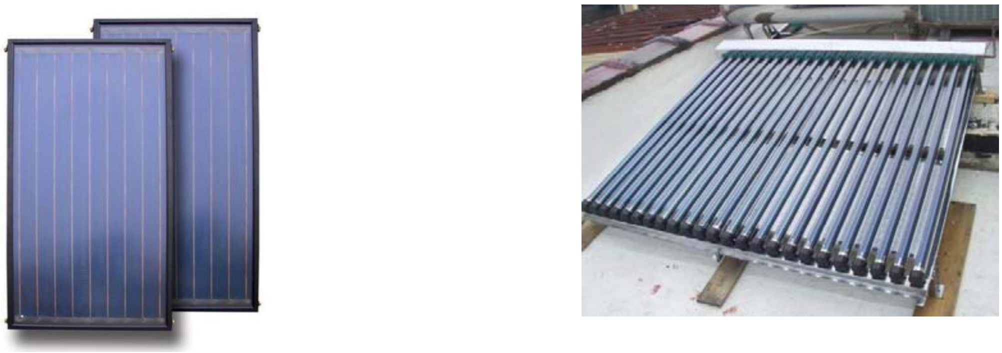

(a) (b)

Figure 3.6: Thermal solar collectors: flat-plate (a) and evacuated-tube (b) collectors. [TSU: source missing]

Evacuated-tube collectors are usually made of parallel rows of transparent glass tubes connected to a header pipe (Figure 3.6b). To reduce heat loss within the frame by convection, the air is pumped out of the collector tubes to generate a vacuum. This makes it possible to achieve very high temperatures (more than 150°C), useful for cooling (see below) or industrial applications.

Solar water heating systems used to produce hot water can be classified as passive solar water heaters and active solar water heaters. Also of interest are active solar cooling systems, which transform the hot water produced by solar energy into cold water.

Passive solar water heaters can be either integral collector-storage systems or thermosyphon systems (Figure 3.7). Integral collector-storage systems, also known as ICS or "batch" systems, are made of one or more black tanks or tubes in an insulated glazed box. Cold water first passes through the solar collector, which preheats the water, and then continues to the conventional backup water heater. In climates where freezing temperatures are unlikely, many evacuated-tube collectors include an integrated storage tank at the top of the collector. This design has many cost and user-friendly advantages compared to a system that uses a separate standalone heat-exchanger tank. It is also appropriate in households with significant daytime and evening hot-water needs; but they do not work well in households with predominantly morning draws because they lose most of the collected energy overnight.

Active solar water heaters rely on electric pumps and controllers to circulate the carrier fluid through the collectors (Figure 7b). Three types of active solar water-heating systems are available. *Direct circulation systems* use pumps to circulate pressurized potable water directly through the collectors. These systems are appropriate in areas that do not freeze for long periods and do not have hard or acidic water. *Antifreeze indirect-circulation systems* pump heat-transfer fluid, which is usually a glycol-water mixture, through collectors. Heat exchangers transfer the heat from the fluid to the water for use. *Drainback indirect-circulation systems* use pumps to circulate water through the collectors. The water in the collector and the piping system drains into a reservoir tank when the pumps stop, eliminating the risk of freezing in cold climate. This system should be carefully designed and installed to ensure that the piping always slopes downward to the reservoir tank. Also, stratification should be carefully considered in the design of the water tank (Hadorn, 2005).

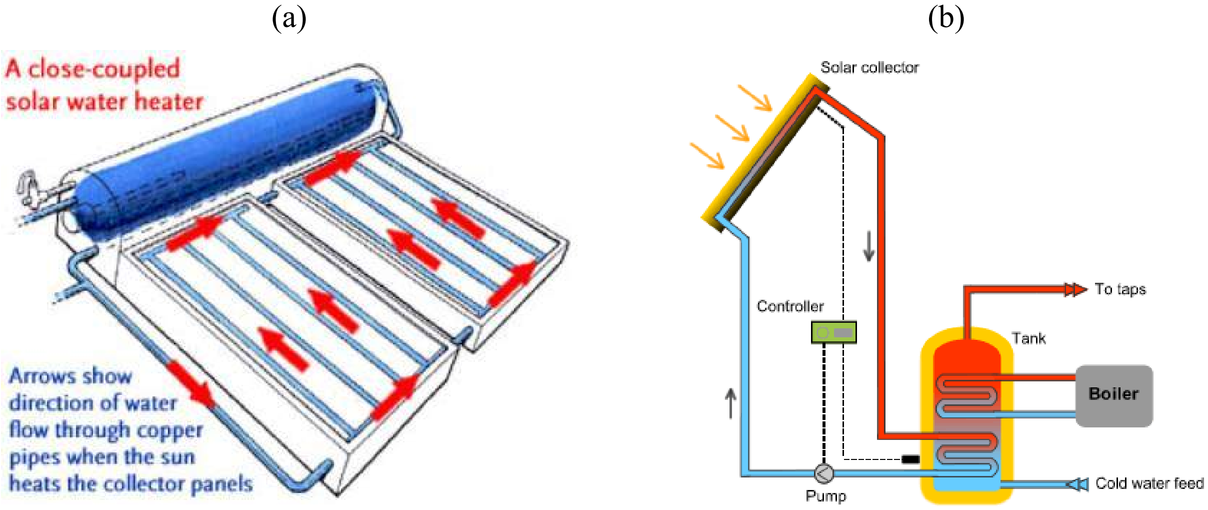


Figure 3.7: Thermal solar system: passive (a) and active (b) system. [TSU: sources missing], [TSU: figure (a): quality insufficient]

Solar cooling can be broadly categorized into solar electric refrigeration, solar thermal refrigeration, and solar thermal air-conditioning. In the first category, the solar electric compression refrigeration uses photovoltaic panels to power a conventional refrigeration machine (Fong *et al.*, 2010). In the second category, the refrigeration effect can be produced through solar thermal gain; solar mechanical compression refrigeration, solar absorption refrigeration, and solar adsorption refrigeration are the three common options. In the third category, the conditioned air can be directly provided through the solar thermal gain by means of desiccant cooling. Both solid and liquid sorbents are available, such as silica gel and lithium chloride, respectively.

Active thermal solar cooling is used when solar heat powers an absorption chiller. This system can be used as an air-conditioning system in any building. Deploying such a technology depends heavily on the industrial deployment of low-cost small-power absorption chillers.

Open cooling cycle (or desiccant cooling) systems are mainly of interest for the air conditioning of buildings. They can use solid or liquid sorption. The central component of any open solar-assisted cooling system is the dehumidification unit. In most systems using solid sorption, this unit is a desiccant wheel. Various sorption materials can be used, such as silica gel or lithium chloride. All other system components are found in standard air-conditioning applications with an air-handling unit and include the heat-recovery units, heat exchangers, and humidifiers. Liquid sorption techniques have been demonstrated successfully.

The heat required for the regeneration of the sorption wheel can be provided at low temperatures (45° to 90°C), which suits many solar collectors on the market. Other types of desiccant dehumidifiers exist that use solid sorption. These have some thermodynamic advantages and can lead to higher efficiency, but place higher demands on the material and equipment.

Closed heat-driven cooling systems using these cycles have been known for many years and are usually used for large capacities, from 100 kW and greater. The physical principle used in most systems is based on the sorption phenomenon. Two technologies are established to produce thermally driven low- and medium-temperature refrigeration: absorption and adsorption.

Absorption technologies cover the majority of the global thermally driven cooling market. The main advantage of absorption cycles is their higher coefficient of performance (COP) values, which range from 0.6 to 0.8 for single-stage machines, and from 0.9 to 1.3 for double-stage technologies.

Typical heat-supply temperatures are 80° to 95°C and 130° to 160°C, respectively. The absorption pair used is either lithium bromide and water, or ammonia and water.

Adsorption refrigeration cycles using silica gel and water, for instance, as the adsorption pair can be driven by low-temperature heat sources down to 55°C, producing temperatures down to 5°C. This kind of system achieves COP values of 0.6 to 0.7. Today, the financial viability of adsorption systems is limited due to the far higher production costs compared to absorption systems.

Thermal storage within thermal solar systems is a key component to ensure reliability and efficiency. Four main types of thermal energy storage technologies can be distinguished: sensible, latent, sorption, and thermochemical heat storage (Hadorn, 2005).

Sensible heat storage systems use the heat capacity of a material. The vast majority of systems on the market use water for heat storage. Water heat storage covers a broad range of capacities, from several hundred litres to tens of thousands of cubic metres.

Latent heat storage systems store thermal energy during the phase change, either melting or evaporation, of a material. Depending on the temperature range, this type of storage is more compact than heat storage in water. Melting processes have energy densities on the order of 100 kWh/m^3 compared to 25 kWh/m^3 for sensible heat storage. Most of the current latent heat storage technologies for low temperatures store heat in building structures to improve thermal performance, or in cold storage systems. For medium-temperature storage, the storage materials are nitrate salts. Pilot storage units in the 100-kW range currently operate using solar steam.

Sorption heat storage systems store heat in materials using water vapour taken up by a sorption material. The material can either be a solid (adsorption) or a liquid (absorption). These technologies are still largely in the development phase, but some are on the market. In principle, sorption heat storage densities can be more than four times higher than sensible heat storage in water.

Thermochemical heat storage systems store heat in an endothermic chemical reaction. Some chemicals store heat 20 times more densely than water; but more typically, the storage densities are 8 to 10 times higher. Few thermochemical storage systems have been demonstrated. The materials currently being studied are the salts that can exist in anhydrous and hydrated form. Thermochemical systems can compactly store low- and medium-temperature heat. Thermal storage is discussed with specific reference to higher-temperature CSP in section 3.3.4.

Underground thermal energy storage (UTES) is used for seasonal storage and includes the various technologies described below.

The most frequently used storage technology, which makes use of the underground, is *aquifer thermal energy storage* (ATES). This technology uses a natural underground layer (e.g., a sand, sandstone, or chalk layer) as a storage medium for the temporary storage of heat or cold. The transfer of thermal energy is realized by extracting groundwater from the layer and by re-injecting it at the modified temperature level at a separate location nearby. Most applications are about the storage of winter cold to be used for the cooling of large office buildings and industrial processes. Aquifer cold storage is gaining interest because savings on electricity bills for chillers are about 75%, and in many cases, the payback time for additional investments is shorter than five years. A major condition for the application of this technology is the availability of a suitable geologic formation.

The other technologies for underground thermal energy storage are *borehole storage* (BTES), *cavern storage* (CTES), and *pit storage*. Which of these technologies is selected depends strongly on the local geologic conditions. With borehole storage, vertical heat exchangers are inserted into the underground, which ensure the transfer of thermal energy toward and from the ground (clay, sand, rock). Ground heat exchangers are also frequently used in combination with heat pumps, where the ground heat exchanger extracts low-temperature heat from the soil. With cavern storage and pit storage, large underground water reservoirs are created in the subsoil to serve as thermal energy storage systems. These storage technologies are technically feasible, but the actual application is still limited because of the high level of investment.

Improved designs are expected to address longer lifetimes, lower installed costs, and increased temperatures. The following are some design options: 1) The use of plastics in residential solar water-heating systems; 2) Powering air-conditioning systems using solar-energy systems, especially focusing on compound parabolic concentrating collectors; 3) The use of flat-plate collectors for residential and commercial hot water; and 4) Concentrating and evacuated-tube collectors for industrial-grade hot water and thermally activated cooling.

Research to decrease the cost of solar water-heating systems is mainly oriented toward developing the next generation of low-cost, polymer-based systems for mild climates. The focus includes testing the durability of materials. The work to date includes unpressurized polymer ICS systems that use a load-side immersed heat exchanger and direct thermosyphon systems.

For **active solar heating and cooling applications**, the amount of hot water a solar heater produces depends on the type and size of the system, amount of sun available at the site, seasonal hot-water demand pattern, and installation of the system. An industrial or agricultural process heat system comprises a solar collector, intermediate heat storage, and a means of conveying the collected heat from the storage unit to the application. The solar collector is usually selected based on outlet temperature matched to the required process heat (Norton, 2001).

Some process heat applications can be met with temperatures delivered by “ordinary” low-temperature collectors, namely, from 30° to 80°C. However, the bulk of the demand for industrial process heat requires temperatures from 80° to 250°C.

Process heat collectors are another application field for solar thermal heat collectors. Typically, these systems require a large capacity (hence, large collector areas), low costs, and high reliability and quality. Although low- and high-temperature collectors are offered in a dynamically growing market, process heat collectors are at a very early stage of development and no products are available on an industrial scale. In addition to “concentrating” collectors, improved flat collectors with double and triple glazing are currently being developed, which might be interesting for process heat in the range of up to 120°C.

Solar refrigeration is used, for example, to cool stores of vaccines. The need for such systems is greatest in peripheral health centers in rural communities in the developing world, where no electrical grid is available.

Solar cooling is a specific area of application for solar thermal. Either high-efficiency flat plates or evacuated tubes can be used to drive absorption cycles to provide cooling. For a greater COP, collectors with low concentration levels can provide the temperatures (up to around 250°C) needed for double-effect absorption cycles. There is a natural match between solar and the need for cooling.

A number of thermally driven cooling systems have been built employing closed thermally driven cooling cycles, using solar thermal energy as the main energy source. These systems often cater to large cooling capacities of up to several hundred kW. In the last 5 to 8 years, a number of systems have been developed in the small-capacity range, below 100 kW, and, in particular, below 20 kW and down to 4.5 kW. These small systems are single-effect machines of different types, used mainly for residential buildings and small commercial applications.

Although open cooling cycles are generally used for air conditioning in buildings, closed heat-driven cooling cycles can be used for both air-conditioning and industrial refrigeration.

Solar energy may be used for space heating of agricultural buildings. The guiding principles are similar to the solar space heating of non-agricultural buildings. Low-cost, roof-based, air-heating solar collectors tend to be used because of the low initial investment required. To assure excellent performance, one must establish good fabrication quality control and adequately educate installers about the proper sizing of the relevant system components.

Other solar applications are listed below. The production of potable water using solar energy has been readily adopted in remote or isolated regions. Fundamentally, three potable water extraction processes use solar energy: 1) Distillation, where water evaporated using solar heat is then condensed, thus separated from its mineral content; 2) Reverse osmosis, where a pressure gradient across a membrane causes water molecules to pass from one side to the other; larger mineral molecules cannot cross the membrane; and 3) Electrodialysis, where a selective membrane containing positive and negative ions separates water from minerals using solar-generated electricity.

Solar stills were widely used in some parts of the world (e.g., Puerto Rico) to supply water to households of up to 10 people. The modular devices supply up to 8 litres of drinking water from an area of roughly 2 m² [TSU: not clear, insert temporal relation]. The potential for technical improvements is to be found in reducing the cost of materials and designs. Increased reliability and better-performing absorber surfaces would slightly increase production per m². Today, they are only used in developing countries, but depending on the environmental conditions their efficiency can be very low.

In appropriate insolation conditions, solar detoxification can be an effective low-cost treatment for low-contaminant waste. In *photolytic* detoxification, exposure to 1000-fold concentrated insolation destroys contaminants directly. *Photocatalytic* oxidation destroys contaminants by the ultraviolet component of insolation activating a catalyst that destroys the contaminants. Solar photocatalysis is effective for decontaminating bacterial, pesticide, organic, or chemical pollution of water supplies.

Multiple-effect humidification (MEH) desalination units indirectly use heat from highly efficient solar thermal collectors to induce evaporation and condensation inside a thermally isolated, steam-tight container. Using a solar thermal system to enhance humidification of air inside the box, water and salt are separated, because salt and dissolved solids from the fluid are not carried away by steam. When the steam is recondensed in the condenser, most of the energy used for evaporation is regained. This reduces the energy input for desalination, which requires temperatures of between 70° and 85°C. The specific water production rate is about 20 to 30 litres per m² absorber area per day. The specific investment is less than for the solar still, and this system is available for sizes from 500 to 50,000 litres per day. These MEH systems are now beginning to appear in the market. Also see the report on water desalination by CSP (German Aerospace Center [DLR], 2007) and discussion of SolarPACES Task VI (SolarPACES, 2009b).

In solar drying, solar energy is used either as the sole source of the required heat or as a supplemental source, and the air flow can be generated by either forced or free (natural) convection (Fudholi *et al.*, 2010). Forced-convection dryers have higher drying rates compared to passive dryers and can be used for high production rates; but they are more complex and expensive. Free-convection dryers are simple to design and have low installation and operating costs; but the capacity per unit area of the dryer is limited and for small-scale operations only.

Solar cooking is one of the most widely used solar applications in developing countries. A solar cooker uses sunlight as its energy source, so no fuel is needed and operating costs are zero. Also, a reliable solar cooker can be constructed easily and quickly from common materials. Solar cookers basically concentrate sunlight and convert it into heat, which is then trapped and used for cooking. Different types of solar cookers include box, panel, parabolic, and hybrid cookers, as well as solar kettles. In some regions, solar cooking is promoted to help slow deforestation and desertification, which are caused by using wood as fuel.

3.3.3 Photovoltaic Solar Electricity Generation

This subsection discusses photovoltaic (PV) solar electricity generation technologies and applications.

Photovoltaic technologies generate electricity directly from solar radiation. PV cells (or “solar cells”) take advantage of the photovoltaic effect to generate electricity. First, photons making up solar radiation are absorbed by a semiconductor material, exciting negatively charged electrons and freeing them from within their atomic structure (Figure 3.8). The excited electrons leave behind positively charged “holes” that can also migrate through the semiconductor. Second, the generated electrons and holes are separated spatially at a selective interface (or junction), which provides a separated negative charge on one side of the junction and positive charge on the other side. This resulting charge separation creates an electrical potential difference (or voltage) resulting in an electric field across the interface. In most solar cells, the junction is formed by stacking two different semiconductor layers (one p-type, the other n-type). The layers can be made from the same semiconductor material (forming a homojunction) or from two different semiconductor materials (forming a heterojunction). The doping (p- and n-type) of the layers can be formed by adding different types of impurities (dopants) to the layers. The key feature of a semiconductor junction is that it has a built-in electric field that pushes/pulls electrons to one side and holes to the other side. When the two sides of the illuminated junction are contacted and connected to a load, a current can flow—that is, light-generated electrons flow from one side of the device via the load to the other side of the device. The combination of a voltage and a current is electric power. Thus, when the PV device is illuminated, electrons and holes are continuously generated and separated, and the solar cell can generate electric power.

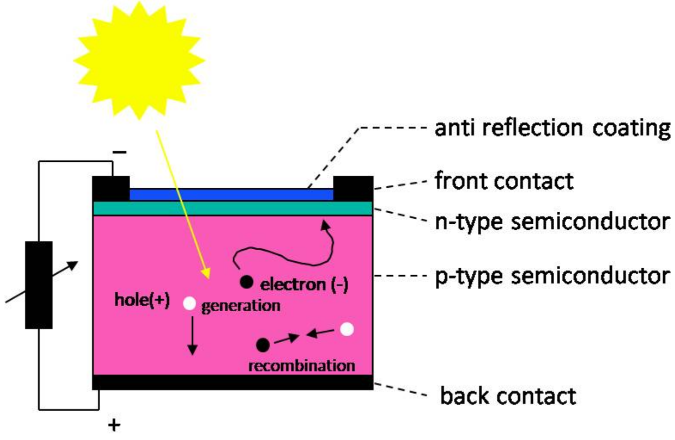


Figure 3.8: Schematic cross-section of a solar cell. [TSU: source missing, figure not clear]

Various PV technologies have been developed in parallel and are discussed below. We distinguish between 1) Existing technologies, which are commercially available, 2) Emerging technologies, which are under development in the laboratory or in (pre-)pilot production stage, and 3) Novel approaches, which are based on potentially disruptive concepts and/or materials.

Existing PV technologies include wafer-based crystalline silicon PV, as well as the thin-film technologies of copper indium/gallium disulfide/diselenide (CIGSS), cadmium telluride (CdTe) and thin-film silicon PV (amorphous and microcrystalline silicon). Mono- and multicrystalline (sometimes called “polycrystalline”) silicon wafer PV (including ribbon technologies) are the dominant technologies on the PV market, with a 2009 market share of about 80%.

Silicon wafer modules are typically produced in a processing sequence along a value chain that starts with purified silicon feedstock that is melted and solidified using different techniques to produce ingots or ribbons with variable degrees of crystal perfection. The ingots are then shaped into bricks and sliced into thin wafers by wire-sawing. In the case of ribbons, wafers are cut from the sheet typically using a laser. Cut wafers and ribbons are processed into solar cells and interconnected in weatherproof or encapsulated packages.

Research single-junction cells have been externally verified to have record conversion efficiencies of 25.0% for monocrystalline silicon and 20.4% for multicrystalline cells (Green *et al.*, 2009b) under standard reporting conditions (i.e., 1000 W m^{-2}, AM1.5, 25°C). The theoretical Shockley-Queisser limit of a single-junction cell with an energy bandgap of crystalline silicon (1.1 electron-volt) is 31% conversion efficiency (Shockley and Queisser, 1961), whereas the specific maximum efficiency for crystalline silicon has been calculated to be 29% (Swanson, 2006).

Several variations for higher efficiency have been developed, e.g., heterojunction solar cells and interdigitated back-contact solar cells. Heterojunction solar cells consist of a crystalline silicon wafer base with a (deposited) amorphous silicon emitter. The highest efficiency of heterojunction solar cells is 23% for a 100-cm^2 cell (Taguchi *et al.*, 2009). In an interdigitated back-contact solar cell, both the base and emitter are contacted at the back of the cell, with one advantage being no shading of the front of the cell by a top electrode. The highest efficiency of such a silicon back-contact silicon wafer cell is reported to be 23.4% (Swanson, 2008).

Wafers have decreased in thickness from 400 μm in 1990 to less than 200 μm in 2009 and have increased in area from 100 cm^2 to over 200 cm^2 in this period. Module efficiency has improved from about 10% in 1990 to typically 13% to 15% today, with the best performers above 17%. And manufacturing facilities have increased from the typical 1 MWp to 5 MWp annual output range in 1990 to hundreds of MWp for today's largest factories. The processes in the value chain have progressed significantly during recent years, but they still have potential for further large improvements. Commercial module efficiencies for wafer-based silicon PV range from 12% to 20%.

Commercial thin-film PV technologies include a range of absorber material systems: amorphous silicon, amorphous silicon-germanium microcrystalline silicon, cadmium telluride (CdTe), and copper indium gallium diselenide (or disulfide) (CIGS). Theses solar cells have an absorber layer thickness of a few micrometers or less and are deposited on glass, metal, or plastic substrates with areas up to 5.7 m^2.

The amorphous silicon (a-Si) solar cell, introduced in 1976 (Carlson and Wronski, 1976) with initial efficiencies of 1% to 2%, has been the first commercially successful thin-film PV technology. Amorphous Si is a quasi-direct-bandgap material and hence has a high light absorption coefficient; therefore, the thickness of an a-Si cell can be more than 100 times thinner than that of a crystalline Si (c-Si) cell. This semiconductor is really an hydrogenated-amorphous Si (a-Si:H), with hydrogen tying up dangling Si bonds that would otherwise create a high density of defect states in the bandgap, which would eliminate any voltage production. Developing better efficiencies for a-Si has been limited by inherent material quality and by light-induced degradation identified as the Staebler-Wronski effect (Staebler and Wronski, 1977). However, research efforts have successfully lowered the impact of the Staebler-Wronski effect to around 10% or less by controlling the microstructure of the film. The highest stabilized efficiency reported is 10.1% (Benagli *et al.*, 2009).

Higher efficiency has been achieved by using multijunction technologies with alloy materials, e.g., germanium and carbon, to form semiconductors with lower or higher bandgaps, respectively, to cover a wider range of the solar spectrum (Yang and Guha, 1992). Another approach to increase the efficiency of thin-film silicon devices is through a tandem consisting of a microcrystalline silicon bottom cell with an amorphous silicon top cell (Yamamoto *et al.*, 1994; Meier *et al.*, 1997). Stabilized efficiencies of 12% to 13% have been measured for various laboratory devices (Green *et al.*, 2010).

CdTe solar cells using a heterojunction with CdS have always been technologically interesting, because CdTe has a suitable energy bandgap of 1.45 electron-volts (eV) with a high coefficient of light absorption. The best efficiency of this cell is 16.5% (Green *et al.*, 2008; Green *et al.*, 2009a) and the best commercially available modules have an efficiency of about 10%–11%. Goncalves et al. (2008) estimated that the maximum efficiency will be 17.6%, and future improvements will focus on PV efficiency and how to further reduce manufacturing costs—which are already the lowest in the industry at $0.83/W in 2009.

The toxicity of metallic cadmium and the relative scarcity of tellurium are issues commonly associated with this technology. CdTe itself is a semiconductor and only limited toxicological data are available. Therefore, the evaluation of potential health risks has been based on other forms of cadmium (Sinha *et al.*, 2008). The currently known toxic health effects of CdTe described on a typical material safety data sheet are limited to dust inhalation and ingestion. Recent investigations on CdTe by Zayed et al. on the acute oral and inhalation toxicity of CdTe in rats show that the toxicity potential is much lower than that of cadmium (Zayed and Philippe, 2009). But this potential hazard is mitigated by using a glass-sandwiched module design and by recycling the entire module and any industrial waste (Sinha *et al.*, 2008). Contrary to the commonly assumed scarcity of tellurium, Wadia et al. (2009) found that the currently known economic tellurium reserves would allow the installation of about 10 TW of CdTe solar cells.

The CIGS material family is the basis of the highest efficiency thin-film solar cells to date. The $CuInSe_2/CdS$ solar cell was invented in the early 1970s at Bell Laboratories (Wagner *et al.*, 1974). Incorporating Ga and/or S to produce $CuInGa(Se,S)_2$ (CIGSS) results in the benefit of a widened bandgap depending on the composition (Dimmler and Schock, 1996). CIGS-based solar cells have been validated at an efficiency of 20.0% (Repins *et al.*, 2008), using a doubly graded layer of Ga in the absorption layer to realize both high current density and high open-circuit voltage. Due to higher efficiencies and lower manufacturing energy consumptions, CIGSS cells are currently in the industrialisation phase, with best commercial module efficiencies of up to 13.1% (Kushiya, 2009) for $CuInGaSe_2$ and 8.6% for $CuInS_2$ (Meeder *et al.*, 2007). As with tellurium reserves, Wadia et al. (2009) found that the currently known economic indium reserves would allow the installation of more than 10 TW of CIGSS-based PV systems.

High-efficiency solar cells based on GaAs and InGaP (i.e., III-V semiconductors) have superior efficiencies, but are also expensive devices. Double- and triple-junction devices are currently being commercialized. An economically feasible application is the use of these cells in concentrator PV systems (Bosi and Pelosi, 2007). The most commonly used cell is a three-junction device based on GaInP/GaAs/Ge, with a record efficiency of 41.6% for a lattice-matched cell (Boeing-Spectrolab) and 41.1% for a metamorphic or lattice-mismatched device (Fraunhofer). Submodule efficiencies have reached 27% (Green *et al.*, 2009b) (may be 30% from Amonix). These cells were developed for space use. However, to achieve an economically suitable transition for terrestrial purposes, the solution is use these devices in a concentrator system. The advantage is that cell efficiencies increase with higher irradiance (Bosi and Pelosi, 2007) and the cell area decreases in proportion to the concentration level (i.e., under 1000-sun concentration, the area of the cell is about 1/1000 less than at 1-sun). Concentrator applications require a high fraction of direct (versus diffuse) irradiation, and is thus are only suited for Sunbelt regions with low cloud coverage.

Emerging technologies are technologies still under development and in laboratory or (pre-) pilot stage, but that could become commercially viable within the next decade. They are based on very low-cost materials and/or processes and include technologies such as dye-sensitized solar cells, organic solar cells, and low-cost (printed) versions of existing inorganic thin-film technologies.

Electricity generation by d*ye-sensitized solar cells* (DSSCs) is based on light absorption in dye molecules (the “sensitizers”) attached to the very large surface area of a nanoporous oxide semiconductor electrode (usually titanium dioxide), followed by injection of excited electrons from the dye into the oxide. The dye/oxide interface thus serves as the separator of negative and positive charges, like the p-n junction in other devices. The injected electrons are then replenished by electrons supplied through a liquid electrolyte which penetrates the pores and which provides the electrical path from the counter electrode (Gratzel, 2001). State-of-the-art DSSCs have achieved a top conversion efficiency of 10.4% (Chiba *et al.*, 2005). Despite the gradual improvements since its discovery in 1991 (O'Regan and Gratzel, 1991), long-term stability against ultraviolet light irradiation, electrolyte leakage, and high ambient temperatures continue to be key issues in commercializing these PV cells.

Organic PV (OPV) cells use stacked solid organic semiconductors, either polymers or small organic molecules. A typical structure of a small-molecule OPV cell consists of a stack of p-type and n-type organic semiconductors forming a planar heterojunction. The short-lived nature of the excited states (excitons) formed upon light absorption limits the thickness of the semiconductor layers that can be used—and therefore, the efficiency of such devices. Note that excitons need to move to the interface where positive and negative charges can be separated before they de-excite. If the travel distance is short, the “active” thickness of material is small and not all light can be absorbed within that thickness.

The efficiency that can be achieved with single-junction OPV cells is about 5% (Li *et al.*, 2005), although predictions indicate about twice that value or higher (Forrest, 2005; Koster *et al.*, 2006). To decouple exciton transport distances from optical thickness (light absorption), so-called bulk-heterojunction devices have been developed. In these devices, the absorption layer is made of a nanoscale mixture of p- and n-type materials (respectively, polymers such as P3HT and fullerenes) to allow the excitons to reach the interface within their lifetime, while also enabling a sufficient macroscopic layer thickness. This bulk-heterojunction structure plays a key role in improving the efficiency, to a record value of 7.9% in 2009 (Green *et al.*, 2010). The developments in cost and processing (Brabec, 2004; Krebs, 2005) of materials have caused OPV research to advance further. Also, the main development challenge is to achieve a sufficiently high stability in combination with a reasonable efficiency.

Novel technologies are potentially disruptive (high-risk, high-potential) approaches based on new materials, devices, and conversion concepts. Generally, their practically achievable conversion efficiencies and cost structure are still unclear. Examples of these approaches include intermediate-band semiconductors, hot-carrier devices, spectrum converters, plasmonic solar cells, and various applications of quantum dots (see subsection 3.7.3). The emerging technologies described in the previous section primarily aim at very low cost, while achieving a sufficiently high efficiency and stability. However, for novel technologies, most aim at reaching very high efficiencies by making better use of the entire solar spectrum from infrared to ultraviolet.

PV Systems: A *photovoltaic system* is composed of the PV module, as well as the balance of systems (BOS), which includes storage, system utilization, and the energy network. The system must be reliable, cost effective, attractive, and match with the electric grid in the future (U.S. Photovoltaic Industry Roadmap Steering Committee, 2001; Navigant Consulting Inc., 2006; EU PV European Photovoltaic Technology Platform, 2007; Energy Information Administration [DOE], 2008; Kroposki *et al.*, 2008; NEDO, 2009).

At the component level, a major objective of BOS development is to extend the lifetime of BOS components for grid-connected applications to that of the modules—typically 20 to 30 years—in addition to further reducing the cost of components and installation. The highest priority is given to developing inverters, storage devices, and new designs for specific applications such as building-integrated PV. For systems installed in isolated, off-grid areas, component lifetime should be increased to around 10 years, and components for these systems need to be designed so that they require little or no maintenance. Storage devices are necessary for off-grid PV systems and will require innovative approaches to the short-term storage of small amounts of electricity (1 to 10 kWh); in addition, approaches are needed for integrating the storage component into the module, thus providing a single streamlined product that is easy to use in off-grid and remote applications. Moreover, devices for storing large amounts of electricity (over 1 MWh) will be adapted to large PV systems in the new energy network. As new module technologies emerge in the future, some of the ideas relating to BOS may need to be revised. Furthermore, the quality of the system needs to be assured and adequately maintained according to defined standards, guidelines, and procedures. To ensure system quality, assessing performance is important, including on-line analysis (e.g., early fault detection) and off-line analysis of PV systems. The knowledge gathered can help to validate software for predicting the energy yield of future module and system technology designs.

To increasingly penetrate the energy network, PV systems must use technology that is compatible with the electric grid and energy supply and demand. System designs and operation technologies must also be developed in response to demand patterns by developing technology to forecast power generation volume and to optimize the storage function. Moreover, inverters must improve the quality of grid electricity by controlling reactive power or filtering harmonics with communication in a new energy network such as the Smart Grid.

Photovoltaic applications include PV power systems classified into two major types: those not connected to the traditional power grid (i.e., off-grid applications) and those that are connected (i.e., grid-connected applications). In addition, there is a much smaller, but stable, market segment for consumer applications.

Off-grid systems have a significant potential in the unelectrified areas of developing countries. Figure 3.9 shows the ratio of various off-grid and grid-connected systems in the Photovoltaic Power Systems (PVPS) Programme countries. Of the total capacity installed in the IEA PVPS countries during 2008, only about 1% was installed in off-grid systems, and these now make up 5.5% of the cumulative installed PV capacity of the IEA PVPS countries (IEA, 2009c).

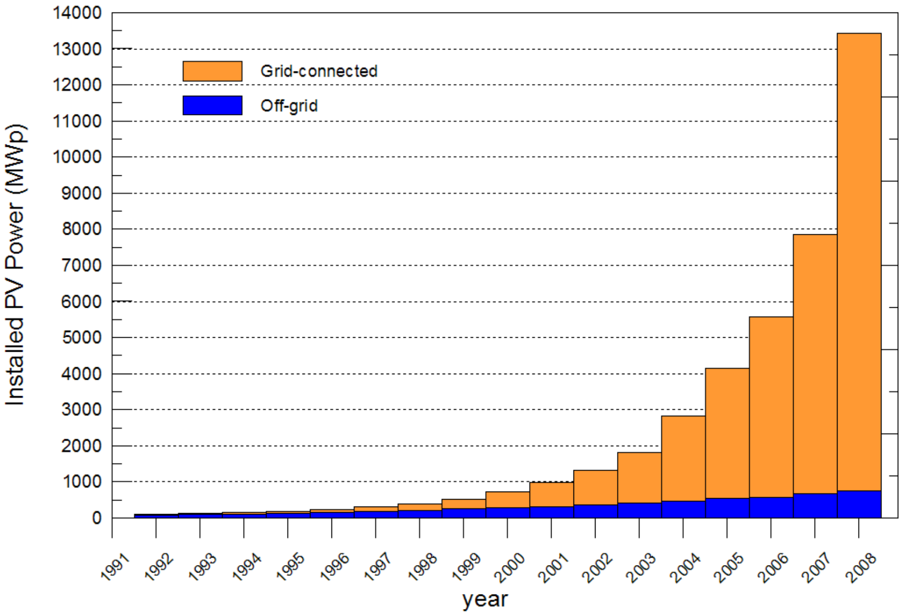


Figure 3.9: Historical trends of off-grid and grid-connected systems in the Organisation for Economic Co-operation and Development (OECD) countries (IEA, 2009c). [TSU: Caption not clear (cumulative installed capacity)]

Off-grid centralized PV mini-grid systems have become a reliable alternative for village electrification over the last years. In a PV mini-grid system, energy allocation is possible. For a village located in an isolated area and with houses not separated by too great a distance, the power may flow in the mini-grid without considerable losses. Centralized systems for local power supply have different technical advantages concerning electrical performance, reduction of storage needs, availability of energy, and dynamic behaviour. Photovoltaic centralized mini-grid systems could be the least-cost options for a given level of service, and they may have a diesel generator set as an optional backup system or operate as a hybrid photovoltaic-wind-diesel system. These kinds of systems are relevant for reducing and avoiding diesel generator use in remote areas (Muñoz *et al*., 2007; Sreeraj *et al*., 2010).

Grid-connected PV systems use an inverter to convert electricity from direct current (DC) as produced by the PV array to alternating current (AC), and then supply the generated electricity to the electricity network.

Compared to an off-grid installation, system costs are lower because energy storage is not generally required, since the grid is used as a buffer. The annual output yield ranges from 300 to 2000 kWh/kW (Clavadetscher and Nordmann, 2007; Gaiddon and Jedliczka, 2007; Kurokawa *et al*., 2007; PVGIS Photovoltaic Geographic Information System, 2008) for several installation conditions in the world. The average annual performance ratio—the ratio between average AC system efficiency and standard DC module efficiency—ranges from 0.7 to 0.8 (Clavadetscher and Nordmann, 2007) and gradually increases further to about 0.9 for specific technologies and applications. Grid-connected PV systems are classified into two types of applications: distributed and centralized.

Grid-connected distributed PV systems are installed to provide power to a grid-connected customer or directly to the electricity network. Such systems may be: 1) on or integrated into the customer's premises, often on the demand side of the electricity meter; 2) on public and commercial buildings; or 3) simply in the built environment such as on motorway sound barriers. Typical sizes are 1 to 4 kW for residential systems, and 10 kW to several MW for rooftops on public and industrial buildings.

These systems have a number of advantages: distribution losses in the electricity network are reduced because the system is installed at the point of use; extra land is not required for the PV system and costs for mounting the systems can be reduced if the system is mounted on an existing structure; and the PV array itself can be used as a cladding or roofing material, as in "building-integrated PV" (BIPV) (Eiffert, 2002; Ecofys Netherlands BV, 2007; Elzinga, 2008).

An often-cited disadvantage is the greater sensitivity to grid-interconnection issues, such as overvoltage and unintended islanding (Kobayashi and Takasaki, 2006; Cobben *et al*., 2008; Ropp *et al*., 2008). However, this is no longer the case as, according to the standards by IEEE and Underwriter Laboratories (IEEE 1547 (2008), UL 1741), all inverters must have the function of the anti-islanding effect.

Grid-connected centralized PV systems perform the functions of centralized power stations. The power supplied by such a system is not associated with a particular electricity customer, and the system is not located to specifically perform functions on the electricity network other than the supply of bulk power. Typically, centralized systems are mounted on the ground, and they are larger than 1 MW.

The economical advantage of these systems is the optimization of installation and operating cost by bulk buying and the cost effectiveness of the PV components and balance of systems in large scale. In addition, the reliability of centralized PV systems is greater than distributed PV systems because they can have maintenance systems with monitoring equipment, which is a more reasonable portion of the total system cost.

Multi-functional PV and solar thermal components involving PV or solar thermal that have already been introduced into the built environment include the following: shading systems made from PV and/or solar thermal collectors; hybrid PV/thermal (PV/T) systems that generate electricity and heat from the same "panel/collector" area; façade collectors; PV roofs; thermal energy roof systems; and solar thermal roof-ridge collectors. Currently, fundamental and applied R&D activities are also under way related to developing other products, such as transparent solar thermal window collectors, as well as facade elements that consist of vacuum-insulation panels, PV panels, heat pump, and a heat-recovery system connected to localized ventilation.

3.3.4 Concentrating Solar Power Solar Electricity Generation

This subsection discusses concentrating solar power (CSP) solar electricity generation technologies and applications.

CSP technologies produce electricity by concentrating the sun to heat a liquid, solid, or gas that is then used in a downstream process for electricity generation. The majority of the world's electricity today—whether generated by coal, gas, nuclear, oil, or biomass—comes from creating a hot fluid. CSP simply provides an alternative heat source. Therefore, an attraction of this technology is that it builds on much of the current know-how on power generation in the world today. And it will benefit not only from ongoing advances in solar concentrator technology, but also, as improvements continue to be made in steam and gas turbine cycles.

Some of the key advantages of CSP include the following: 1) Can be installed in a range of capacities to suit varying applications and conditions, including tens of kW (dish/Stirling systems) through multiple MWs (tower Brayton systems) to large centralized plants (tower and trough systems); 2) Can integrate thermal storage for operational purposes (less than 1 hour), through medium-size storage for peaking and intermediate loads (3 to 6 hours), and ultimately, for full dispatchability through thermochemical systems; 3) Modular and scalable components; and 4) Does not require exotic materials.

Below, we discuss the various types of CSP systems and thermal storage for these systems.

Large-scale CSP plants most commonly concentrate sunlight by reflection, as opposed to refraction with lenses. Concentration is either to a line (linear focus) as in trough or linear Fresnel systems or to a point (point focus) as in central-receiver or dish systems. The major features of each type of CSP system are described below.

In *trough concentrators*, long rows of parabolic reflectors concentrate the sun on the order of 70 to 100 times onto a heat-collection element (HCE) that is mounted along the reflector's focal line. The troughs track the sun around one axis, with the axis typically oriented north-south. The HCE comprises a steel inner pipe (coated with a solar-selective surface) and a glass outer tube, with an evacuated space in between. Heat-transfer oil is circulated through the steel pipe and heated to about 390°C. The hot oil from numerous rows of troughs is passed through a heat exchanger to generate steam for a conventional steam turbine generator. Land requirements are of the order of 2 km^2 for a 100-MW_e plant, assuming a solar multiple of one (for explanation of solar multiple, see IEA, 2010a). Alternative heat-transfer fluids to the synthetic oil commonly used in trough receivers, such as steam and molten salt, are being developed to enable higher temperatures and overall efficiencies, as well as integrated thermal storage in the case of molten salt.

Linear Fresnel reflectors use long lines of flat or nearly flat mirrors, which allow the moving parts to be mounted closer to the ground, thus reducing structural costs. (In contrast, large trough reflectors presently use thermal bending to achieve the curve required in the glass surface.) The receiver is a fixed inverted cavity that can have a simpler construction than evacuated tubes and be more flexible in sizing. The attraction of linear Fresnel reflectors is that the installed costs on a m^2 basis can be lower than trough systems. However, the annual optical performance is less than a trough.

Central receivers (or power towers), which are one type of point-focus collector, are able to generate much higher temperatures than troughs and linear Fresnel reflectors, although requiring two-axis tracking. This higher temperature is a benefit because thermodynamic cycles used for generating electricity are more efficient. This technology uses an array of mirrors (heliostats), with each mirror tracking the sun and reflecting the light onto a fixed receiver atop a tower. Temperatures of more than 1000°C can be reached. Central receivers can easily generate the maximum temperatures of advanced steam turbines, can use high-temperature molten salt as the heat-transfer fluid, and can be used to power gas turbine (Brayton) cycles.

Dish systems include an ideal optical reflector and therefore are suitable for applications requiring the highest temperatures. Dish reflectors are a paraboloid and concentrate the sun onto a receiver mounted at the focal point, with the receiver moving with the dish. Dishes have been used to power Stirling engines at 900°C, and also for steam generation. There is now significant operational experience with dish/Stirling engine systems, and commercial rollout is planned. To date, the capacity of each Stirling engine is small—on the order of 10 to 25 kW_e. The largest solar dishes have a 400-m^2 aperture and are in research facilities, with the Australian National University presently testing a solar dish with a 485-m^2 aperture.

Another type of solar thermal electricity technology is the *solar chimney*. It is not strictly a form of CSP, because there is no concentration involved. Instead, a large glazed area acts like a greenhouse, heating the air underneath, and drawing the air to the centre and up a stack. The high stack creates buoyancy, otherwise known as the stack effect. The fast-moving air is drawn across a wind turbine at the bottom of the stack, producing electricity. A small prototype was tested in Spain in the 1980s.

Thermal energy storage integrated into a system is an important attribute of CSP. Until recently, this has been primarily for operational purposes, providing 30 minutes to 1 hour of full-load storage. This eases the impact of thermal transients such as clouds on the plant, assists start-up and shut-down, and provides benefits to the grid. Trough plants are now being designed for 6 to 7.5 hours of full-load storage, which is enough to allow operation well into the evening when peak demand can occur and tariffs are high. Trough plants in Spain are now operating with molten-salt storage. Towers, with their higher temperatures, can charge and store molten salt more efficiently. Gemasolar (formerly known as Solar Tres), a 17-MW_e solar tower being developed in Spain, is designed for 15 hours of storage, giving a 67% annual capacity factor.

In thermal storage, the heat from the solar field is stored prior to reaching the turbine. Storage takes the form of sensible or latent (Gil *et al.*, 2010; Medrano *et al.*, 2010). Thermal storage for CSP systems needs to be at a temperature higher than that needed for the working fluid of the turbine. As such, systems are generally between 400° and 600°C, with the lower end for troughs and the higher end for towers. Allowable temperatures are also dictated by the limits of the media available. Examples of storage media include molten salt (presently comprising separate hot and cold tanks), steam accumulators (for short-term storage only), solid ceramic particles, high-temperature phase-change materials, graphite, and high-temperature concrete. The heat can then be drawn from the storage to generate steam for a turbine, as and when needed. Compressed air energy storage (CAES) in underground caverns is another form of storage available for CSP. Another type of storage associated with high-temperature CSP is thermochemical storage, where solar energy is stored as a fuel. This is discussed more fully in 3.3.5 and 3.7.5.

Thermal storage is a means of providing dispatchability. Hybridisation with conventional fuels is another way in which CSP can be designed to be dispatchable. Although the back-up fuel itself may not be renewable (unless it is biomass-derived), it provides significant operational benefits for the turbine and improves solar yield.

Concentrating solar power applications range from small distributed systems of tens of kW all the way to large centralized power stations of hundreds of MW.

Distributed generation in CSP can be illustrated by the dish/Stirling technology, which has been under development for many years, with advances in dish structures, high-temperature receivers, use of hydrogen as the circulating working fluid, as well as some experiments with liquid metals and improvements in Stirling engines—all bringing the technology closer to commercial deployment. Although the individual unit size can be on the order of 10 kW_e, power stations having a large capacity up to 800 MW_e have been proposed by aggregating many modules (Figure 3.10a). Because each dish represents a stand-alone electricity generator, from the perspective of distributed generation there is great flexibility in the capacity and rate at which units are installed.


(a) (b)

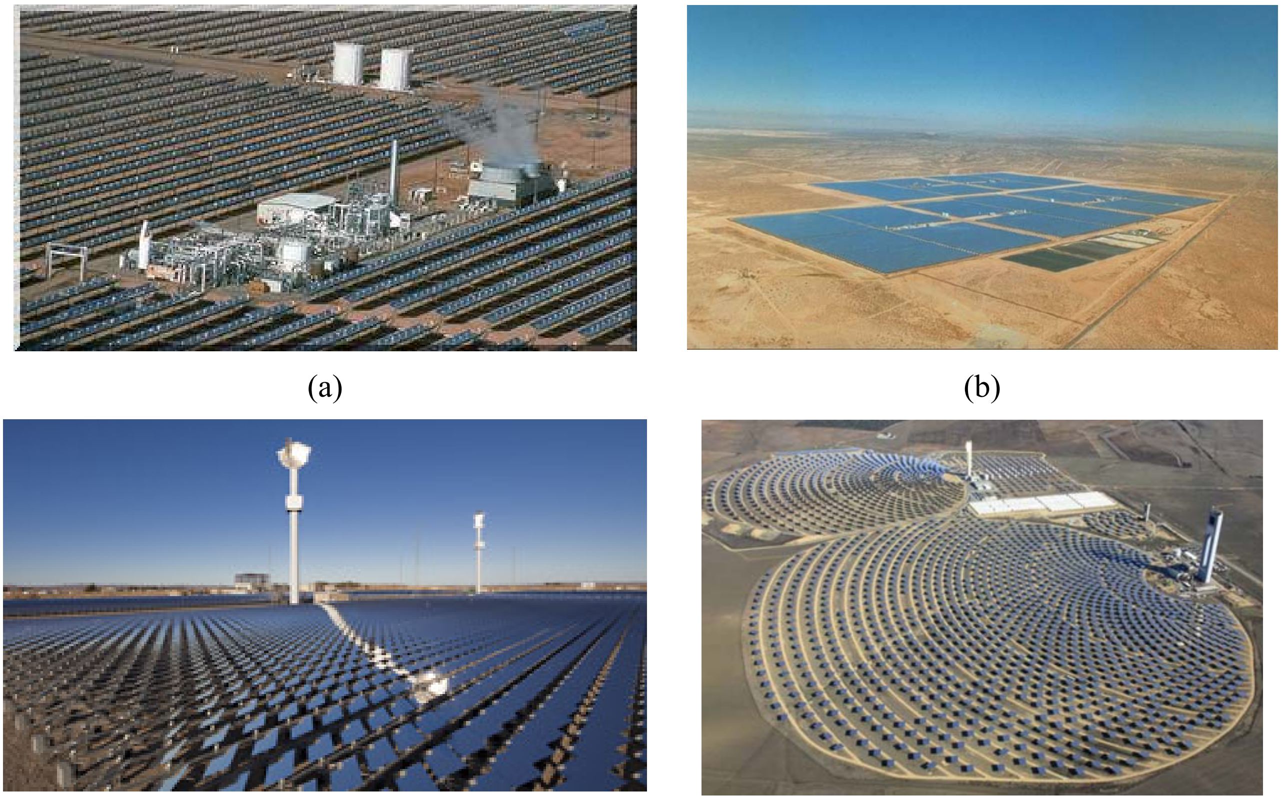
Figure 3.10: (a) Rendering of aggregated dish/Stirling units, and (b) a solar tower for powering a Brayton cycle microturbine (courtesy CSIRO).

An alternative to the Stirling engine is the microturbine based on the Brayton cycle (Figure 3.10b). The attraction of these engines for CSP is that they are already in significant production, being used for distributed generation fired on landfill gas or natural gas. In the solarized version, the air is instead heated by concentrated solar radiation from a tower or dish reflector. It is also possible to integrate with the biogas or natural gas combustor to back up the solar. Several developments are currently under way based on solar tower and microturbine combinations.

Centralized CSP benefits from the economies of scale offered by large-scale plants. Based on conventional steam and gas turbine cycles, much of the technological know-how of large power-station design and practice is already in place. However, although larger capacity has significant cost benefits, it has also tended to be an inhibitor until recently because of the much larger commitments required by investors. In addition, larger power stations require strong infrastructural support, and new or augmented transmission may be needed.

The earliest commercial CSP plants were the Solar Electric Generating Stations (SEGS) in California, where 354 MW of solar electric power was deployed between 1985 and 1991. The SEGS plants have operated reliably in a commercial environment and continue to do so today. As a result of the positive experiences and lessons learned from these early plants, the trough systems tend to be the technology most often applied today as the CSP industry grows. In Spain, regulations to date have mandated that the largest-capacity unit that can be installed is 50 MW_e, which is to help stimulate industry competition. In the United States, this limitation does not exist, and proposals are in place for much larger plants—280 MW_e in the case of troughs and 100- and 200-MW_e plants based on towers. Abengoa Solar has recently commissioned commercially operational towers of 10 and 20 MW_e, and all tower developers plan to increase capacity in line with technology development, regulations, and investment capital. Figure 3.11 provides photos of various large-scale CSP plants.

CSP or PV electricity can also be used to power reverse-osmosis plants for desalination. Dedicated CSP desalination cycles based on pressure and temperature are also being developed for desalination (see 3.3.2).



(a) (b)

(c) (d)

Figure 3.11: Large-scale CSP plants: (a) one of the original SEGS plants in California built by LUZ, operating for 20 years, showing the trough collectors and steam turbine plant; (b) aerial view of the five SEGS III-VII plants at Kramer Junction, California; (c) photo of eSolar's 5-MW$_e$ demonstration plant in California; (d) aerial view of Abengoa Solar's PS10 and PS20 solar towers in operation near Seville, Spain. [TSU: sources missing, (c) blurry]

3.3.5 Solar Fuel Production

This subsection discusses solar fuel production technologies and applications.

Solar fuel technologies convert solar energy into chemical fuels, which is an attractive method of storing and transporting solar energy. Solar fuel processes can be used for upgrading fossil fuels, combusted to generate heat, used in high-efficiency gas-turbine cycles or internal combustion engines, or used directly to generate electricity in fuel cells to meet energy demands whenever and wherever required by the customers. The challenge is to produce large amounts of chemical fuels directly from sunlight in cost-effective ways and to minimize adverse effects on the environment (Steinfeld and Meier, 2004).

There are four basic routes, alone or in combination, for producing storable and transportable fuels from solar energy. The *electrochemical* route uses solar electricity made from PV or CSP systems followed by an electrolytic process; the *photochemical / photobiological* route makes direct use of solar photon energy for photochemical and photobiological processes; the *thermochemical* route uses solar heat at high temperatures followed by an endothermic thermochemical process; and the *solar fuel synthesis from solar hydrogen and* CO_2 combines the electrochemical route with the thermochemical route using CO_2 synthesis (Steinfeld and Meier, 2004; Sterner, 2009).

The thermochemical route offers attractive opportunities for CSP with broad economic implications. Figure 3.12 illustrates possible pathways to produce hydrogen (H_2) or synthesis gas (syngas) from water and/or fossil fuels using concentrated solar energy as the source of high-temperature process heat (Steinfeld and Meier, 2004), (Steinfeld, 2005). Feedstocks include *inorganic* compounds such as water (H_2O) and carbon dioxide (CO_2), and *organic* sources such as coal, biomass, and natural gas (NG). The forms of solar fuels are H_2 gas, syngas (with H_2 and CO as main constituents), and their derivatives such as methanol, dimethyl ether (DME), and synthesis oil. Refer also to Chapter 2 for parallels with biomass-derived syngas.

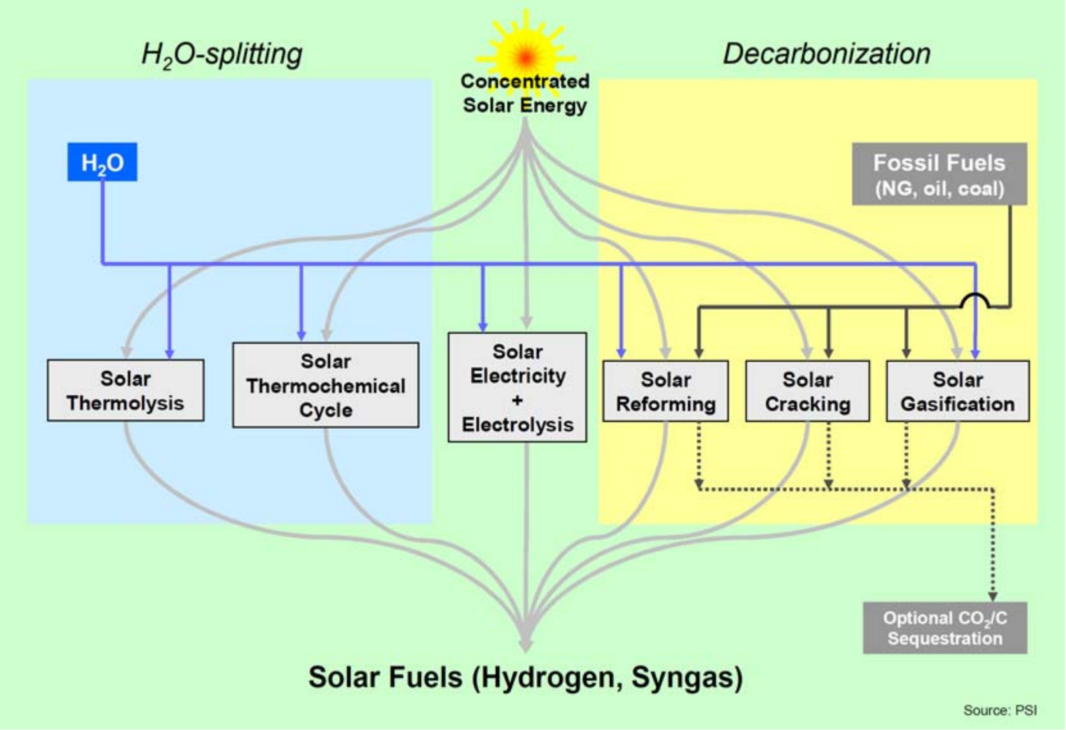


Figure 3.12: Thermochemical routes for solar fuels production, indicating the chemical source of H_2: H_2O for solar thermolysis and solar thermochemical cycles; fossil or biomass fuels for solar cracking, and a combination of fossil/biomass fuels and H_2O for solar reforming and gasification. For solar decarbonization processes, optional CO_2/C sequestration is considered. (from Steinfeld and Meier, 2004; Steinfeld, 2005) [TSU: source not clear]

Electrolysis of water can use solar electricity generated by PV or CSP technology in a conventional (alkaline) electrolyzer, considered a benchmark for producing solar hydrogen. With current technologies, the overall solar-to-hydrogen energy conversion efficiency ranges between 10% and 14%, assuming electrolyzers working at 70% efficiency and solar electricity being produced at 15% (PV) and 20% (CSP) annual efficiency. The electricity demand for electrolysis can be significantly reduced if the electrolysis of water proceeds at higher temperatures (800°–1000°C) via solid-oxide electrolyzer cells (SOEC) (Jensen *et al.*, 2007). In this case, concentrated solar energy can be applied to provide both the high-temperature process heat and the electricity needed for the high-temperature electrolysis.

Decarbonization of fossil fuels is a near- to mid-term transition process to solar hydrogen that encompasses the carbothermal reduction of metal oxides (Epstein *et al.*, 2008), and the decarbonization of fossil fuels via solar cracking (Spath and Amos, 2003; Rodat *et al.*, 2009), reforming (Moller *et al.*, 2006), and gasification (Z'Graggen and Steinfeld, 2008; Piatkowski *et al.*, 2009). These routes are being considered by European, Australian, and USA academic and industrial research organizations (Figure 3.13). Solar hybrid fuel—such as methanol, DME, and synthetic oil from syngas—can be produced by supplying concentrated solar thermal energy to the endothermic processes of methane and biomass reforming.

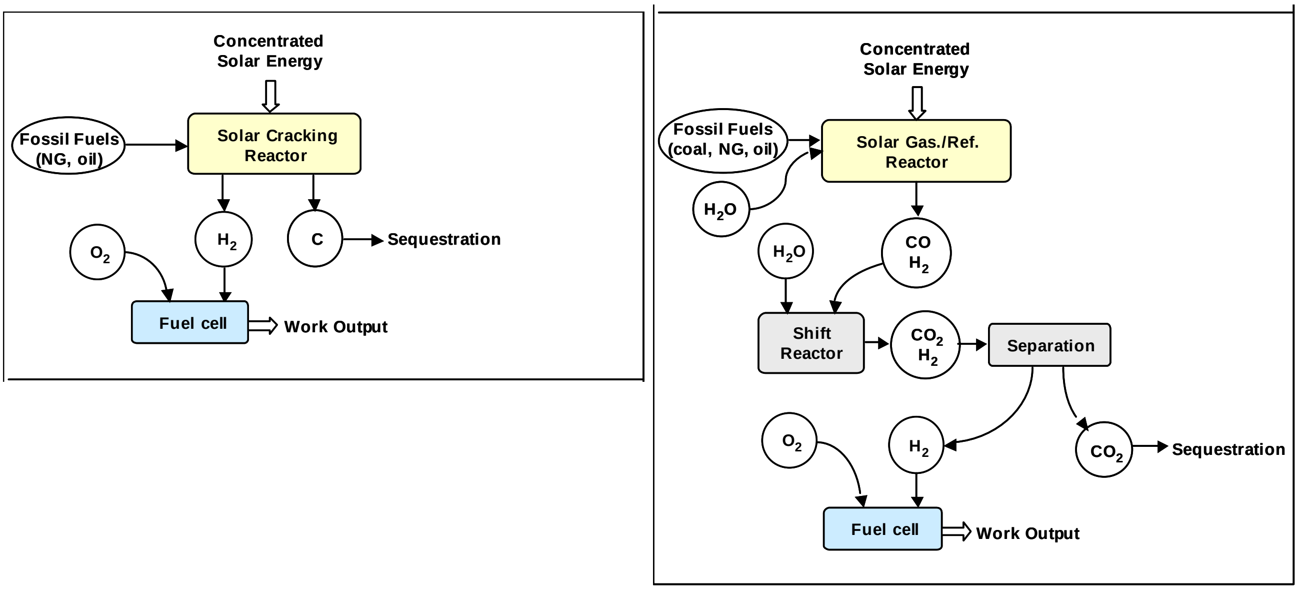


Figure 3.13: Schematic of solar thermochemical routes for H_2 production using fossil fuels and H_2O as the chemical source: solar cracking (left), and solar reforming and gasification (right). From (Steinfeld and Meier, 2004).

Thermolysis and thermochemical cycles are a long-term sustainable and carbon-neutral approach for hydrogen production from water. This route involves energy-consuming (endothermic) reactions that make use of concentrated solar radiation as the energy source of high-temperature process heat (Abanades *et al.*, 2006). Solar thermolysis requires temperature levels above 2200°C and raises difficult challenges for reactor materials and gas separation. Water-splitting thermochemical cycles allow operation at lower temperature, but require several chemical reaction steps and also raise challenges because of inefficiencies associated with heat transfer and product separation at each step. Leading candidates for multi-step thermochemical cycles are the three-step sulfur iodine cycle and the two-step sulfur hybrid cycle (with one electrolysis step), both based on the thermal decomposition of sulfuric acid at 850°C in a catalytic receiver reactor or at 1200°C without catalyser (Kolb *et al.*, 2007; Le Duigou *et al.*, 2007). Potentially more-efficient two-step thermochemical cycles use metal-oxide redox reactions (Figure 3.14)—e.g., based on zinc oxide (Zn/ZnO) (Steinfeld, 2002) and tin oxide (SnO/SnO_2) (Abanades *et al.*, 2008). The thermal decomposition of ZnO and SnO_2 proceeds at high temperatures above 1500°C with estimated exergy (available energy) efficiencies of 29% and 30%, respectively. Other metal oxides, such as manganese oxide or cobalt oxide, as well as mixed oxides redox pairs—mainly based on iron—have also been considered (Lemort *et al.*, 2006; Diver *et al.*, 2008).

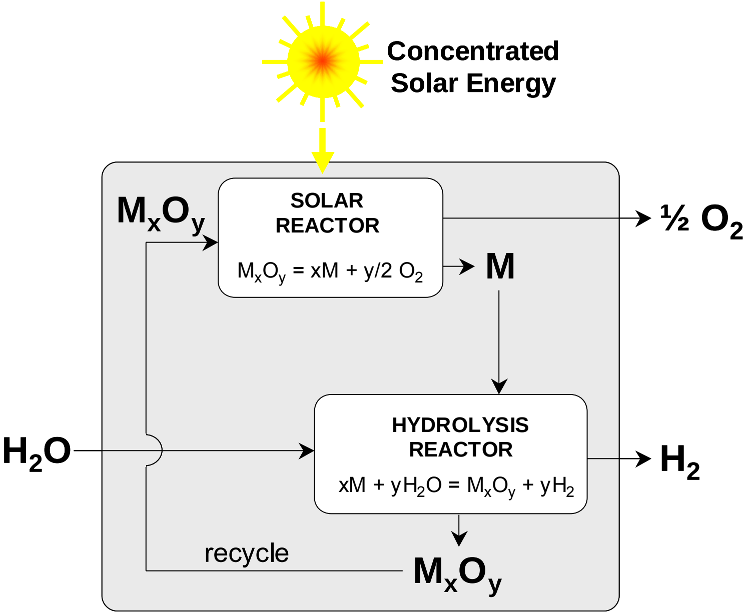


Figure 3.14: Representation of a two-step water-splitting thermochemical cycle using metal-oxide redox reactions. M denotes a metal and M_xO_y denotes the corresponding metal oxide. From (Steinfeld and Meier, 2004).

Solar fuel synthesis from solar hydrogen and CO_2 produces hydrocarbons that are compatible with existing energy infrastructures such as the natural gas network or conventional fuel supply structures. The renewable methane process combines solar hydrogen with CO_2 from the atmosphere or other sources in a synthesis reactor with a nickel catalyst at 6–8 bars and 300°–500°C. In this way, a substitute for natural gas is produced that can be stored, transported, and used in gas power plants, heating systems, and gas vehicles. The solar power-to-gas conversion has an efficiency of 60% without using surplus heat and is thus slightly less efficient than pure solar hydrogen. This drawback is compensated by the benefit of additional flexibility in using the existing energy infrastructure of natural gas (Sterner, 2009).

Solar methane can be produced anywhere where water, air, and renewable power are available. Possible CO_2 sources are biomass, industry processes, or the atmosphere. CO_2 is regarded as the carrier for hydrogen in the energy system. By separating CO_2 from the combustion process of solar methane, CO_2 can be recycled in the energy system or stored permanently. Thus, carbon sink energy systems powered by renewable energy can be created (Sterner, 2009). First pilot plants at the kW scale with atmospheric CO_2 absorption have been set up in Germany, proving the technical feasibility. Scaling up to the utility MW scale is planned in the next few years (Specht *et al.*, 2010).

In an alternative conversion step, liquid conventional fuels such as Fischer-Tropsch diesel, dimethylether (DME), methanol, or solar kerosene (jet fuel) can be produced from solar energy and CO_2 for long-distance transportation (Figure 3.15). The main advantages of these solar fuels are no limitation of vehicle range like solar electromobility, less competition on land use, and higher hectare yields compared to biofuels. Solar energy can be harvested via natural photosynthesis in biofuels with an efficiency of 0.5%, and via photovoltaic power and solar fuel conversion (technical photosynthesis) with an efficiency of 10%. Using wind power even allows combined energy and agro farming because the land below the wind turbine can be used for agriculture (Sterner, 2009).

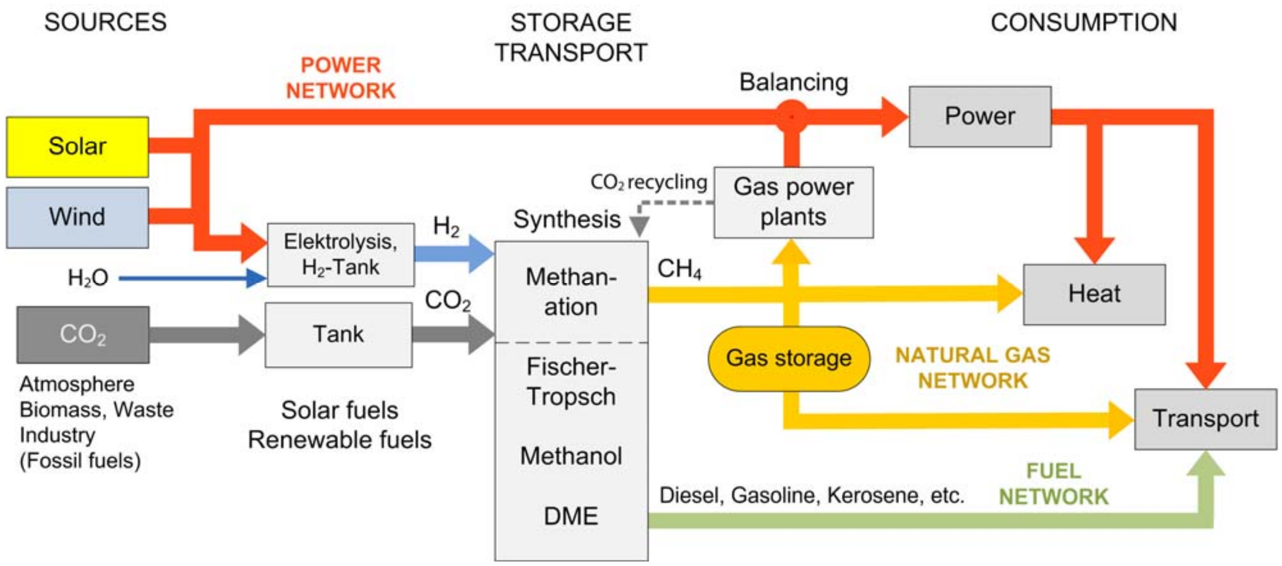


Figure 3.15: Solar fuel conversion pathways for synthesis of renewable H2 and CO2. Basically any hydrocarbon can be produced from solar energy, air, and water via synthesis of CO2, which is extracted from the atmosphere by adsorption or from biomass, industry processes, or CO2 recycling from gas power plants. Adapted from Sterner (2009).

Solar fuel applications, to some extent, are a natural progression from the high concentration solar technology used for electricity generation. The processes required to produce solar fuels are generally above 600°C with some of the processes well above 1,000°C. Thus, central-receiver towers and parabolic dishes are the preferred concentrator technologies for solar fuels. The lessons and experience gained as these technologies increase their operating temperature for CSP steam-generation systems will be beneficial for moving beyond steam to solar fuels.

Solar fuels are valuable because they convert solar energy into a form that is more transportable and storable than electricity. In addition, solar fuels can be used in a much wider variety of higher-efficiency applications than just Rankine cycles, and they can be used to power gas-turbine combined cycles or fuel cells for electricity generation with 50% higher efficiency than Rankine cycles, as well as used as transportation fuels or in chemical and industrial processes.

Some countries such as in the Middle East and Australia—where there are vast solar and natural gas resources, but a relatively small domestic energy market—are in a position to produce and export solar energy in the form of liquid fuels.

Hydrogen has been mooted as a future transportation fuel due to its versatility, pollutant-free end use, and storage capability. The key is a sustainable, CO_2-free source of hydrogen such as solar, cost-effective storage and appropriate distribution infrastructure. The production of solar hydrogen by itself does not produce a hydrogen economy, as many factors are needed in the chain. The suggested path to solar hydrogen is to begin with solar enhancement of existing steam reforming processes, with a second generation involving solar electricity and advanced electrolysis, and a third generation using thermolysis or advanced thermochemical cycles, with many researchers aiming for the production of fuels from concentrated solar energy and carbon dioxide.

Steam reforming of natural gas for hydrogen production is a conventional industrial-scale process producing most of the world's hydrogen today, with the heat for the process derived from burning a significant proportion of the fossil fuel feedstock. Using concentrated solar power, instead, as the source of the heat embodies solar energy in the fuel. The solar steam-reforming of natural gas and other hydrocarbons, and the solar steam-gasification of coal and other carbonaceous materials yield a high-quality syngas, which is the building block for a wide variety of synthetic fuels including Fischer-Tropsch-type chemicals, hydrogen, ammonia, and methanol. If hydrogen is the desired end-product, then the CO content in the syngas can be shifted to H2 via the catalytic water-gas shift reaction (CO + H2O = H2 + CO2), and the product CO2 can be separated from H2. Whereas hydrogen requires significant infrastructural changes, liquid solar hybrid fuels such as methanol, DME, and synthetic oil, with their embodied solar energy, can be used in conventional processes today. Synthetic oil can be used directly for automobiles and power stations. Methanol and DME can be used for fuel cells after reforming. DME can also be used in place of liquefied petroleum gas. The syngas feedstock needed to produce the liquid fuel requires a certain CO/H2 ratio. The solar steam-reforming process described above can be modified to use CO2 as the reforming agent, which allows control of the CO/H2 ratio. This also saves water and makes use of a waste product. Catalysts for CO2 reforming—also known as dry reforming—are still under development.

The solar cracking route refers to the thermal decomposition of natural gas (NG) and other hydrocarbons. Besides H2 and carbon (C), other compounds may also be formed, depending on the reaction kinetics and on the presence of impurities in the raw materials. The thermal decomposition yields a carbon-rich condensed phase and a hydrogen-rich gas phase. The carbonaceous solid product can either be sequestered without CO2 release or used as material commodity (carbon black) under less severe CO2 restraints. It can also be applied as reducing agent in metallurgical processes. The hydrogen-rich gas mixture can be further processed to high-purity hydrogen that is not contaminated with oxides of carbon and, thus, can be used in proton-exchange-membrane fuel cells without inhibiting platinum electrodes. From the point of view of carbon sequestration, it is easier to separate, handle, transport, and store solid carbon than gaseous CO2. Further, the thermal cracking accomplishes the removal and separation of carbon in a single step. The major drawback of the thermal cracking method is the energy loss associated with the sequestration of carbon. Thus, the solar cracking may be the preferred option for NG and other hydrocarbons with high H2/C ratio.

3.4 Global and Regional Status of Market and Industry Development

This section looks at the five key solar technologies, first focusing on installed capacity and generated energy, then on industry capacity and supply chain, and finally, on the impact of policies specific to these technologies.

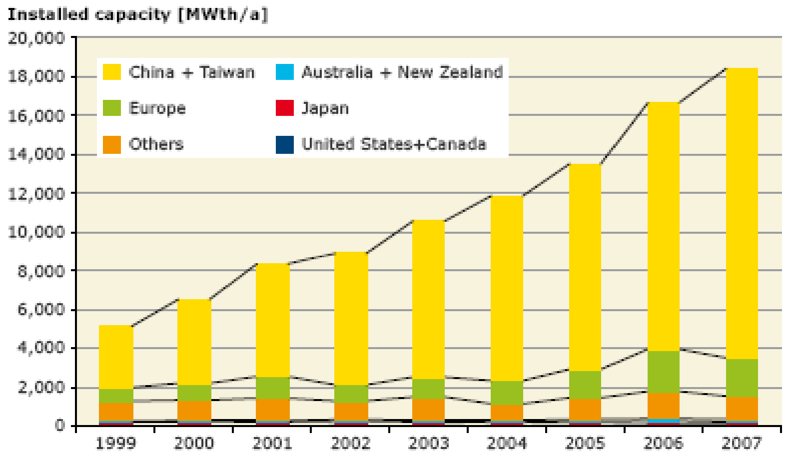
3.4.1 Installed Capacity and Generated Energy

This subsection discusses the installed capacity and generated energy within the five technology areas of passive solar, active solar heating and cooling, PV electricity generation, CSP electricity generation, and solar fuel production.

For **passive solar technologies**, no estimates are available at this time for the installed capacity of passive solar or the energy generated through this technology.

For **active solar heating**, the world global market totaled an estimated 19.9 GW_{th} in 2007 (Figure 3.16) and about 19 GW_{th} in 2008 (REN21, 2009). In 2008, flat-plate and evacuated-tube collectors accounted for 18.4 GW_{th}, which is 92.5% of the overall market. The main markets for unglazed collectors are in the USA (0.8 GW_{th} in 2008) and Australia (0.4 GW_{th} in 2008). South Africa, Canada, Mexico, The Netherlands, Sweden, Switzerland, and Austria also have notable markets, but all with values below 0.1 GW_{th} of new installed unglazed collectors in 2007.

Comparison of markets in different countries is difficult, due to the wide range of designs used for different climates, and different demand requirements. In Scandinavia and Germany, a solar heating system will typically be a combined water-heating and space-heating system with a collector area of 10 to 20 m^2. In Japan, the number of solar domestic water-heating systems is large. However, most installations are simple integral preheating systems. The market in Israel is large due to a favourable climate, as well as regulations mandating installation of solar water heaters. The largest market is in China, where there is widespread adoption of advanced evacuated-tube solar collectors. In terms of per capita use, Cyprus is the leading country in the world, with one operating solar water heater for every 3.7 inhabitants.



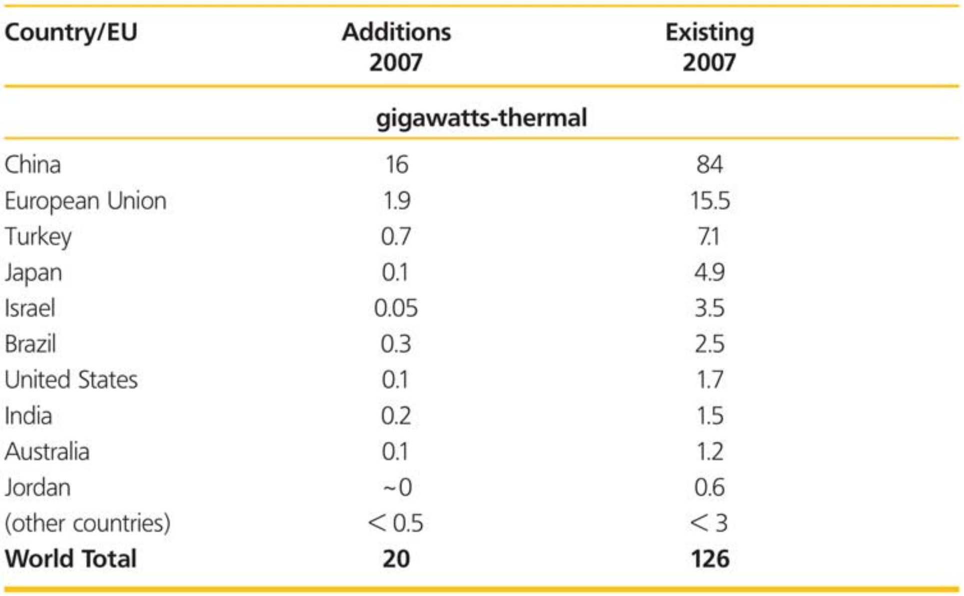
Europe: EU-27, Albania, Macedonia, Norway, Overseas Departments of France, Switzerland;
Others: Barbados, Brazil, India, Israel, Jordan, Mexico, Namibia, South Africa, Thailand, Tunisia and Turkey

Figure 3.16: Installed solar thermal collector capacity (Weiss *et al.*, 2009) [TSU: specify in caption annual added (not cumulative) capacity]

To make comparisons easier, the International Energy Agency's Solar Heating & Cooling Programme, together with European Solar Thermal Industry Federation (ESTIF) and other major solar thermal trade associations, decided to publish statistics in kW$_{th}$ (kilowatt thermal) and have agreed to use a factor of 0.7 kW$_{th}$/m^2 to convert square meters of collector area into kW$_{th}$.

In current trends, solar thermal energy is increasingly popular in a growing number of countries worldwide (Table 3.3), with the worldwide market having grown continuously since the beginning of the 1990s (European Solar Thermal Technology Platform [ESTTP], 2006). In absolute terms, China, by far, comprises most of the worldwide solar thermal market. Europe has only a small market share worldwide, despite the strong technological leadership of the European solar thermal industry and the great variety of available solar thermal technologies. North America and Oceania play an insignificant role. Among the “others,” solar thermal is mainly used in Turkey, Israel, and Brazil.

Table 3.3: Solar hot water installed capacity, top 10 countries and world total, 2007 (from (REN21, 2009). Note: Figures do not include swimming pool heating (unglazed collectors). Existing figures include allowances for retirements. By accepted convention, 1 million square meters =0.7 GW$_{th}$. China added an estimated 14 GW$_{th}$ in 2008, which, along with extrapolating 2007 additions for other countries, yields a 2008 estimate of 145 GW$_{th}$. [TSU: additional information, not table caption] Source: (Weiss *et al.*, 2009); also estimates by the China Renewable Energy Industries Association. [TSU: figure 3.16 and this table report varying figures for 2007 added capacity]



Country/EU	Additions 2007	Existing 2007
	gigawatts-thermal	
China	16	84
European Union	1.9	15.5
Turkey	0.7	7.1
Japan	0.1	4.9
Israel	0.05	3.5
Brazil	0.3	2.5
United States	0.1	1.7
India	0.2	1.5
Australia	0.1	1.2
Jordan	~0	0.6
(other countries)	< 0.5	< 3
World Total	**20**	**126**

In 2007, about 15.4 GW_{th} (22 million m^2) of capacity was sold in China. This portion was 77% of the world global solar thermal market, which totaled an estimated 19.9 GW_{th}. In China, the installation rate has been growing by almost 30% per year; at present, solar thermal systems constitute 12% of the national water-heater market in that country.

Solar hot-water systems have been installed and operated successfully at a number of hotels and public buildings in the southern regions of European Russia, East Siberia, and the Far East. The individual solar systems of hot-water supply are in great demand for country houses. Several Russian firms have begun production of solar collectors. The new concept of heat-and-power engineering could replace more than 50% of the organic fuel used during the warm season.

In Europe, the market size more than tripled between 2002 and 2008. However, even in the leading European solar thermal markets of Austria, Greece, and Germany, only a minor portion of residential homes use solar thermal. For example, in Germany, only about 5% of one- and two-family homes are using solar thermal energy.

The use of solar thermal energy clearly varies greatly in different countries (Figure 3.17). In China and Taiwan (80.8 GW_{th}), Europe (15.9 GW_{th}) and Japan (4.9 GW_{th}), plants with flat-plate and evacuated-tube collectors are mainly used to prepare hot water and to provide space heating. However, in North America (USA and Canada), swimming pool heating is still the dominant application, with an installed capacity of 19.8 GW_{th} of unglazed plastic collectors.

There is a growing market for unglazed solar air heating in Canada and the USA. These unglazed air collectors are used for commercial and industrial building ventilation, air heating, and agricultural applications.

Europe has the most sophisticated market for different solar thermal applications. It includes systems for hot-water preparation, plants for space heating of single- and multi-family houses and hotels, large-scale plants for district heating, as well as a growing number of systems for air conditioning, cooling, and industrial applications.

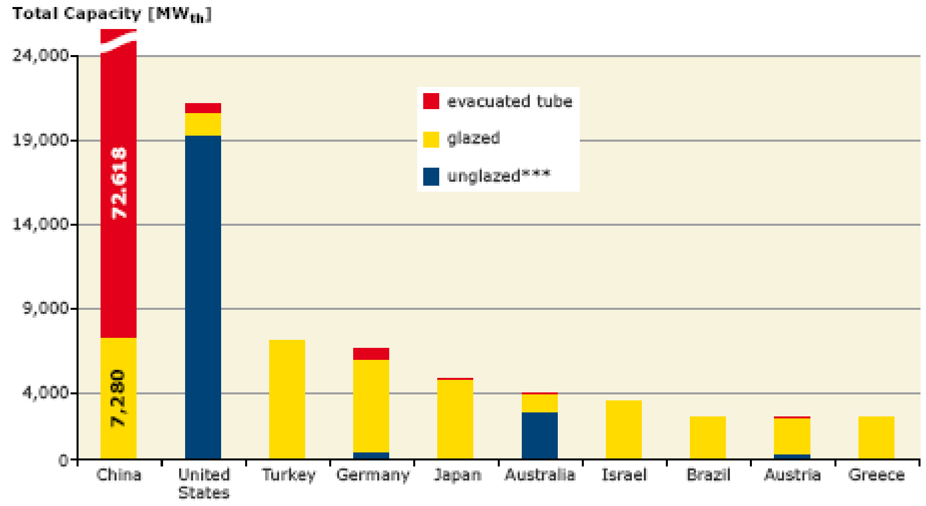


Figure 3.17: Total capacity in operation of water collectors of the 10 leading countries at the end of 2007 (Weiss *et al.*, 2009).

The solar thermal market in the EU and Switzerland showed strong performance in 2008, growing by 60% to 3.3 GW_{th} of new capacity (4.75 million m^2 of collector area). The biggest push clearly came from the German market, which more than doubled. However, demand for solar thermal technology also grew strongly in smaller markets. Although in comparison the Austrian growth rate of 24% seems almost modest, the newly installed capacity per capita reached 29 kW_{th} per 1 000—surpassed only by Cyprus' 61 kW_{th} per 1 000 capita. Despite Austria having rather average potential with respect to its climate, building stock, and prevailing heating systems, it is more than six times ahead of the EU average, and 10 to 40 times ahead of most other countries—including those with high potential such as Italy, Spain, and France.

With 2.1 million m^2 of newly installed capacity, the German domestic market increased its share of the European market (EU27 + Switzerland) to 44% in 2008. Spain, Italy, and France overtook Greece, which was in second position in 2007. Together, these six countries currently account for 84% of Europe's solar thermal market (for comparison, these countries account for only 54% of Europe's population and 61% of its gross domestic product).

These huge gaps between neighbouring countries are not due to dramatically different technological barriers or objective conditions. Rather, the gaps are mainly due to market dynamics and conditions related to the political framework. Even in Austria, with its comparatively large stock of solar thermal capacity, there is not the slightest indication of market saturation. If the current trend in the Austrian solar thermal market continues, Austria will reach the per capita level of Cyprus in less than a decade.

At present, other European countries such as Spain, France, Italy, and the UK are also systematically developing their solar thermal markets. However, both within Europe and at a global level, solar thermal market development has previously been characterized by huge gaps between a small number of front-runner countries and a large number of countries still in the starting blocks.

Another segment of the solar thermal market is solar pool heating using plastic unglazed absorbers. This market is dominated by the USA, where 2007 shipments of solar pool-heater collectors totaled 785 MW_{th}, with 57% of the installations in Hawaii and Florida (Energy Information Administration [DOE], 2008).

Advanced applications such as solar cooling and air conditioning (Henning, 2004; Henning, 2007), industrial applications (POSHIP Potential of Solar Heat for Industrial Processes, 2001), and desalination/water treatment are in the early stages of development, with only a few hundred first-generation systems in operation.

Estimates from the European Solar Thermal Technology Platform, solar thermal will cover 50% of the heating demand in Europe in the long term, when this technology will be used in almost every building—covering more than 50% of the heating and cooling demand in retrofitted buildings and 100% in new buildings. Solar thermal will also be used in district heating systems, and in commercial and industrial applications with many new and improved solar thermal technologies (European Solar Thermal Technology Platform [ESTTP], 2008).

ESTIF set the goal of 1 m² solar capacity per capita in operation by 2020 as a short-medium goal, which is equivalent to a capacity of 700 kW_{th} per 1000 capita. ESTIF's Solar Thermal Action Plan for Europe offers a systematic analysis of the barriers to growth of solar thermal with existing technologies, and guidelines on how to overcome them through industry actions and public policies. It can be expected that the upcoming EU Directive will reduce these gaps and allow for a more rapid exploitation of the short-medium-term solar thermal potential. The increased market volumes will provide the solar thermal industry the means for a substantial increase in R&D investments. This will extend the boundaries of the solar thermal potential, opening the way for implementing the European Solar Thermal Technology Platform's vision for 2030. Unfortunately, similar data for other parts of the world are unavailable.

For **photovoltaic electricity generation**, newly installed capacity in 2009 is estimated between 6.6 and 7.9 GW with shipments to first point in the market at 7.9 GW (Mints, 2010). This addition brought the cumulative installed PV capacity worldwide to about 22 GW—a capacity able to generate up to 26 TWh per year. More than 90% of this capacity is installed in three leading markets: the EU27 with 16 GW (73%); Japan with 2.6 GW (12%); and the USA with 1.7 GW (8%) (Jäger-Waldau, 2010). These markets are dominated by grid-connected PV systems, and growth within PV markets has been stimulated by various government programmes around the world. Examples of such programmes include feed-in tariffs in Germany and Spain, and buy-down incentives coupled with investment tax credits in the United States.

Figure 3.18 illustrates the cumulative installed capacity for the top eight PV markets through 2009, including Germany (9800 MW), Spain (3500 MW), Japan (2630), USA (1650 MW), Italy (1140 MW), Korea (460 MW), France (370 MW), and PR China (300 MW). Spain and Germany have seen, by far, the largest amounts of solar installed in recent years, with Spain seeing a huge surge in 2008 and Germany having experienced steady growth over the last five years.

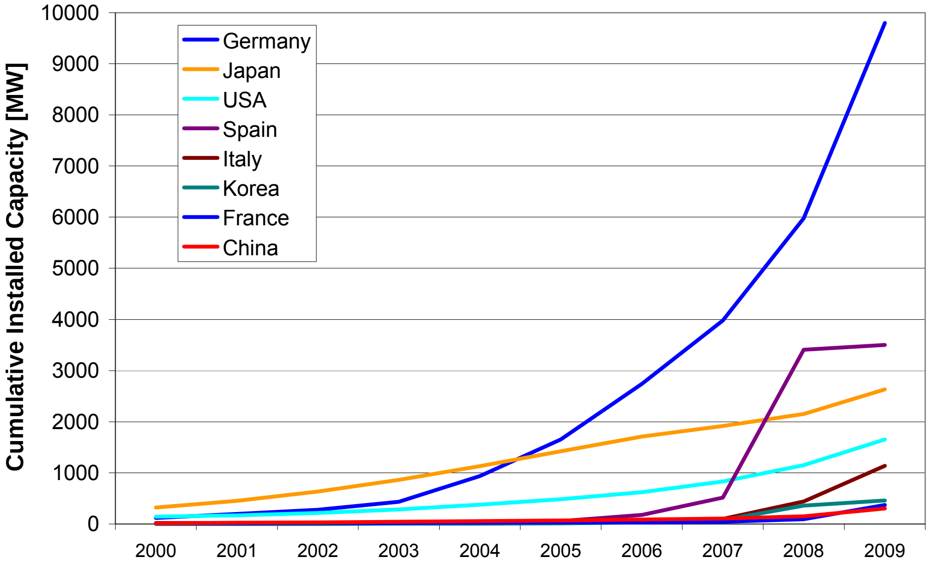


Figure 3.18: Installed PV capacity in eight markets (data source: (EurObserv'ER, 2009; IEA, 2009c; REN21, 2009; Jäger-Waldau, 2010))

Concentrating photovoltaics (CPV) is an emerging market with about 17 MW cumulative installed capacity at the end of 2008. The two main tracks are high-concentration > 300-suns (HCPV) and low- to medium-concentration with a concentration factor of 2 to about 300. To maximize the benefits of CPV, the technology requires high direct-beam irradiance, and these areas have a limited geographical range—the "Sun Belt" of the Earth. The market share of CPV is still small, but an increasing number of companies are focusing on CPV. In 2008, about 10 MW of CPV were produced and market estimates for 2009 are in the 20 to 30 MW range; for 2010, about 100 MW are expected.

Photovoltaic market predictions at the end of 2009 for the short term until 2013 indicate a steady increase, with annual growth rates ranging between 30% and 50%. The main market drivers for the period up to 2020 are considered the following:

- The National Development and Reform Commission (NDRC) expects renewable energy to supply 15% of China’s total energy demand by 2020. Specifically for installed solar capacity, the NDRC’s 2007 energy plan set a target of 1,800 MW by 2020. Recently, however, these goals have been discussed as being too low, and the possibility of reaching 10,000 MW or more by 2020 seems more likely (Shen and Wong, 2009).
- The 2009 European Directive on the Promotion of Renewable Energy set a target of 20% RE in 20020 and the Strategic Energy Technology plan is calling for electricity from PV in Europe for up to 12% in 2020.
- The 2009 Indian Solar Plan (“India Solar Mission”) calls for a goal of 20 GW of solar power in 2022: 12 GW are to come specifically from ground-mounted PV and solar thermal power plants, 3 GW from rooftop PV systems, another 3 GW from off-grid PV arrays in villages, and 2 GW from other PV projects, such as on telecommunications towers.
- The U.S. Department of Energy (in its FY 2010 Congressional Budget Request) states its PV goals for the United States in terms of $/kWh, rather than $/W, because the Solar Energy Technologies Program is designed to affect the levelized cost of energy (LCOE).
    - PV goals: 10 to 18 cents/kWh by 2010 and 5 to 10 cents/kWh by 2015. In these cost ranges, the first number is the low end for the utility market and the second number is the high end for the residential market.

  Relating to U.S. cumulative installed capacity by 2030, the DOE-sponsored Solar Vision Study is exploring the following two scenarios:
    - 10% solar target: 180 GW PV (120 GW central, 60 GW distributed).
    - 20% solar target: 300 GW PV (200 GW central, 100 GW distributed).

Regarding **CSP electricity generation**, between 1985 and 1991, 354 MW_e of solar trough technology was deployed in southern California. These plants are still in commercial operation today and have demonstrated the potential for long-term viability of CSP. During this period, world energy prices dropped and remained relatively low through the 1990s. CSP technology based on Rankine cycles is generally most economically viable in larger-scale installations. However, with such worldwide market conditions, there were insufficient market signals or greenhouse gas incentives to continue to support such large installations at that time. Currently, though, the emerging demand for rapid and deep cuts in GHG emissions makes the large capacities offered by CSP an advantage, and one that is being realized through a large and renewed development surge of CSP plants since about 2006.

At the end of 2009, more than 700 MW_e of grid-connected CSP plants are installed worldwide, with another 1500 MW_e under construction (Torres *et al.*, 2010). The majority of installed plants use parabolic trough technology. Central-receiver technology comprises a growing share of plants under construction and those announced. The bulk of the operating capacity is installed in Spain and the southwestern United States.

In 2007, after more than 15 years, the first new major CSP plants came on line with Nevada Solar One (64 MW_e, USA) and PS10 (11 MW_e, Spain). In Spain, successive Royal Decree's have been in place since 2004 and have stimulated the CSP industry in that country. *Royal Decree 661/2007* has been a major driving force for CSP plant construction and expansion plans. As of November 2009, 2,340 MW_e of CSP projects have been preregistered for the tariff provisions of the Royal Decree. In the USA, more than 4,500 MW_e of CSP are currently under power purchase agreement contracts. The different contracts specify when the projects must start delivering electricity between 2010 and 2014 (Kautto and Jäger-Waldau, 2009). More than 10,000 MW_e of new CSP plants have been proposed in the USA. More than fifty CSP electricity projects are currently in the planning phase, mainly in North Africa, Spain, and the USA. In Australia, the federal government has called for 1,000 MW_e of new solar plants, covering both CSP and PV, under the Solar Flagships program.

Hybrid solar/fossil plants have received much greater attention in recent years, and several integrated solar combined-cycle (ISCC) projects are now under construction in the Mediterranean region and the USA. In Algeria, Abengoa Solar is building the first such project consisting of a 150-MW_e ISCC system with 30-MW_e solar capacity. A similar project is under construction in Morocco where Abengoa Solar has been selected to build the plant. In Italy, another example of an ISCC project is Archimede; however, the plant's 31,000-m^2 parabolic trough solar field will be the first to use molten salt as the heat-transfer fluid (SolarPACES, 2009a).

Figure 3.19 shows the current and planned developments to add more CSP capacity in the near future.

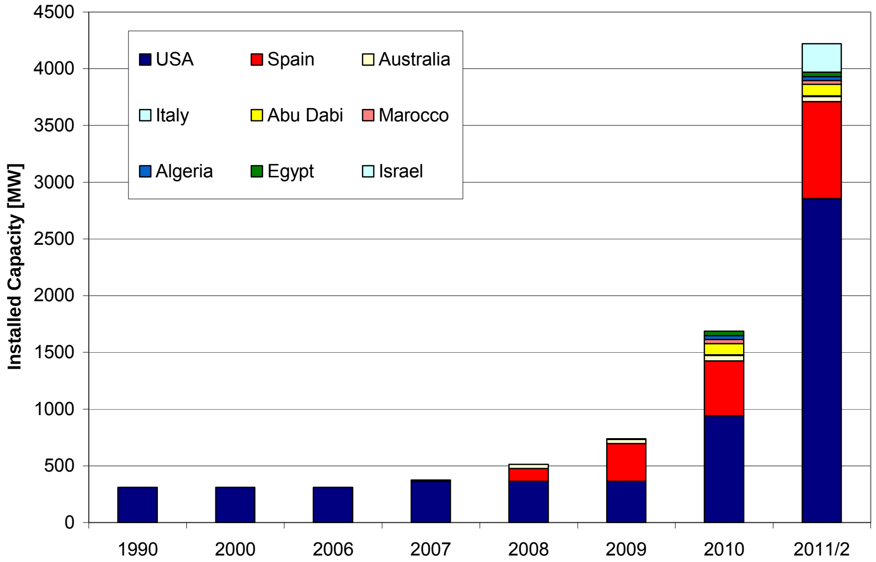


Figure 3.19: Installed and planned concentrated solar thermal electricity plants by country. (Kautto and Jäger-Waldau, 2009)

The average capital investment costs for a CSP plant vary substantially from plant to plant due to the level of integrated thermal storage. Plants with storage cost more due to the storage itself, as well as the additional collector area needed to charge the storage. However, storage also increases the annual capacity factor, so the LCOE can be lower. But even if storage caused the LCOE to increase marginally, this increase could be more than recovered by the ability to dispatch electricity at times of peak tariffs in the market. Thus, a strategic approach to storage can improve a project's internal rate of return.

The U.S. Department of Energy (in its FY 2010 Congressional Budget Request) states its CSP goals for the United States in terms of $/kWh, rather than $/W, because the Solar Energy Technologies Program is designed to affect the levelized cost of energy (LCOE) and includes significant storage.

- CSP goals: 10 to 12 cents/kWh by 2010, 7 to 9 cents/kWh (with 6 hours of thermal storage) by 2015, and 5 to 7 cents/kWh (with 12 to 17 hours of thermal storage) by 2020.

Relating to U.S. cumulative installed capacity by 2030, the DOE-sponsored Solar Vision Study is exploring the following two scenarios:

- 10% solar target: 75 GW CSP
- 20% solar target: 120 GW CSP.

Solar fuels production technologies are in an earlier stage of development than solar thermal electricity production using CSP. Typically, the high-temperature solar reactor technology is being developed at laboratory scale of 1–10 kW_{th} solar power input. Scaling up thermochemical processes for hydrogen production to the 100 kW_{th} power level is reported for a medium-temperature mixed iron oxide cycle (800°–1200°C) (Roeb *et al.*, 2006; Roeb *et al.*, 2009) and for the high-temperature ZnO dissociation reaction at above 1700°C (Schunk *et al.*, 2008; Schunk *et al.*, 2009). Pilot plants in the power range of 300–500 kW_{th} have been built for the carbothermic reduction of ZnO (Epstein *et al.*, 2008), the steam methane reforming of methane (Moller *et al.*, 2006), and the steam gasification of petcoke (Z'Graggen and Steinfeld, 2008). Solar-to-gas has been demonstrated in a 30-kW scale to drive a commercial natural gas vehicle, applying a nickel catalyst (Specht *et al.*, 2010). Demonstration at the MW scale should be warranted before erecting commercial solar chemical plants for fuels production, which are expected to be available only after 2020 (Pregger *et al.*, 2009).

Direct conversion of solar energy to fuel is not yet widely demonstrated or commercialized. But two options appear commercially feasible in the near to medium term: 1) the solar hybrid fuel production system (including solar methane reforming, and solar biomass reforming), and 2) PV- or CSP-solar electrolysis. These technologies are keys for reducing GHG emissions by solar fuel conversion. During the transition to a sustainable energy system, fossil fuels and concentrated solar energy are both used to produce solarized fuels. Thus, solar energy can begin to make an impact in non-electricity markets. As experience with high-temperature thermochemical technology is developed in the market place, the use of fossil fuels can be phased out and pure solar fuels can be introduced.

Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) is running a 250-kW_{th} reactor and plans to build a 4-$MW_{chemical}$ demonstration plant using solar steam-reforming technology, with an eventual move to CO_2 reforming for higher performance and less water usage. With such a system, liquid solar fuels can be produced in sunbelts such as Australia and solar energy shipped on a commercial basis to Asia and beyond.

Oxygen (O_2) gas produced by solar electrolysis (PV or CSP) can be used for coal gasification and partial oxidation of natural gas. With the combined process of the solar electrolysis and partial oxidation of coal or methane, about 10% to 15% of solar energy is incorporated theoretically into the methanol or DME. Also, the production cost of the solar hybrid fuel can be lowered compared to the solar hydrogen produced by the solar electrolysis process only.

At favourable solar sites with direct-normal irradiance (DNI) exceeding 2300 $kWh/m^2/year$, the equivalent of about 9.2 TWh (33.1 PJ) in the form of solar fuel can be produced by a system having 10% efficiency and equipped with a distributed collector area of 200 km × 200 km.

3.4.2 Industry Capacity and Supply Chain

This subsection discusses the industry capacity and supply chain within the five technology areas of passive solar, active solar heating and cooling, PV electricity generation, CSP electricity generation, and solar fuel production.

We first discuss industry capacity and supply chain issues of **passive solar technologies** within the areas of the overall building industry, windows, and thermal storage.

The ***building industry*** in most countries is fragmented and often characterized by a piecemeal approach to building design, construction, and operation. The integration of passive solar systems with the active heating/cooling air-conditioning systems both in the design and operation stages of the building is essential to achieve good comfort conditions while saving energy. However, this is usually overlooked because of the absence of any systematic collaboration for integrating building design between architects and engineers. Thus, the architect often designs the building envelope based solely on qualitative passive solar design principles, and the engineer often designs the heating-ventilation-air-conditioning (HVAC) system based on extreme design conditions without factoring in the benefits due to solar gains and natural cooling. The result may be an oversized system and inappropriate controls incompatible with the passive system and that can cause overheating and discomfort (Athienitis and Santamouris, 2002). Collaboration between the disciplines involved in building design is improving with the adoption of computer tools. But fundamental institutional barriers remain due to the basic training of architects and engineers, which does not foster an integrated design approach.

The design of high-mass buildings with significant near-equatorial-facing window areas is common in some areas of the world such as Southern Europe. However, a systematic approach to designing such buildings is still not widely employed. This is changing with the introduction of the passive house standard in Germany and other countries (PassivHaus Planning Package [PHPP], 2004; CEPHEUS, 2009)

Glazing and window technologies have progressed tremendously in the last twenty years (Hollands *et al.*, 2001). New-generation windows result in low energy losses, high daylight efficiency, solar shading, and noise reduction. However, selection of the proper glazing for a building is a trade-off between the cooling, heating, and lighting requirements. Different window materials or technologies improves lighting vs. heating or cooling. New technologies such as transparent photovoltaics and electrochromic windows provide many possibilities in the design of solar houses and offices with abundant daylight. Triple-glazed, low-emissivity, argon-filled windows with efficient framing were used in the EQuilibrium^{TM} demonstration houses, and they are expected to become more common in climates with cold winters. The change from regular double-glazed to double-glazed low-emissivity argon windows is presently occurring in Canada and is accelerated by the rapid drop in prices of these windows.

The primary materials for ***low-temperature thermal storage*** in passive solar systems are concrete, bricks, and water. A review of thermal storage materials is given by (Hadorn, 2008) under IEA SHC Task 32, focusing on a comparison of the different technologies. Phase-change material (PCM) thermal storage (Mehling and Cabeza, 2008) is particularly promising in the design, control, and load management of solar buildings because it reduces the need for structural reinforcement needed for heavier traditional sensible storage in concrete-type construction. Recent developments facilitating integration include microencapsulated PCM that can be mixed with plaster and applied to interior surfaces (Schossig *et al.*, 2004). PCM in microencapsulated polymers are now on the market and can be added to plaster, gypsum, or concrete to enhance the thermal capacity of a room. For renovation, they provide a good alternative to new heavy walls, which would require additional structural support (Hadorn, 2008).

In spite of the advances in PCM, concrete has certain advantages for thermal storage when a massive building design approach is used, as in many of the Mediterranean countries. In this approach, the concrete also serves as the structure of the building and is thus likely more cost effective than thermal storage without this added function. The EcoTerra house includes a hollow-core concrete floor slab in the basement that is actively charged with solar-heated air from its roof-integrated photovoltaic/thermal system; but the release of the heat is passive, so this is hybrid thermal storage. A combination of passive and active thermal storage may enable the use of more solar gain and facilitate reaching the net-zero energy goal in a more cost-effective manner.

The next technology we look at is **active solar heating and cooling**. Due to the different application modes—including domestic hot water, heating, preheating, and combined systems, as well as varying climatic conditions—a number of different collector technologies and system approaches have been developed, according to the European Solar Thermal Technology Platform, "Solar Heating and Cooling for a Sustainable Energy Future in Europe."

Flat-plate collectors comprise more than 80% of the worldwide installed systems. In 2007, a worldwide installed capacity of 19.9 GW_{th} corresponded to 28.4 million m^2 of solar collectors. Flat-plate and evacuated-tube collectors accounted for 18.4 GW_{th}, which is 92.5% of the overall market.

It is remarkable that the market of evacuated-tube collectors grew 23.4% compared to 2006, whereas the markets of flat-plate collectors and unglazed collectors decreased 18.3% and 7.2%, respectively. However, data of installed unglazed collectors are officially collected in only a few countries.

In some parts of the production process, such as selective coatings, large-scale industrial production levels have been attained. A number of different materials, including copper, aluminium, and stainless steel, are applied and combined with different welding technologies to achieve a highly efficient heat-exchange process in the collector. The materials used for the cover glass are structured or flat, low-iron glass. The first antireflection coatings are coming onto the market on an industrial scale, leading to efficiency improvements of about 5%.

In general, vacuum-tube collectors are more efficient, especially for higher-temperature applications. The production of vacuum-tube collectors is currently dominated by the Chinese Dewar tubes, where a metallic heat exchanger is integrated to connect them with the conventional hot-water systems. In addition, some standard vacuum-tube collectors, with metallic heat absorbers, are on the market.

The largest exporters of solar heaters are Australia, Greece, and the USA. The majority of exports from Greece are to Cyprus and the near-Mediterranean area. France also exports a substantial number of systems to its overseas territories. The majority of USA exports are to the Caribbean region. Australian companies export about 50% of production (mainly thermosyphon systems with external horizontal tanks) to most of the areas of the world that do not have hard-freeze conditions.

In this next section, we look at **PV electricity generation** and discuss the industry capacity and supply chain issues of photovoltaic technologies under the areas of overall solar cell production, thin-film module production, and polysilicon production.

The development characteristic of the photovoltaic sector is much different than the traditional power sector. It more closely resembles the semiconductor market, with annual growth rates between 40% to 50% and a high learning rate. Therefore, scientific and peer-reviewed papers can be several years behind the actual market developments due to the nature of statistical time delays and data consolidation. The only way to keep track of such a dynamic market is to use commercial market data. Global ***PV cell production*** reached more than 10 GW in 2009. The estimates of the global cell production[1] in 2009 vary between 10.5 and 12 GW, which is again an increase of 40% to 50% compared to 2008. Figure 3.20 shows the increase in production from 2000 through 2009, showing regional contributions (Jäger-Waldau, 2009). The compound annual growth rate in production from 2003 to 2009 was more than 50%.

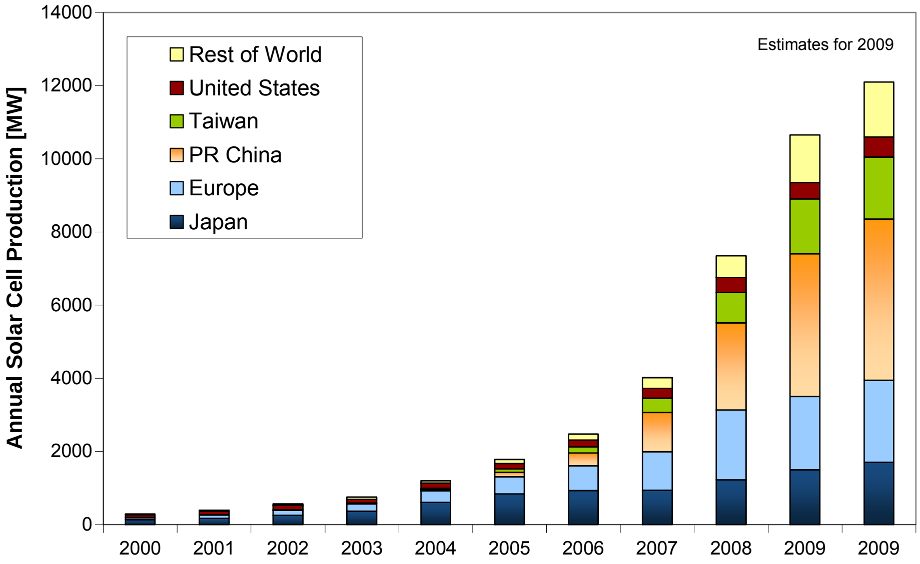


Figure 3.20: Worldwide PV production from 2000 to 2009 (Jäger-Waldau, 2010).

The announced increases of production capacities—based on a survey of more than 300 companies worldwide—increased despite very difficult economic conditions in 2009 (Figure 3.21) (Jäger-Waldau, 2010). Only published announcements of the respective companies and no third-party information were used. The cut-off date of the information included was April 2010. This method has the drawback that not all companies announce their capacity increases in advance and that in times of financial tightening, announcements of scale-backs in expansion plans are often delayed to prevent upsetting financial markets. Therefore, the capacity figures give a trend, but do not represent final numbers.

In 2008 and 2009, Chinese (PRC) and Taiwanese production capacity increased over-proportionally. In actual production, the PRC surpassed all other countries. China's production was estimated between 3.9 and 4.4 GW, Europe with 2.0–2.2 GW, followed by Japan and Taiwan each with 1.5–1.7 GW (Jäger-Waldau, 2010). Market estimates vary between 6.6 and 7.9 GW with shipments to first point in the market at 7.9 GW (Mints, 2010). In terms of production, First Solar (US/DE/FR/Malaysia) was number one (1,082 MW), followed by Suntech (PRC) estimated at 750 MW, and Sharp (JP) estimated at 580 MW.

If all these ambitious plans can be realised by 2015, then China will have about 31% of the worldwide production capacity of 67 GW, followed by Europe (18%), Taiwan (18%), and Japan (14%).

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[1] **Solar cell production capacities** mean the following: For wafer-silicon-based solar cells, only the cells; for thin films, the complete integrated module. Only those companies that actually produce the active circuit (solar cell) are counted; companies that purchase these circuits and make cells are not counted.[TSU: definition not clear]

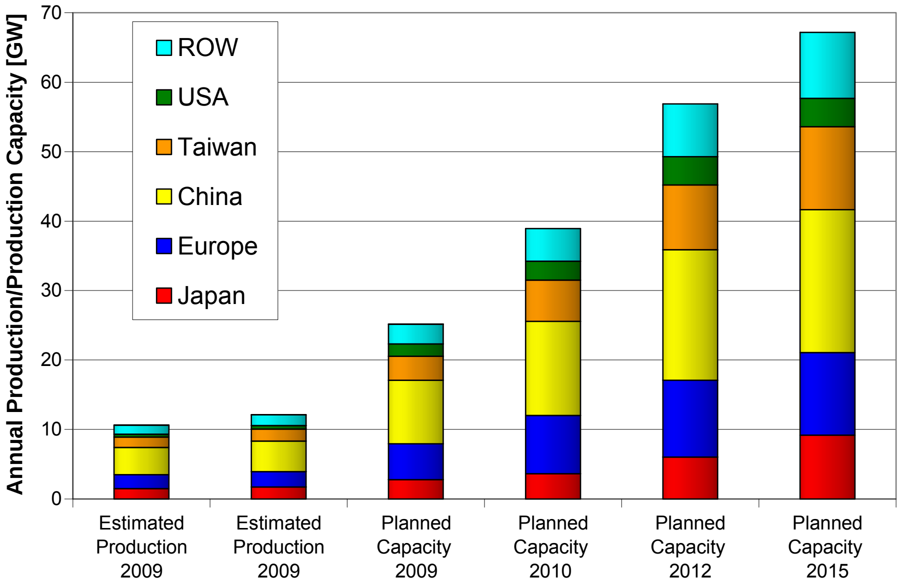


Figure 3.21: Worldwide PV production and with future planned production capacity increases. [TSU: caption not clear, source missing]

Worldwide, some 200 factories produce silicon wafer-based solar cells and more than 300 produce solar modules. In 2009, ***silicon-based solar cells and modules*** represented about 80% of the worldwide market (Figure 3.22). Despite a massive increase in production capacities, the total market share of wafer-based silicon is expected to decrease over the next few years.

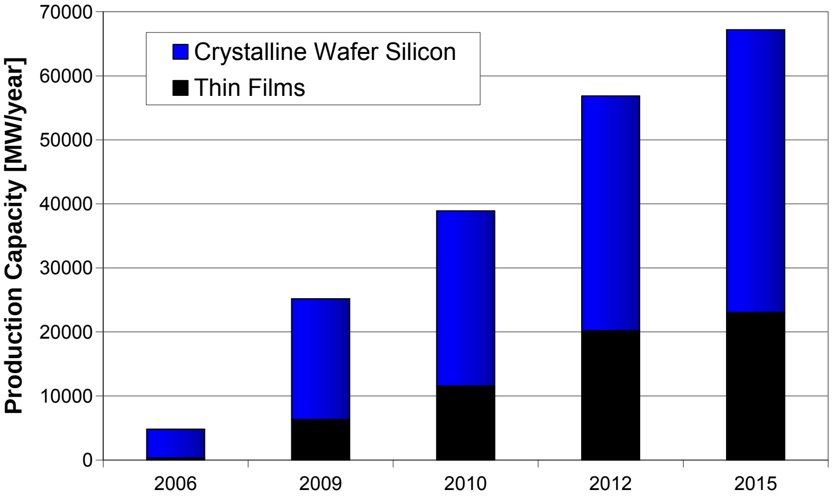


Figure 3.22: Actual and planned production capacities of thin-film and crystalline silicon-based solar modules (Jäger-Waldau, 2010). [TSU: specify actual/planned figures in graph]

The drive to cost reduction and securing key markets has led to the emergence of two interesting trends. One is the move to large original design manufacturing (ODM) units, similar to the developments in the semiconductor industry. A second is that an increasing number of solar manufacturers move parts of their module production close to the final market to demonstrate the local job creation potential and ensure the current policy support.

In 2005, production of ***thin-film PV modules*** grew to more than 100 MW per year. Since then, the compound annual growth rate of thin-film PV module production was higher than that of the industry, thus increasing the market share of thin-film products from 6% in 2005 to about 20% in 2009. Most of this thin-film share comes from the largest PV company.

More than 150 companies are involved in the thin-film solar cell production process, ranging from R&D activities to major manufacturing plants. The first 100-MW thin-film factories became operational in 2007 and the announcements of new production capacities accelerated again in 2008. If all expansion plans are realised in time, thin-film production capacity could be 20.2 GW, or 36% of the total 56.9 GW in 2012, and 23.0 GW, or 34% of a total of 67.2 GW in 2015 (Jäger-Waldau, 2009; Jäger-Waldau, 2010). The first thin-film factories with GW production capacity are already under construction for various thin-film technologies.

The rapid growth of the PV industry since 2000 led to the situation where between 2004 and early 2008, the demand for ***polysilicon*** outstripped the supply from the semiconductor industry. This led to a silicon shortage, which resulted in silicon spot-market prices as high as 500 $/kg and consequently higher prices for PV modules. This extreme price hike triggered the massive capacity expansion, not only of established companies, but many new entrants, as well.

The six companies that reported shipment figures shipped together about 43,900 metric tons of polysilicon in 2008, as reported by Semiconductor Equipment and Materials International (SEMI). In 2008, these companies had a production capacity of 48,200 metric tons of polysilicon (RTS Corporation, 2009). However, all polysilicon producers, including new entrants with current and alternative technologies, had a production capacity of more than 90,000 metric tons of polysilicon in 2008. Considering that not all new capacity actually produced polysilicon at nameplate capacity in 2008, it was estimated that 62,000 metric tons of polysilicon could be produced. Subtracting the needs of the semiconductor industry and adding recycling and excess production, the available amount of silicon for the PV industry was estimated at 46,000 metric tons of polysilicon. With an average material need of 8.7 g/Wp, this would have been sufficient for 5.3 GW of crystalline silicon PV cells.

The regional distribution of the polysilicon production capacities are as follows: China 20,000 metric tons (MT); Europe 17,500 MT; Japan 12,000 MT; and USA 37,000 MT (Chinese Academy of Science, 2009; RTS Corporation, 2009).

For 2009, about 88,000 MT of solar-grade silicon production were reported, sufficient for about 11 GW assuming an average materials need of 8 g/Wp (Displaybank, 2010). China produced about 18,000 MT or 20%, fulfilling about half of the domestic demand (Baoshan, 2010).

Projected silicon production capacities available for solar in 2012 vary between 140,000 MT from established polysilicon producers, up to 185,000 MT including the new producers [Gary Homan, Presentation at Intersolar 2009] and 250,000 MT (Bernreuther and Haugwitz, 2010). The possible solar cell production will also depend on the material use per Wp. Material consumption could decrease from the current 8 g/Wp to 7 g/Wp or even 6 g/Wp, but this may not be achieved by all manufacturers.

Projected silicon production capacities available for solar in 2010 vary between 99,500 MT (PV News, 2008) and 245,000 MT (EuPD Research and IFO Institut fur Wirtschaftforschung Universitat Munchen, 2008). In addition, the possible solar cell production will depend on the material use per Wp.

Next, we look at **CSP electricity generation.** When considering industry capacity, it is important to factor in that CSP is based on adapted knowledge from the existing power industry such as steam and gas turbines. The collectors themselves benefit from a range of existing skill sets such as mechanical, structural, and control engineers, metallurgists, and others. Often, the material or components used in the collectors are already mass-produced, such as glass mirrors.

The CSP industry commenced when the first commercial trough/oil plants were installed and commissioned between 1985 and 1991. Nine individual plants, making up a combined 354 MW_e, were built by Luz, and they continue to operate today, although with new owners.

The next commercial plant was the 64-MW_e Nevada Solar One, built and owned by Acciona, and commissioned in 2007 in Nevada, USA. This plant uses, for the first time, fully recyclable troughs constructed of aluminum, rather than steel, for the structural components. Several years ago, there were only a handful of companies involved in the supply chain for CSP components and construction. Now, however, strong competition is emerging and many companies are now claiming to be capable of supplying components. Nonetheless, the large evacuated tubes (heat-collection elements) designed specifically for use in trough/oil systems for power generation remain a specialized component, and only two companies have been capable of supplying large orders of tubes, with a third company now emerging. The trough concentrator itself comprises know-how in both structures and thermally sagged glass mirrors. Although more companies are now offering new trough designs and considering alternatives to conventional rear-silvered glass (such as new polymer-based reflective films), the essential technology of concentration remains unchanged. Direct steam generation in troughs is under demonstration, as is direct heating of molten salt, but these designs are not yet commercially available. As a result of the long and successful commercial history, trough/oil technology is presently the technology leader.

Linear Fresnel and central receiver systems comprise a high level of know-how, but the essential technology is such that there is the potential for a greater variety of new industry participants. Although only a couple of companies have historically been involved with central receivers, new players have entered the market over the last few years. Abengoa Solar with PS10 and PS20 have been the major commercial central receiver plants, with new players presently having projects at the demonstration level (China, USA, Israel, Australia, Spain). Central-receiver developers are aiming for higher temperatures, and, in some cases, alternative heat-transfer fluids such as molten salts. The accepted standard to date has been for large heliostats, but many of the new entrants are pursuing much smaller heliostats for the cost reductions potentially afforded through mass production. The diverse range of companies now interested in heliostat development ranges from optics companies to the automotive industry looking to diversify. High-temperature steam receivers will benefit from existing knowledge in the boiler industry. Similarly, with linear Fresnel, a range of new developments are occurring, although not yet as developed as the central-receiver technology.

Dish technology is much more specialized, and most effort presently has been toward developing the dish/Stirling concept as a commercial product. Again, the technology can be developed as specialized components through specific industry know-how such as the Stirling engine mass-produced through the automotive industry.

Within just a few years, the CSP industry has gone from negligible activity to over 2,400 MW_e either commissioned or under construction. A list of new CSP plants and their characteristics can be found at the IEA SolarPACES Web site (SolarPACES, 2010). More than ten different companies are now active in building or preparing for commercial-scale plants, compared to perhaps only two or three who were in a position to build a commercial-scale plant three years ago. These companies range from large organizations with international construction and project management expertise who have acquired rights to specific technologies, to start-ups based on their own technology developed in house. In addition, major renewable energy independent power producers such as Acciona, and utilities such as Iberdrola and Florida Power & Light are making plays through various mechanisms for a role in the market.

The supply chain is not limited by raw materials, because the majority of required materials are bulk commodities such as glass, steel/aluminum, and concrete. At present, evacuated tubes for trough plants can be produced at a sufficient rate to service several hundred MW/yr. However, expanded capacity can be introduced fairly readily through new factories with an 18-month lead time.

Solar fuel technology is still at an emerging stage—thus, there is no supply chain in place at present for commercial applications. However, solar fuels will comprise much of the same solar-field technology being deployed for other high-temperature CSP systems, with solar fuels requiring a different receiver/reactor at the focus and different downstream processing and control. Much of the downstream technology, such as Fischer-Tropsch liquid fuel plants, would come from existing expertise in the petrochemical industry. The scale of solar fuel demonstration plants is being ramped up to build confidence for industry, which will eventually expand operations.

3.4.3 Impact of Policies

Direct solar energy technologies face a range of potential barriers to achieve wide-scale deployment, and policies to advance markets generally target three issues: 1) accelerating technology improvements through use of incentives in the near-term, 2) streamlining planning and permitting processes, and 3) harmonizing global codes and standards. For electricity-producing technologies, longer-term support for enabling technologies (e.g., storage, smart grids) is being pursued. Current technology-specific policies and barriers are summarized below.

Solar Water Heating, Space Heating and Cooling, and Lighting. Energy efficiency technologies are supported by tax credits, grants and soft loans, and a few renewable electricity standards (RES) legal frameworks (Rickerson *et al.*, 2009). Because these technologies are a relatively low-cost pathway to carbon emissions reductions, countries are increasing installation rates (Weiss *et al.*, 2009). Yet, similar to PV, these technologies face inconsistent certification and standards issues.

Photovoltaics. Direct financial support measures from governments are driving growth in PV markets. Feed-in-tariffs (FIT), popularized after boosting levels of deployment in Germany and Spain, set a legal framework for utilities to purchase PV-generated electricity at premium rates. In various forms, FIT policies are now implemented in more than 40 countries (REN21, 2009). Tax credits and soft loans are another set of direct financial tools that are frequently used to increase demand and support manufacturing. Additionally, market penetration requirements, such as RES, increase demand by obligating power suppliers to provide a specified fraction of electricity from renewable energy technologies. Most common in the United States (IEA, 2009a), RES policies allow power suppliers flexibility in meeting targets by use of tradable certificate programs (Sullivan *et al.*, 2009) and compliance penalties.

Through successful policy designs (Ragwitz *et al.*, 2007), governments have stimulated strong growth in the industry despite several challenges, such as: 1) Inconsistent interconnection standards, net metering policy, and time-varying utility rate structures that capture the value of PV-generated electricity; 2) Complex access laws, permitting procedures, and fees; 3) Lagging regulatory structures that capture environmental and risk mitigation benefits; and 4) Lack of financing mechanisms that offset relatively high tax burdens and capital costs (Denholm *et al.*, 2009).

Concentrating Solar Power. The general design of policy measures to support the deployment of CSP systems is similar to the options listed above for PV (feed-in tariffs and renewable energy portfolios); however, common barriers differ due to the much greater scale of CSP plants, and the need for investment by major companies rather than, for example, householders. These include: 1) Inconsistent policy supporting utility-scale deployment; 2) Insufficient transmission capacity for large plants linking remote resources regions to load centers; and 3) Siting and permitting challenges to develop land with favourable solar resources (Denholm *et al.*, 2009).

3.5 Integration into Broader Energy System

This section discusses how direct solar energy technologies are part of the broader energy framework, focusing specifically on building-integrated solar energy, low-capacity energy demand, and district heating and other thermal loads.

3.5.1 Building-Integrated Solar Energy

Before considering how solar energy is integrated with other energy technologies, it is important to consider how it is integrated within the building envelope and with energy-conservation methods. Much work over the last decade or so has gone into this integration, culminating in the “net-zero” energy building.

Much of the early emphasis was on integrating PV systems with thermal and daylighting systems. (Bazilian *et al.*, 2001; Tripanagnostopoulos, 2007) listed methods for doing this and reviewed case studies where the methods had been applied. For example, PV cells can be laid on the absorber plate of a flat-plate solar collector. About 6% to 20% of the solar energy absorbed on the cells will be converted to electricity; the remaining roughly 80% will be available as low-temperature heat to be transferred to the fluid being heated. The resulting unit will produce both heat and electricity and require only slightly more than half the area used if the two conversion devices had been mounted side by side and worked independently. PV cells have also been developed to be applied to windows to allow daylighting and passive solar gain.

Considerable work has also been done on architecturally integrating the solar components into the building. Any new solar building should be very well insulated, well sealed, and have highly efficient windows and heat-recovery systems. (Probst and Roecker, 2007), after surveying the opinions of more than 170 architects and engineers who examined a slate of existing solar buildings, concluded the following: 1) best integration is achieved when the solar component is integrated as a construction element, and 2) appearance—including collector colour, orientation, and jointing—must sometimes take precedence over performance in the overall design.

The idea of the net-zero energy solar building has sparked recent interest. Such buildings will send as much excess electrical energy (from PV) to the grid as the energy they draw over the year. An International Energy Agency Task has been set up to consider ways of achieving this goal (IEA Web, 2009). Recent examples for the Canadian climate have been provided by (Athienitis, 2008). Starting from a building that meets the highest levels of conservation, these homes use hybrid air-heating/PV panels on the roof; the heated air is used for space heating or as a source for a heat pump. Solar water-heating collectors are included, as is fenestration permitting a large passive gain through equatorial-facing windows. A key feature is a ground-source heat pump, which provides a small amount of residual heating in the winter as well as cooling in the summer.

3.5.2 Low-Capacity Electricity Demand

There can be comparative advantages for using solar energy rather than fossil fuels in many developing countries. Within a country, the advantages are higher in rural areas compared to urban areas. Indeed, solar energy has the advantage to provide small and decentralized supplies, as well as large centralized ones. It can be very well adapted to small and decentralized demand. Most solar technologies are modular; with PV, for example, there are no large economies of scale.

A common approach for rural electrification is to consider any of the conventional technologies, e.g., diesel or gas generators, and to make the final choice based on the current economic efficiency. However, such an approach does not take into consideration the impact of possible increasing fuel costs on the economic situation of a country. In addition, such an approach does not consider all consumers and does not necessarily lead to sustainable development for the country or for the area to be electrified.

In a wide range of countries, particularly those that are not oil producers, solar energy and other forms of renewable energy can be the most appropriate. If electricity demand exceeds supply, the lack of electricity can prevent development of many economic sectors. Even in countries with high solar energy potential, renewable energy is often only considered to satisfy high-power requirements such as the industrial sector. However, large-scale technologies such as CSP are often not available to them due, for example, to resource conditions or suitable land-area availability. In such cases, it is reasonable to keep the electricity generated near the source to provide high power to cover industrial needs.

Applications that have low power consumption, such as lighting in rural areas, can then primarily be satisfied using on-site PV—even if the business plan for the electrification of the concerned rural area indicates that a connection to the grid would be more profitable. Furthermore, the criteria to determine the most-suitable technological option for the electrification of a rural area should include benefits such as local economic development: exploiting natural resources, creating jobs, reducing the country's dependence on imports, and protecting the environment. [TSU: section lacks references]

3.5.3 District Heating and Other Thermal Loads

In China, Greece, and Israel, **solar water heaters** make a significant contribution to residential energy demand. In addition, solar water heating is widely used for pool heating in Australia and the USA. The power output from 100,000 m^2 of flat-plate solar collectors is on the order of 50 MW during the middle of the day (assuming 1,000 W/m^2 incident radiation and 50% collector efficiency). Thus, the peak power capacity of solar water heaters in a number of countries already exceeds 1,000 MW. In countries where electricity is a major resource for water heating, e.g., Australia, Canada, and USA, the impact of the installation of a large number of solar domestic water heaters on the operation of an electricity grid depends on the load management strategies of the utility.

For a utility that uses centralized load switching to manage electric water-heater load, the impact of solar water heaters is limited to fuel savings. If a utility does not use load switching, then the installation of a large number of solar water heaters may have the additional benefit of reducing peak demand on the grid. For a utility that has a summer peak, the time of maximum solar water-heater output corresponds with peak electrical demand, and there is a capacity benefit from load displacement of electric water heaters. Large-scale implementation of solar water heating can benefit both the customer and the utility. Another benefit to utilities is emissions reduction, because solar water heating will displace the marginal and most-polluting generating plant used to produce peak-load power.

Highly insulated buildings can be heated easily with relatively low-temperature district-heating systems (where solar energy is ideal) or quite small quantities of renewable-generated electricity (Boyle, 1996).

Combining **biomass and low-temperature solar thermal energy** could provide zero-emissions, high-capacity-factor solutions well suited to areas with less frequent direct-beam solar radiation. In the short term, such areas often have high biomass availability due to increased rainfall (from the thick cloud cover). On the other hand, solar technology is much more land efficient and greatly reduces the need for biomass growing area and biomass transport cost. It is likely that some optimum ratio of solar thermal electricity and biomass supply would exist at each site. Research is being conducted on tower and dish systems to develop technologies, such as solar-driven gasification of biomass, that optimally combine both these renewable resources.

In the longer term, greater interconnectedness across different climate regimes may provide more stability of supply as a total grid system, reducing the need for occasional fuel supply for each individual solar thermal electricity system.

3.5.4 PV Generation Characteristics and Smoothing Effect

PV system generation at a single point varies periodically in a day and a year, but also randomly according to weather conditions. The variation of PV generation is supposed to have a large impact on voltage and power flow of the local transmission/distribution system from the early penetration stage, and supply-demand balance in a total power system operation in the deep penetration stage. The impact of supply-demand balance may be a critical constraint of PV integration into a power system. Currently, there are not enough data on generation characteristics to evaluate the smoothing effect. The data collection from a sufficiently large number of sites, periods, and time resolution has just begun in several areas in the world. The total electricity generation of numerous PV systems in a broad area should have less random and fast variation because the generation output variations of numerous PV systems have slight correlation and cancel each other. Otani et al. (1998) analyzed the non-correlational irradiation/generation characteristics of several PV systems/sites that are dispersed spatially. (Ramachandran *et al.*, 2004) analyzed the reduction in power output fluctuation for spatially dispersed PV systems and for different time periods, and they proposed a cluster model to represent very large numbers of small, geographically dispersed PV systems. However, the critical impact on supply-demand balance of a power comes from the total generation of the PV system of a power system (Ogimoto *et al.*, 2010).

Oozeki et al. (2010) quantitatively evaluated the smoothing effect in a load dispatch control area in Japan to determine the importance of data accumulation and analysis. The study also proposed a methodology to calculate the total PV output from a limited number of measurement data using Voronoi Tessellation, which assumes the total PV generation as the weighted sum of the each measurement by the Voronoi cell area. Collecting reliable measurement data with sufficient time resolution and time synchronization, the smoothed generation characteristics of the PV penetration will be analyzed precisely and contribute to the economical and reliable integration of PV into the energy system.

3.5.5 CSP Generation Characteristics and Grid Stabilization

CSP plants can be designed for solar-only electricity generation to satisfy a peak-load demand; but ideally, with thermal storage systems, up to a 100% solar share could be achieved in the future. This potential and their ability to dispatch power on demand during peak periods are key characteristics that have motivated regulators in the Mediterranean Region, starting with Spain, to support large-scale implementation of this technology with tailored feed-in tariffs. CSP is suitable for large-scale 10 to 200 MW_e plants, replacing conventional thermal power capacity. With thermal storage or fossil backup, CSP plants can also produce power when radiation is low and at night. Solar thermal power plants can reliably deliver firm, scheduled power while the grid remains stable.

Solar thermal plants may be combined with a high fossil share in fuel-efficient integrated solar combined-cycle (ISCC) systems. In ISCC power plants, a solar parabolic-trough field is integrated in a modern gas and steam power plant, where the waste-heat boiler is modified and the steam turbine is oversized to provide additional steam from a solar steam generator. Better fuel efficiency and extended operating hours make combined solar/fossil power generation much more cost-effective than in separate CSP and combined-cycle plants. Without storage, however, solar steam could only be supplied for some 2000 of the 6000–8000 combined-cycle operating hours. Furthermore, since the solar steam is only feeding the combined-cycle turbine—which supplies only a third of its power—the solar share obtainable is under 10%. This is especially of interest for oil- and gas-producing Sunbelt countries, where solar power technologies can be introduced on their fossil-based power market (SolarPACES, 2008).

3.6 Environmental and Social Impacts

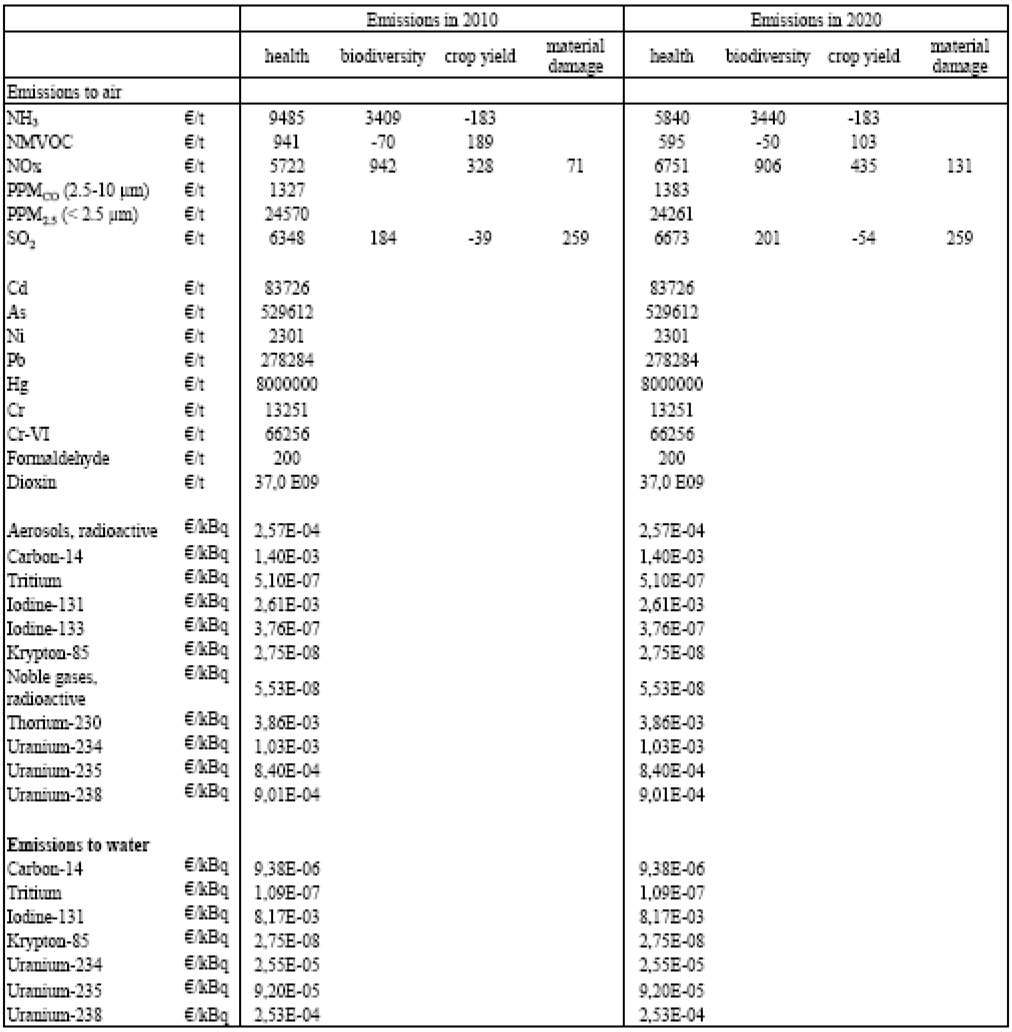
The section first discusses the environmental impacts of direct solar technologies, and then describes potential social impacts.

3.6.1 Environmental Impacts

No consensus exists on the premium, if any, that society should pay for cleaner energy. However, in recent years, there has been progress in analyzing environmental damage costs, thanks to several major projects to evaluate the externalities of energy in the USA and Europe (Gordon, 2001). Although solar energy has been considered desirable because it poses a much smaller environmental burden than conventional sources of energy, this argument has almost always been justified by qualitative appeals. Fortunately, this has begun to change.

Results for damage costs per kilogram of pollutant were presented by the International Solar Energy Society (ISES) in (Gordon, 2001). Table 3.4 correspond to the “uniform world model,” with a regional average (land and water) population density of 80 persons per km^2. For other regions, these numbers should be scaled according to population density.

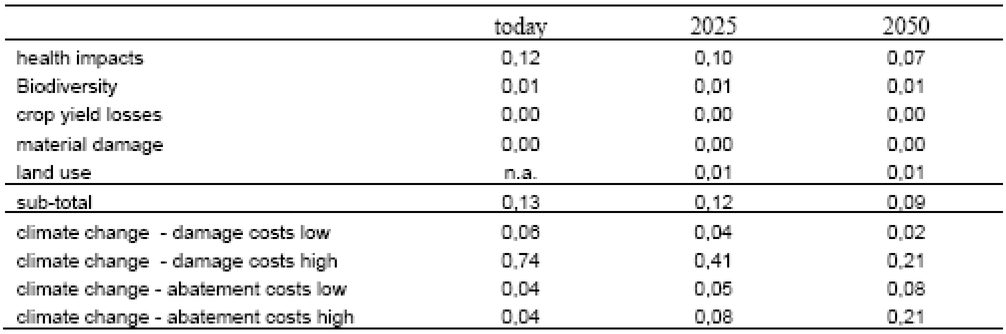
Table 3.4: Unit damage costs for air pollutants in €2000 per elementary flow (source: (NEEDS, 2009). [TSU: convert to US $ 2005], [TSU: graph not readable, specifications not clear]



		Emissions in 2010				Emissions in 2020			
		health	biodiversity	crop yield	material damage	health	biodiversity	crop yield	material damage
Emissions to air									
NH_3	€/t	9485	3409	-183		5840	3440	-183	
NMVOC	€/t	941	-70	189		595	-50	103	
NOx	€/t	5722	942	328	71	6751	906	435	131
PPM_{CO} (2.5-10 µm)	€/t	1327				1383			
$PPM_{2,5}$ (< 2.5 µm)	€/t	24570				24261			
SO_2	€/t	6348	184	-39	259	6673	201	-54	259
Cd	€/t	83726				83726			
As	€/t	529612				529612			
Ni	€/t	2301				2301			
Pb	€/t	278284				278284			
Hg	€/t	8000000				8000000			
Cr	€/t	13251				13251			
Cr-VI	€/t	66256				66256			
Formaldehyde	€/t	200				200			
Dioxin	€/t	37,0 E09				37,0 E09			
Aerosols, radioactive	€/kBq	2,57E-04				2,57E-04			
Carbon-14	€/kBq	1,40E-03				1,40E-03			
Tritium	€/kBq	5,10E-07				5,10E-07			
Iodine-131	€/kBq	2,61E-03				2,61E-03			
Iodine-133	€/kBq	3,76E-07				3,76E-07			
Krypton-85	€/kBq	2,75E-08				2,75E-08			
Noble gases, radioactive	€/kBq	5,53E-08				5,53E-08			
Thorium-230	€/kBq	3,86E-03				3,86E-03			
Uranium-234	€/kBq	1,03E-03				1,03E-03			
Uranium-235	€/kBq	8,40E-04				8,40E-04			
Uranium-238	€/kBq	9,01E-04				9,01E-04			
Emissions to water									
Carbon-14	€/kBq	9,38E-06				9,38E-06			
Tritium	€/kBq	1,09E-07				1,09E-07			
Iodine-131	€/kBq	8,17E-03				8,17E-03			
Krypton-85	€/kBq	2,75E-08				2,75E-08			
Uranium-234	€/kBq	2,55E-05				2,55E-05			
Uranium-235	€/kBq	9,20E-05				9,20E-05			
Uranium-238	€/kBq	2,53E-04				2,53E-04			

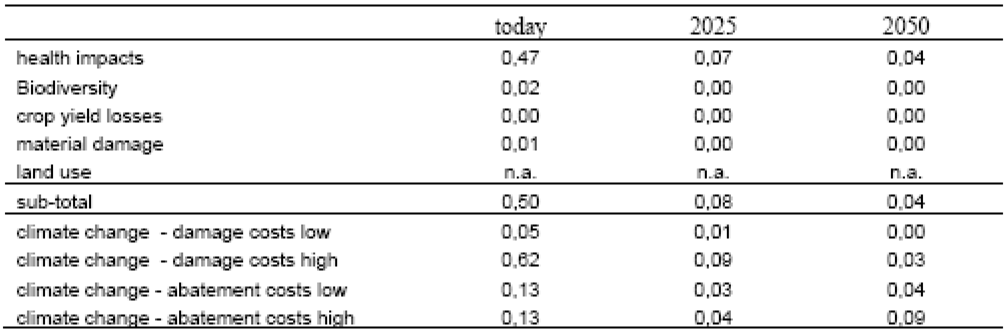
Gordon also presented results for damage costs per kWh. The results of studies such as NEEDS (2009), summarized in Table 3.5, confirm that this [TSU: context missing] is usually the case, but not always. Table 3.6 shows quantifiable external costs for concentrated solar thermal power.

Table 3.5: Quantifiable external costs: Photovoltaic, tilted-roof, single-crystalline silicon, retrofit, average European conditions; in €ct2000/kWh (NEEDS, 2009). [TSU: convert to US $ 2005], [TSU: caption/table content not clear]



	today	2025	2050
health impacts	0,12	0,10	0,07
Biodiversity	0,01	0,01	0,01
crop yield losses	0,00	0,00	0,00
material damage	0,00	0,00	0,00
land use	n.a.	0,01	0,01
sub-total	0,13	0,12	0,09
climate change - damage costs low	0,06	0,04	0,02
climate change - damage costs high	0,74	0,41	0,21
climate change - abatement costs low	0,04	0,05	0,08
climate change - abatement costs high	0,04	0,08	0,21

Table 3.6: Quantifiable external costs: Concentrated solar thermal power; in €ct2000/kWh (NEEDS, 2009). [TSU: convert to US $ 2005], [TSU: caption/table content not clear]



	today	2025	2050
health impacts	0,47	0,07	0,04
Biodiversity	0,02	0,00	0,00
crop yield losses	0,00	0,00	0,00
material damage	0,01	0,00	0,00
land use	n.a.	n.a.	n.a.
sub-total	0,50	0,08	0,04
climate change - damage costs low	0,05	0,01	0,00
climate change - damage costs high	0,62	0,09	0,03
climate change - abatement costs low	0,13	0,03	0,04
climate change - abatement costs high	0,13	0,04	0,09

It is possible to factor environmental and social costs and benefits into an ordinary financial analysis, but this is rarely done (Gordon, 2001). A critical error is that the economics of renewable energy systems are often calculated without reference to their environmental benefits. This omission constitutes a very strong bias in favour of polluting technologies. Relying on traditional levelized-cost accounting for all aspects of energy is untenable without a wider cost/benefit analysis that includes all inputs and outputs.

Environmental benefits must ultimately be included in a rational marketplace. However, many of these benefits cannot be applied across the spectrum in different areas related to energy; this is because they tend to be location specific, and hence, sensitive to local conditions. Conventional energy generation and distribution may reap these benefits by merging with other technologies related to energy efficiency.

One approach that takes account of emissions is to estimate the cost of carbon avoidance, for example, for existing or near-term solar thermal electricity technology (taken from (Kolb, 1998; Mills and Dey, 2000).

All energy technologies have land requirements that differ quite significantly. A recent study (see Figure 3.23) reviewed and updated the land-transformation metric for conventional- and renewable-fuel cycles for generating electricity (Fthenakis and Kim, 2009). The study shows that the PV life cycle of power plants in the U.S. Southwest involves less disturbance of land than do conventional and other renewable-fuel cycles. Even under average U.S. solar irradiation, the land requirement of PV is less than that of coal-based fuel cycles. In contrast to the fossil- and nuclear-fuel cycles, PV does not disturb land by extracting and transporting fuel to the power plants. Furthermore, PV eliminates the necessity of reclaiming mine lands or securing additional lands for waste disposal. Accounting for secondary effects—including water contamination, change of the forest ecosystem, and accidental land contamination—makes the advantages of the PV cycle even greater than those described herein. Further investigation is needed to assess these impacts on a regional and global level.

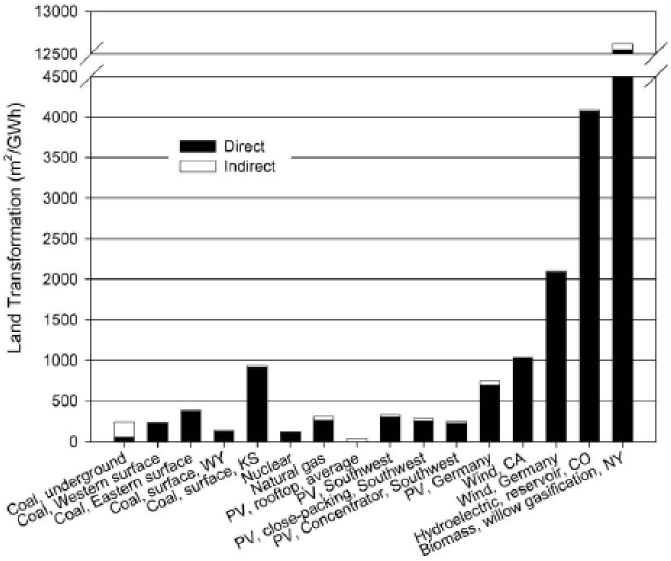


Figure 3.23: Life-cycle land transformation for fuel cycles based on 30-year timeframe (U.S. cases, unless otherwise specified). The estimates for PV are based on multicrystalline PV modules with 13% efficiency. The reference case refers to a ground-mount installation with the U.S. Southwest insolation of 2400 kWh/m^2/year, whereas the rooftop case is based on the U.S. average insolation of 1800 kWh/m^2/year. For Germany, the insolation of Brandis, 1120 kWh/m^2/year, has been used. The packing ratio of the close-packing case is 2.1, compared with 2.5 for the reference case. The estimate for wind is based on a capacity factor of 0.24 for California and 0.2 for Germany (Fthenakis and Kim, 2009).

Considering ***passive solar technology***, higher insulation levels provide many benefits in addition to reducing heating loads and associated costs (Harvey, 2006). The small rate of heat loss associated with high levels of insulation creates a more comfortable dwelling because temperatures are more uniform. This can indirectly lead to higher efficiency in the equipment supplying the heat. It also permits alternative heating systems that would not otherwise be viable, but which are superior to conventional heating systems in many respects. Better-insulated houses eliminate moisture problems associated, for example, with thermal bridges and damp basements. Increased roof insulation also increases the attenuation of outside sounds such as from aircraft.

For ***active solar heating and cooling***, the environmental impact of solar water-heating schemes in the UK would be very small according to (Boyle, 1996). For example, in the UK, the materials used are those of everyday building and plumbing. Solar collectors are installed to be almost indistinguishable visually from normal roof lights. In Mediterranean countries, the use of free-standing thermosyphon systems on flat roofs can be visually intrusive. However, the collector is not the problem, but rather, the storage tank above it.

PV systems do not generate any type of solid, liquid, or gaseous by-products during the production of the electricity. Also, they do not emit noise or use non-renewable resources during operation. However, two topics need to be considered: 1) the emission of pollutants and the use of energy during the production of the PV modules, and 2) the possibility of recycling the PV module materials when the systems are decommissioned.

The energy payback ranges from 2.0 to 2.5 years. Life-cycle GHG emissions range from 30 and 35g CO_2-eq/kWh for microcrystalline silicon and monocrystalline silicon PV, respectively, taking into account use in locations with moderate solar irradiation levels around 1700 kWh/m^2/year (Perpiñan *et al.*, 2009; Fthenakis and Kim, 2010) show payback times of grid-connected PV systems that range from 2 to 5 years for locations with global irradiation ranges from 1900 to 1400 kWh/m^2/year. Fthenakis and Kim (2010) present the future forecast for energy payback time and for GHG emissions, Figures 3.24a and 3.24b.

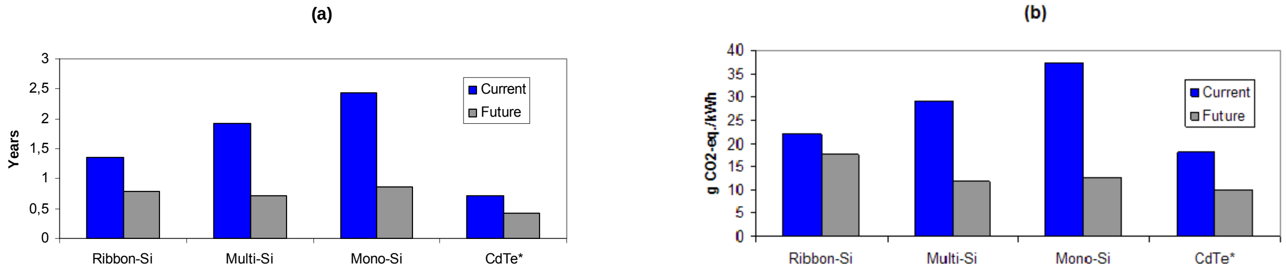


Figure 3.24: Future forecast for energy payback time and GHG emissions from the life cycles of PV modules. Estimates are based on the Southern European irradiation level, 1700 kWh/m^2/year, a performance ratio of 0.75, and lifetime of 30 years (* Based on the average U.S. irradiation level of 1800 kWh/m^2/year and a performance ratio of 0.8) (Fthenakis and Kim, 2010).

The PV industry uses some toxic and explosive gases, as well as corrosive liquids, in its production lines—for instance, silane, NF_3, HF, Cd, Pb, Se, Cu, Ni, and Ag. The presence and amount of those materials depend strongly on the cell type. However, the intrinsic needs of the productive process of the PV industry force the use of quite rigorous control methods that minimize the emission of potentially hazardous elements during module production.

Recycling the material in PV modules is already economically viable, mainly for concentrated and large-scale applications. Predictions are that between 80% and 96% of the glass, ethylene vinyl acetate (EVA), and metals (Te, Se, and Pb) will be recycled. Other metals, such as Cd, Te, Sn, Ni, Al, and Cu, should be saved or they can be recycled by other methods.

An exhaustive literature search of all PV-related life cycle assessment (LCA) studies published after 1980 was conducted. Of the 220 pieces of literature gathered, 74 met screening criteria for quality and relevance to potential technology deployment. The quality screen eliminated studies that did not meet the basic requirements set forth in the ISO 14000 series of standards for LCA, including boundary definition and documentation of assumptions and results. Life-cycle GHG emissions were reported for 106 technology scenarios in 21 of the 74 pieces of literature that passed the screen. Figure 3.25 shows that the majority of life-cycle GHG emission estimates cluster between about 30 and 70 g CO_2-equivalent/kWh, with potentially important outliers at greater values. Additional harmonization efforts to explain these outliers and further LCA studies to increase the number of estimates for some technologies (e.g., CdTe) are recommended.

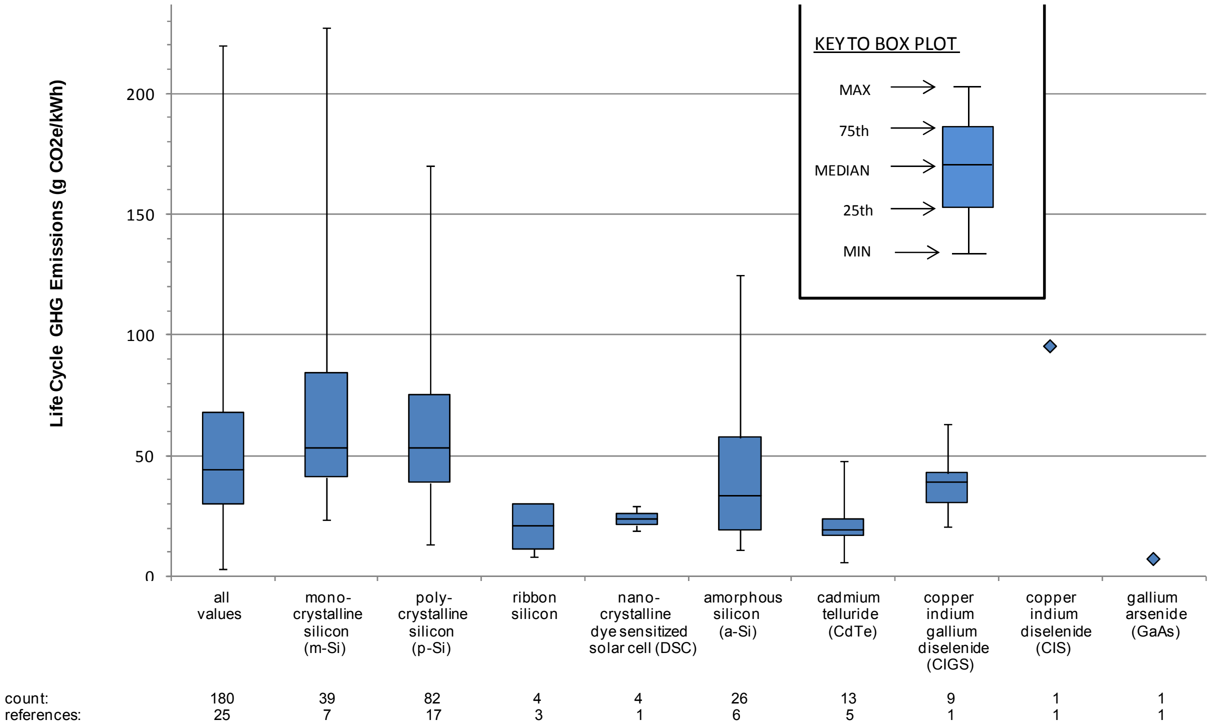


Figure 3.25: Life-cycle GHG emissions of PV technologies (unmodified literature values, after quality screen).

For ***CSP plants***, the environmental consequences vary depending on the technology. In general, greenhouse gas emissions and other pollutions are reduced without incurring additional environmental risks. Each square meter of CSP concentrator surface is enough to avoid the annual production of 250 to 400 kilograms of carbon dioxide. The energy payback time of CSP systems is on the order of just five months, which compares very favorably with their lifespan of about 25 to 30 years. Most CSP solar field materials can be recycled and reused in new plants (SolarPACES, 2008).

Land consumption and impacts on local flora and wildlife during the build-up of the heliostat field and other facilities are the main environmental issues of the concentrating solar systems (Pregger *et al.*, 2009). Other impacts are associated with the construction of the steel-intensive infrastructure for solar energy collection due to mineral and fossil resource consumption, as well as discharge of pollutants related to today's steel production technology (Felder and Meier, 2008).

The cost of land generally represents a very minor cost proportion of the whole plant. A 100-MW CSP plant with a solar multiple of one would require 2 km^2 of land. However, the land does need to be relatively flat (particularly for linear trough and Fresnel systems), near transmission lines and roads for construction traffic, and not on environmentally sensitive land. For Rankine-cycle systems, a water source for cooling is desirable; however, it is not mandatory and dry or hybrid cooling can be used although at an additional cost. Tower and dish Brayton and Stirling systems are being developed for their ability to operate efficiently without water. Although the mirror area itself is typically only about 25% to 35% of the land area occupied, the site of a solar plant will generally be arid. Thus, it is generally not suitable for other agricultural pursuits. For this kind of system, sunny deserts close to the electricity infrastructure are needed. As CSP plant capacity is increased, the economics of longer electricity transport distances improves, and so, more distant siting could be possible. Attractive sites exist in many regions of the world, including southern Europe, northern African countries, the Middle East, Australia, China, and the southwestern USA.

In the near term, water availability will be important to keep the cost of Rankine-cycle-based systems lower. Water is also needed for steam-cycle make-up and mirror cleaning, although the latter two uses represent only a few percent of that needed if wet cooling is used. However, there will be otherwise highly favourable sites where water is not available for cooling. The additional cost of electricity from a dry-cooled plant is 2%–10% (U.S. Department of Energy, 2009), although it depends on many factors such as ambient conditions and technology (e.g., tower plants operating at higher temperature require less cooling per MWh than troughs).

In ***solar fuel production***, solar thermal processes use concentrated solar radiation as the main or sole source of high-temperature process heat. A solar thermal plant consists of a central-receiver system comprising a heliostat field focusing direct solar radiation on a receiver that is mounted on a tower. The receiver comprises a chemical reactor or a heat-exchanging device. Direct CO_2 emissions released by the thermochemical processes are negligible or significantly lower than from current processes (Pregger *et al.*, 2009). All other possible effects are comparable to the conventional processes or can be prevented by safety measures and equipment that are common practice in the chemical industry.

3.6.2 Social Impacts

Solar energy has the potential to meet rising energy demands and decrease greenhouse gas emissions, but solar technologies have faced resistance due to public concerns among some groups. The land-area requirements for centralized CSP and PV plants raise concerns for visual impacts, which can be minimized during the siting phase by choosing locations in areas with low population density, although this will usually be the case for suitable solar sites any way. Visual concerns also exist for distributed solar systems in built-up areas, which may find greater resistance for applications on historical or cultural buildings versus modern constructions. By avoiding conservation areas and incorporating solar technologies into building design, these conflicts can be minimized. Noise impacts may be of concern in the construction phase, but impacts can be mitigated in the site-selection phase and by adoption of good work practices (Tsoutsos *et al.*, 2005). Community engagement throughout the planning process of renewable projects can also significantly increase public acceptance of projects (Zoellner *et al.*, 2008).

Increased deployment of consumer-purchased systems still faces barriers with respect to costs, subsidy structures that may be confusing, and misunderstanding about reliability and maintenance requirements (Faiers and Neame, 2006). Effective marketing of solar technologies, including publicizing impacts relative to traditional power generation facilities and environmental and energy security benefits, have helped to accelerate social acceptance and increase willingness to pay (Batley *et al.*, 2001). Government spending on solar technologies through fiscal incentives and R&D could garner increased public support through increased quantification and dissemination of the economic impacts associated with those programs. A recent study comparing job impacts across energy technologies showed that solar PV had the greatest job-generating potential at an average of 0.87 job-years per GWh, while CSP yielded an average of 0.23 jobs generated per GWh, both of which exceeded job creation estimates for fossil technologies (Wei *et al.*, 2010).

Solar technologies can also improve the health and livelihood opportunities for many of the world's poorest populations. Solar technologies have the potential to address some of the gap in availability of modern energy services for the about 1.6 billion people who do not have access to electricity and the more than 2 billion people who rely on traditional biomass for home cooking and heating needs (International Energy Agency [IEA], 2002).

Solar home systems and PV-powered community grids can provide economically favourable electricity to many areas for which connection to a main grid is impractical, such as in remote, mountainous, and delta regions. Electric lights are the most frequently owned and operated household appliance in electrified households, and access to electric lighting is widely accepted as the principal benefit of electrification programs (Barnes, 1988). Electric lighting may replace light supplied by kerosene lanterns, which are generally associated with poor-quality light, high household fuel expenditures, and pose fire and poisoning risks. The improved quality of light allows for increased reading by household members, study by children, and home-based enterprise activities after dark, resulting in increased education and income opportunities for the household. Higher-quality light can also be provided through solar lanterns, which can afford the same benefits achieved through solar home system-generated lighting. Solar-lantern models can be stand-alone or can require central-station charging, and programs of manufacture, distribution, and maintenance can provide microenterprise opportunities. Use of solar lighting can represent a significant cost savings to households over the lifetime of the technology compared to kerosene, and it can reduce the 190 million metric tons of estimated annual CO2 emissions attributed to fuel-based lighting (Mills, 2005). Solar-powered street lights and lights for community buildings can increase security and safety and provide night-time gathering locations for classes or community meetings. PV systems have been effectively deployed in recent disaster situations to provide safety, care, and comfort to victims in the United States and Caribbean and could be similarly deployed worldwide for crisis relief (Young, 1996).

Solar home systems can also power televisions, radios, and cellular telephones, resulting in increased access to news, information, and distance education opportunities. A study of Bangladesh's Rural Electrification Program revealed that in electrified households all members are more knowledgeable about public health issues, women have greater knowledge of family planning and gender equality issues, the income and gender discrepancies in adult literacy rates are lower, and immunization guidelines for children are adhered to more regularly when compared with non-electrified households (Barkat *et al.*, 2002). Electrified households may also buy appliances such as fans, irons, grinders, washing machines, and refrigerators to increase comfort and reduce the drudgery associated with domestic tasks (Energy Sector Management Assistance Programme [ESMAP], 2004).

Indoor smoke from solid fuels is responsible for more than 1.6 million deaths annually and 3.6% of the global burden of disease. This mortality rate is similar in scale to the 1.7 million annual deaths associated with unsafe sanitation and more than twice the estimated 0.8 million yearly deaths from exposure to urban air pollution (Ezzati *et al.*, 2002). In areas where solar cookers can satisfactorily produce meals, these cookers can reduce unhealthy exposure to high levels of particulate matter from traditional use of solid fuels for cooking and heating and the associated morbidity and mortality from respiratory and other diseases. Decreased consumption of firewood will correspondingly reduce the time women spend collecting firewood. Studies in India and Africa have collected data showing that this time can total 2 to 15 hours per week, and this is increasing in areas of diminishing fuelwood supply (Brouwer *et al.*, 1997; Energy Sector Management Assistance Programme [ESMAP], 2004). Risks to women collecting fuel include injury, snake bites, landmines, and sexual violence (Environmental Health Perspectives, 2003; Patrick, 2007); when children are enlisted to help with this activity, they may do so at the expense of educational opportunities (Nankhuni and Findeis, 2004). Well-being may be acutely at risk in refugee situations, as are strains on the natural resource systems where fuel is collected (Lynch, 2002). Solar cookers do not generally fulfil all household cooking needs due to technology requirements or their inability to cook some traditional foods; however, even partial use of solar cookers can realize fuelwood savings and reductions in exposure to indoor air pollution (Wentzel and Pouris, 2007).

Solar technologies also have the potential to combat other prevalent causes of morbidity and mortality in poor, rural areas. Solar desalination and water purification technologies can help combat the high prevalence of diarrheal disease brought about by lack of access to potable water supplies. PV systems for health clinics can provide refrigeration for vaccines and lights for performing medical procedures and seeing patients at all hours. Improved working conditions for rural health-care workers can also lead to decreased attrition of talented staff to urban centers.

Solar technologies can improve the economic opportunities and working conditions for poor rural populations. Solar dryers can be used to preserve foods and herbs for consumption year round and produce export-quality products for income generation. Solar water pumping can minimize the need for carrying water long distances to irrigate crops, which can be particularly important and impactful in the dry seasons and in drought years. Burdens and risks from water collection parallel those of fuel collection, and decreased time spent on this activity can also increase the health and well-being of women, who are largely responsible for these tasks.

The high capital costs of solar systems are often cited as a barrier to increased deployment, and donor programs have experienced issues with fully subsidized systems falling into disrepair (Nieuwenhout *et al.*, 2001). If appropriate financing and after-sales services are offered, markets for solar home systems can develop independently of donor programs. However, market conditions vary widely, and limits of market size and purchasing power can require funds and organizational support from the government or donor agency to yield substantial dissemination of systems (van der Vleuten *et al.*, 2007). Another alternative to user-owned systems, purchased individually or with donor assistance, is ownership by an energy service company, who owns and maintains the system and sells the energy services to the customers (Martinot *et al.*, 2001; Gustavsson and Ellegard, 2004). This arrangement eliminates the need for users to provide up-front capital and increases user satisfaction through proper system maintenance.

3.7 Prospects for Technology Improvements and Innovation

This section considers technical innovations that are possible in the future for a range of solar technologies, under the following headings: passive solar technologies, active solar heat and cooling, PV electricity generation, CSP electricity generation, solar fuel production, and other possible applications.

3.7.1 Passive Solar Technologies

Passive solar technologies, particularly the direct-gain system, are intrinsically highly efficient because no energy is needed to move collected energy to storage and then to a load. The collection, storage, and use are all integrated. Through technological advances such as low-emissivity coatings and the use of gases such as argon in glazings, near-equatorial-facing windows have reached a high level of performance at increasingly affordable cost. Nevertheless, in heating-dominated climates, further advances are possible, such as the following: 1) Reduction of thermal conductance through use of dynamic exterior night insulation (night shutters); 2) Use of evacuated glazing units; and 3) Translucent glazing systems that may include materials that change solar/visible transmittance with temperature (including a possible phase change) while providing increased thermal resistance in the opaque state.

Considering cooling-load reduction in solar buildings, advances are possible in areas such as the following: 1) Use of cool roof technologies involving materials with high solar reflectivity and emissivity; 2) More systematic use of heat dissipation techniques such as use of the ground and water as a heat sink; 3) Use of advanced pavements and outdoor structures to improve the microclimate around the buildings and decrease urban ambient temperatures; and 4) Advanced solar control devices allowing penetration of daylight, but not of the thermal energy.

Advances in thermal storage integrated in the interior of direct-gain zones are still possible, such as phase-change materials integrated in gypsum board, bricks, or tiles and concrete. The target will be to maximize energy storage per unit volume/mass of material so that such materials can be integrated in lightweight wood-framed homes that are common in cold-climate areas. The challenge for such materials will be to ensure that they continue to store and release heat effectively after 10,000 cycles or more while meeting other performance requirements such as fire resistance. Phase-change materials may also be used systematically in plasters to reduce high indoor temperatures in summer.

As explained in subsections 3.4.1 and 3.4.2, increasingly larger window areas become possible and affordable with the recent drop in prices of highly efficient double-glazed and triple-glazed low-e argon-filled windows. These increased window areas make systematic solar-gain control essential in mild-moderate climatic conditions, but also in continental areas that tend to be cold in winter and hot in summer. Solar-gain control techniques may increasingly rely on active systems such as motorized blinds/shades or electrochromic, thermochromic, and gasochromic coatings to admit the solar gains when they are desirable or keep them out when overheating in the living space is detected or anticipated. Solar-gain control, thermal storage design, and heating/cooling system control are three strongly linked aspects of passive solar design and control.

In any solar building, there are normally some direct-gain zones that receive high solar gains and other zones behind that are generally colder in winter. Therefore, it is beneficial to circulate air between the direct-gain zones and back zones in a solar home, even when heating is not required. With forced-air systems commonly used in North America, this is increasingly possible and the system fan may be run at low flow rate when heating is not required, thus helping to redistribute absorbed direct solar gains to the whole house (Athienitis, 2008).

During the summer period, hybrid ventilation systems and techniques may be used to provide fresh air and reduce indoor temperatures (Heiselberg, 2002). Various types of hybrid ventilation systems have been designed, tested, and applied in many types of buildings. Performance tests have found that although natural ventilation cannot maintain appropriate summer comfort conditions, the use of a hybrid system is the best choice—using at least 20% less energy than any purely mechanical system.

Finally, design tools are expected to be developed that will facilitate the simultaneous consideration of passive design, active solar-gain control, HVAC system control, and hybrid ventilation at different stages of the design of a solar building. Indeed, the systematic adoption of these technologies and their optimal integration is essential to move toward the goal of cost-effective solar buildings with net-zero annual energy consumption (IEA, 2009b).

3.7.2 Active Solar Heating and Cooling

The vision of the European Solar Thermal Technology Platform (European Solar Thermal Technology Platform [ESTTP], 2006) is to establish the “Active Solar Building” as a standard for new buildings by 2030, where an Active Solar Building covers 100% of its demand for heating (and cooling, if any) with solar energy.

For existing buildings, ESTTP fosters the Active Solar Renovation, achieving massive reductions in energy consumption through energy-efficiency measures and passive solar energy. The goal is also to cover substantially more than 50% of the remaining heating and/or cooling demands with active solar energy.

Heat storage represents a key technological challenge, because the wide deployment of Active Solar Buildings largely depends on developing cost-effective and practical solutions for seasonal heat storage. The ESTTP vision assumes that by 2030, heat-storage systems will be available that allow for seasonal heat storage with an energy density eight times higher than water.

In the future, active solar systems—such as thermal collectors, PV panels, and photovoltaic-thermal systems—will be the obvious components of roof and façades. And they will be integrated into the construction process at the earliest stages of building planning. The walls will function as a component of the active heating and cooling systems, supporting the thermal energy storage through the application of advanced materials (e.g., phase-change materials). One central control system will lead to optimal regulation of the whole heating, ventilation, and air-conditioning (HVAC) system, maximizing the use of solar energy within the comfort parameters set by users. Heat- and cold-storage systems will play an increasingly important role in reaching maximum solar thermal contributions to cover the thermal requirements in buildings.

Solar heating for industrial processes (SHIP) is currently at a very early stage of development (POSHIP Potential of Solar Heat for Industrial Processes, 2001). Worldwide, less than a hundred operating solar thermal systems for process heat are reported, with a total capacity of about 24 MW_{th} (34,000 m^2). Most systems are experimental and relatively small scale. However, great potential exists for market and technological developments, because 28% of the overall energy demand in the EU27 countries originates in the industrial sector, and much of this demand is for heat below 250°C. Education and dissemination is needed for the deployment of this technology.

In the short term, SHIP will mainly be used for low-temperature processes, ranging from 20° to 100°C. With technological development, an increasing number of medium-temperature applications—up to 250°C—will become feasible within the market. According to a published study (Werner, 2006), about 30% of the total industrial heat demand is required at temperatures below 100°C, which could theoretically be met with SHIP using current technologies. And 57% of this demand is required at temperatures below 400°C, which could largely be supplied by solar in the foreseeable future.

In several specific industry sectors—such as food, wine and beverages, transport equipment, machinery, textiles, and pulp and paper—the share of heat demand at low and medium temperatures (below 250°C) is around 60% (POSHIP Potential of Solar Heat for Industrial Processes, 2001). Tapping into this potential would provide a significant solar contribution to industrial energy requirements. Substantial potential for solar thermal systems also exists in chemical industries and in washing processes.

Among the industrial processes, desalination and water treatment (e.g., sterilization) are particularly promising applications for solar thermal energy, because these processes require large amounts of medium-temperature heat and are often necessary in areas with high solar radiation and high conventional energy costs.

3.7.3 PV Electricity Generation

This subsection discusses photovoltaic technology improvements and innovation within the areas of solar PV cells, as well as the entire PV system.

Photovoltaic modules are the basic building blocks of flat-plate PV systems. Further technological efforts should lead to reduced cost, enhanced performance, and an improved environmental profile. It is useful to distinguish between technology categories that require specific R&D approaches.

First, we look at ***wafer-based crystalline silicon, existing thin-film technologies, and emerging and novel technologies*** (including "boosters" to the first two categories). The following paragraphs list R&D topics that have highest priority, with further details to be found in the various PV roadmaps, e.g., Strategic Research Agenda for Photovoltaic Solar Energy Technology (U.S. Photovoltaic Industry Roadmap Steering Committee, 2001; European Commission, 2007; NEDO, 2009).

- **Efficiency, energy yield, stability, and lifetime.** Research often aims at optimizing rather than maximizing these parameters, which means that additional costs and gains are critically compared. Because research is primarily aimed at reducing the cost of electricity generation, it is important not to focus only on initial costs (€/Wp), but also, on lifecycle gains, i.e., actual energy yield (kWh/Wp over the economic or technical lifetime).

- **High-productivity manufacturing, including in-process monitoring and control.** Throughput and yield are important parameters in low-cost manufacturing and essential to achieve the cost targets. In-process monitoring and control are crucial tools to increase product quality and yield. Dedicated developments are needed to bring PV manufacturing to maturity.

- **Environmental sustainability.** The energy and materials requirements in manufacturing, as well as the possibilities for recycling, are important parameters in the overall environmental quality of the product. Further shortening of the energy payback time, design for recycling and, ideally, avoiding the use of critical materials are the most important issues to be addressed here.
- **Applicability.** As discussed in more detail in the paragraphs on BOS and systems, standardization and harmonization are important to bring down the costs of PV. Some related aspects must be addressed on a module level. In addition, improved ease of installation is partially related to module features. Finally, aesthetic quality of modules (and systems) is an important aspect for large scale use in the built environment.

Some PV technologies represent truly revolutionary approaches—and they will not only greatly change the way we "think and do" technology, but will herald the energy solutions for our consumers of 2030 and beyond. These advanced technologies include those that have passed some proof-of-concept phase or can be considered as mid-term (10–20-year) options to the other approaches already discussed. These emerging concepts are medium to high risk and are based on extremely low-cost materials and processes with high performance. Examples are 4- to 6-junction concentrators, multiple-junction polycrystalline thin films, crystalline silicon in the sub-100-micrometer-thick regime, multiple-junction organic PV, and hybrid solar cells.

Even further out on the timeline are concepts that offer incredible performances and/or low cost—but are yet to be demonstrated beyond some preliminary stages. These technologies are truly high risk, but have extraordinary potential involving new materials, new device architectures, and even new conversion concepts. They go beyond the normal Shockley-Queisser limits and may include biomimetic devices, quantum dots (QDs), multiple-exciton generation (MEG), and plasmonic solar cells.

Second, we look at ***PV concentrator systems*** as a separate category, because the R&D issues are fundamentally different compared to flat-plate technologies. Note, however, that some of the concepts discussed under "Emerging and novel technologies" may ultimately be especially suited for use in concentrator systems.

As mentioned in section 3.3.3, CPV offers a variety of technical solutions and these solutions are given on the system level. The research issues can be divided into the following activities:

- Concentrator solar cell manufacturing
- Optical system
- Module assembly and fabrication method of concentrator modules and systems
- System aspects, such as tracking, inverter, and installation issues.

However, it should be clearly stated once more: CPV is a system approach. The whole system is optimised only if we consider all the interconnections between the components. A corollary is that an optimised component is not necessarily the best choice for the optimal CPV system. Thus, strong interactions are required among the various research groups.

Third, we look at ***balance-of-system components and systems***. A photovoltaic system is composed of the PV module, as well as the balance of system, which can include an inverter, storage, charge controller, system structure, and the energy network. The system must be reliable, cost effective, attractive, and mesh with the electric grid in the future (U.S. Photovoltaic Industry Roadmap Steering Committee, 2001; Navigant Consulting Inc., 2006; EU PV European Photovoltaic Technology Platform, 2007; Energy Information Administration [DOE], 2008; Kroposki *et al.*, 2008; NEDO, 2009). Users meet PV technology at the system level, and their interest is in a reliable, cost-effective, and attractive solution to their energy supply needs. This research agenda concentrates on topics that will achieve one or more of the following:

- Reduce costs at the component and/or system level.
- Increase the overall performance of the system, including aspects of increased and harmonised component lifetimes, reduced performance losses, and maintenance of performance levels throughout system life.
- Improve the functionality of and services provided by the system, thus adding value to the electricity produced.

At the component level, a major objective of balance-of-system development is to extend the lifetime of BOS components for grid-connected applications to that of the modules, typically 20 to 30 years. The highest priority is given to developing inverters, storage devices, and new designs for specific applications such as building-integrated PV. For systems installed in isolated, off-grid areas, component lifetime should be increased to around 10 years, and components for these systems need to be designed so that they require little or no maintenance. Storage devices are necessary for off-grid PV systems and will require innovative approaches to the short-term storage of small amounts of electricity (1 to 10 kWh); in addition, approaches are needed for integrating the storage component into the module, thus providing a single streamlined product that is easy to use in off-grid and remote applications. Moreover, devices for storing large amounts of electricity (over 1 MWh) will be adapted to large PV systems in the new energy network. As new module technologies emerge in the future, some of the ideas relating to BOS may need to be revised. Furthermore, the quality of the system needs to be assured and adequately maintained according to defined standards, guidelines, and procedures. To assure system quality, assessing performance is important, including on-line analysis (e.g., early fault detection) and off-line analysis of PV systems. The knowledge gathered can help to validate software for predicting the energy yield of future module and system technology designs.

To increasingly penetrate the energy network, PV systems must use technology that is compatible with the electric grid and energy supply and demand. System designs and operation technologies must also be developed in response to demand patterns by developing technology to forecast power generation volume and to optimize the storage function. Moreover, inverters must improve the quality of grid electricity by controlling reactive power or filtering harmonics with communication in a new energy network such as the Smart Grid. Furthermore, very-large-scale PV (VLS-PV) systems will be required that have capacities ranging from several megawatts to gigawatts, and practical project proposals need to be developed for implementing VLS-PV systems in desert regions (Komoto *et al.*, 2009). In the long term, VLS-PV will play an important role in the worldwide energy network (DESERTEC Foundation, 2007)

Fourth, we look at ***standards, quality assurance, and safety and environmental aspects***. National and especially local authorities and utilities require that PV systems meet agreed-upon standards (such as building standards, including fire- and electrical-safety requirements). In a number of cases, the development of the PV market is being hindered by either 1) existing standards, 2) differences in local standards (e.g., inverter requirements/settings), or 3) the lack of standards (e.g., PV modules/PV elements not being certified as a building element because of the lack of an appropriate standard). Standards and/or guidelines are required for the whole value chain. In many cases, the development of new and adapted standards and guidelines implies that dedicated R&D is required.

Quality assurance is an important tool that assures the effective functioning of individual components in a PV system, as well as the PV system as a whole. Standards and guidelines are an important basis for quality assurance. In-line production control procedures and guidelines must also be developed. At the system level, monitoring techniques must be developed for early fault detection.

Recycling is an important building block to ensure a sustainable PV industry. To date, most attention has been paid to recycling of crystalline silicon solar modules. Methods for recycling of thin-film modules and BOS components (where no recycling procedures exist) must be addressed in the future. Life-cycle assessment (LCA) studies are an important tool for evaluating the environmental profile of the various renewable energy sources. To assure the position of PV with respect to other sources, reliable LCA data are required. From these data, one can calculate properties such as the CO_2 emission per kWh of electricity produced and the energy payback time. In addition, the results of LCA data can be used in the design phase of new processes and equipment for cell and module production lines.

3.7.4 CSP Electricity Generation

CSP is a proven technology at the utility scale. The longevity of components has been established over two decades; operation and maintenance (O&M) aspects are understood; and there is enough operational experience to have enabled O&M cost-reduction studies to not only recommend, but also to test, those improvements. In addition, field experience has been fed back to industry and research institutes and has led to improved components and more advanced processes. Importantly, there is now substantial experience that allows researchers and developers to better understand the limits of performance, the likely potential for cost reduction, or both. Studies (Sargent and Lundy LLC Consulting Group, 2003) have concluded that cost reductions will come from technology improvement, economies of scale, and mass production. Other needed innovations related to power cycles and collectors are discussed below.

CSP is a technology driven by thermodynamics. Thus, the **thermal energy conversion cycle** plays a critical role in determining overall performance and cost. In general, thermodynamic cycles with higher temperatures will perform more efficiently. Of course, the solar collectors that provide the higher-temperature thermal energy to the process must be able to perform efficiently at these higher temperatures also, and today, considerable R&D attention is being given to increasing the operating temperature of CSP systems. Although CSP works with turbine cycles used by the fossil fuel industry, there are opportunities to refine turbines such that they can better accommodate the duties associated with thermal cycling invoked by solar inputs.

Considerable development is taking place to optimize the linkage between solar collectors and higher-temperature thermodynamic cycles. The most commonly used power block to date is the steam turbine (Rankine cycle). The steam turbine is most efficient and most cost effective in large capacities. Present trough plants using oil as the heat-transfer fluid limit steam-turbine temperatures to 370°C and turbine cycle efficiencies of around 37%, leading to design-point solar-to-electric efficiencies on the order of 18% and annual average efficiency of 14%. To increase efficiency, alternatives to the use of oil as the heat-transfer fluid—such as producing steam directly in the receiver, or molten salts—are being developed for troughs.

These fluids and others are already preferred for central receivers. Central receivers and dishes are capable of reaching the upper limits of these fluids (around 600°C for present molten salts) for advanced steam-turbine cycles, whether subcritical or supercritical pressure, and they can also provide the temperatures needed for higher-efficiency cycles such as gas turbines (Brayton cycle) and Stirling engines. Such high-temperature cycles have the capacity to boost design-point solar-to-electricity efficiency to 35% and annual average efficiency to 25%. The penalty for dry cooling is also reduced.

The collector is the single largest area for potential cost reduction in CSP plants. For **CSP collectors**, the objective is to lower their cost while achieving the higher optical efficiency necessary for powering higher-temperature cycles. Trough technology will benefit from continuing advances in solar-selective surfaces, and central receivers and dishes will benefit from improved receiver/absorber design that allows collection of very high solar fluxes. Linear Fresnel is attractive in part because the inverted cavity design can reduce some of the issues associated with the heat-collection elements of troughs, although with reduced annual optical performance.

Improved overall efficiency yields a corresponding decrease in the area of mirrors needed in the field, and thus, lower collector cost and lower O&M cost. Capital cost reduction is expected to come primarily from the benefits of mass production of key components that are specific to the solar industry, and from economies of scale as the fixed price associated with installation is spread over larger and larger capacities. In addition, the benefits of "learning by doing" cannot be overestimated.

A more detailed assessment of future technology improvements that would benefit CSP may be found in ECOstar, a report by (German Aerospace Center [DLR], 2005).

3.7.5 Solar Fuel Production

The ability to store solar energy in the form of a fuel is attractive not only for the transportation industry, but also, for high-efficiency electricity generation using today's combined cycles, improved combined cycles using advances in gas turbines, and fuel cells. In addition, solar fuels offer a form of storage for solar electricity generation.

Future solar fuel processes will benefit not only from the continuing development of high-temperature solar collectors, but also, from other fields of science such as electro- and bio-chemistry. Many researchers consider hydrogen to offer the most attraction for the future, although intermediate and transitional approaches are also being developed. Hydrogen is considered in this section, with other solar fuels having been covered in previous sections.

In solar *electrochemical* water-splitting, the electricity required is provided by either CSP or PV power stations. The low-temperature alkaline electrolysis process produces molecular hydrogen at the cathode, while organic-compound oxidation occurs under mild conditions at the anode in competition with the production of oxygen. Using solid-oxide fuel cells (SOFCs) in electrolysis mode—called solid-oxide electrolysis cells (SOECs)—offers higher system efficiency than the low-temperature electrolysis systems. This is because the electricity demand for electrolysis can be significantly reduced if the formation of hydrogen occurs at high temperatures (800°–1000°C). At these elevated temperatures, the required electrical energy can be partially substituted by thermal energy as the water-splitting process becomes increasingly endothermic with rising temperature. Thus, the unavoidable heat produced in an electrolysis cell is not lost, but instead, is used in the steam-splitting process. Additional high-temperature heat from concentrating solar sources further reduces the electrical energy demand.

Another future technology innovation for solar electrolysis is the photoelectrochemical (PEC) cell, which converts solar radiation into chemical energy such as H_2. A PEC cell is fabricated using an electrode that absorbs the solar light, two catalytic films, and a membrane separating H_2 and O_2.

Promising *thermochemical* processes for future "clean" hydrogen mass production encompass the hybrid-sulfur cycle and metal-oxide-based cycles. The hybrid-sulfur cycle is a two-step water-splitting process using an electrochemical, instead of thermochemical, reaction for one of the two steps. In this process, sulfur dioxide depolarizes the anode of the electrolyzer, which results in a significant decrease in the reversible cell potential—and, therefore, the electric power requirement for the electrochemical reaction step. A number of solar reactors applicable to solar thermochemical metal-oxide-based cycles have been developed, including a 100-kW_{th} monolithic dual-chamber solar reactor for a mixed-iron-oxide cycle, demonstrated within the European P&D project *HYDROSOL-2* (Roeb *et al.*, 2009); a rotary solar reactor for the ZnO/Zn process being scaled up to 100 kW_{th} (Schunk *et al.*, 2009); the Tokyo Tech rotary-type solar reactor (Kaneko *et al.*, 2007); and the Counter-Rotating-Ring Receiver/Reactor/Recuperator (CR5), a device using recuperation of sensible heat to efficiently produce H_2 in a two-step thermochemical process (Miller *et al.*, 2008).

High temperatures demanded by the thermodynamics of the thermochemical processes pose severe material challenges and also increase re-radiation losses from the reactor, thereby lowering the absorption efficiency (Steinfeld and Meier, 2004). The overall energy conversion efficiency is improved by reducing thermal losses at high temperatures through improved mirror optics and cavity-receiver design, and by recovering part of the sensible heat from the thermochemical processes.

High-temperature thermochemical processes require thermally and chemically stable reactor-wall materials that can withstand the severe operating conditions of the various solar fuel production processes. For many lower-temperature processes (e.g., sulfur-based thermochemical cycles), the major issue is corrosion. For very high-temperature metal-oxide cycles, the challenge is the thermal shock resistance of the ceramic wall materials. Near-term solutions include surface modification of thermally compatible refractory materials such as graphite and silicon carbide. Longer-term solutions include modifications of bulk materials. Novel reactor designs may prevent wall reactions.

A key aspect is integrating the chemical process into the solar concentrating system. The concentrating optics—consisting of heliostats and secondary concentrators (compound parabolic concentrator, CPC)—need to be further developed and specifically optimized to obtain high solar-flux intensities and high temperatures in solar chemical reactors for producing fuels.

Photochemical and photobiological processes are other candidates for solar fuel conversion. Future innovative technologies are being developed for producing biofuels from modified photosynthetic microorganisms and chemical solar cells for fuel production. Both approaches have the potential to provide fuels with solar energy conversion efficiencies much better than those based on field crops. Artificial solar-driven fuel production will require biomimetic nanotechnology, where scientists must develop a series of fundamental and technologically advanced multi-electron redox catalysts coupled to photochemical elements. Hydrogen production by these methods at scale is still distant, but has vast potential.

A combination of all three forms is found in the *synthesis* of biogas with solar hydrogen. Biogas, a mixture of methane and CO_2, is produced via conventional photosynthesis. Solar hydrogen is added by electrochemical water-splitting. Bio-CO_2 reacts with hydrogen in a thermochemical process to generate hydrocarbons such as substitute natural gas (SNG) or liquid solar fuels (Sterner, 2009). These approaches are still nascent, but have a feasible economic potential in the future as fossil fuel prices increase and solar power generation costs continue to decrease.

3.7.6 Other Potential Future Applications

There are also methods for producing electricity by solar thermal without the need for an intermediate thermodynamic cycle. This direct solar thermal power generation includes such concepts as thermoelectric, thermionic, magnetohydrodynamic, and alkali-metal methods. The thermoelectric concept is the most investigated to date, and all have the attraction that the absence of a heat engine should mean a quieter and theoretically more-efficient method of producing electricity, with suitability for distributed generation. Specialised applications include military and space power.

Space-based solar power (SSP) is the concept of collecting vast quantities of solar power in space using large satellites in Earth orbit, then sending that power to receiving antennae (rectennae) on Earth via microwave power beaming. The concept was first introduced in 1968 by Peter Glaser (Glaser, 1968). NASA and the U.S. Department of Energy studied SSP extensively in the 1970s as a possible solution to the energy crisis of that time. Scientists studied system concepts for satellites large enough to send gigawatts of power to Earth and concluded that the concept seemed technically feasible and environmentally safe; but the state of enabling technologies was insufficient to make SSP economically competitive. Since the 1970s, however, great advances have been made in these technologies, such as high-efficiency photovoltaic cells, highly efficient solid-state microwave power electronics, and lower-cost space launch vehicles (Mankins, 1997; Kaya *et al.*, 2001; Hoffert *et al.*, 2002; Mankins, 2002; Mankins, 2009). Still, significant breakthroughs will be required to achieve cost-competitive terrestrial baseload power (National Academy of Sciences, 2004).

3.8 Cost Trends

This section provides cost trends for the five direct solar technology areas.

3.8.1 Passive Solar Technologies

High-performance building envelopes entail greater up-front construction costs, but lower energy-related costs during the lifetime of the building (Harvey, 2006). The total up-front cost of the building may or may not be higher, depending on the extent to which heating and cooling systems can be downsized, simplified, or eliminated altogether as a result of the high-performance envelope. Any additional up-front cost will be compensated for, to some extent, by reduced energy costs over the lifetime of the building.

Figure 3.26 compares differences in the life-cycle costs when additional heating costs are computed for each level of insulation relative to the highest level of insulation considered. Although the specific incremental construction costs that should be used in any given location will differ from those used in Figure 3.26 there is very little difference in the life-cycle cost if insulation levels moderately worse or moderately better than the least-cost level are chosen. Although the life-cycle cost associated with the highest insulation level is not the smallest life-cycle cost, it is not substantially greater than the minimum life-cycle cost when the fuel cost is 15 USD/GJ or 20 USD/GJ, and is less than the life-cycle cost at low levels of insulation.

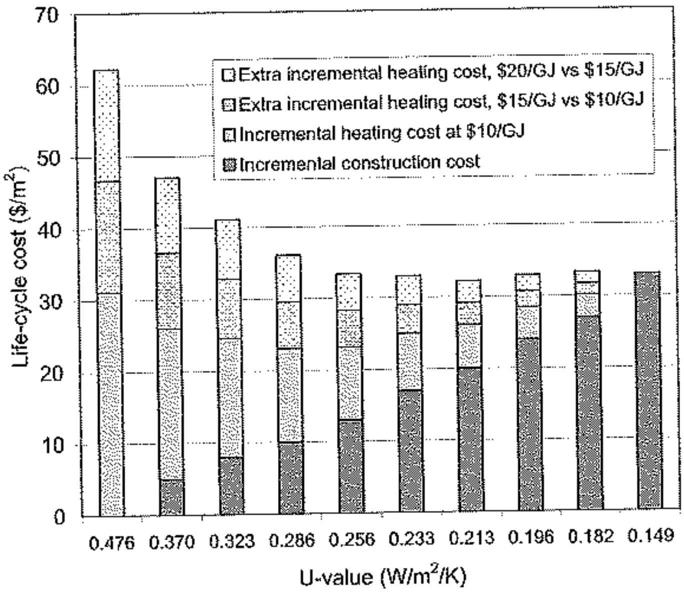


Figure 3.26: Comparison of incremental life-cycle costs of walls with increasing amounts of insulation. [TSU: source missing, geographical location/heat requirements not specified, US $ 2005 conversion?]

Differences in life-cycle costs are influenced by the length of time over which life-cycle costs are computed and by the rate of inflation in energy costs. A 30-year timeframe was chosen in Figure 3.24 [TSU: reference not correct] because mortgages in North America are typically of this duration. However, much longer mortgages are common in Europe, and in any case, the lifespan of the building should be closer to 100 years. Figure 3.27 compares the incremental life-cycle costs for different levels of insulation for 30- and 100-year life spans; the highest insulation level provides the lowest or close to the lowest life-cycle cost.

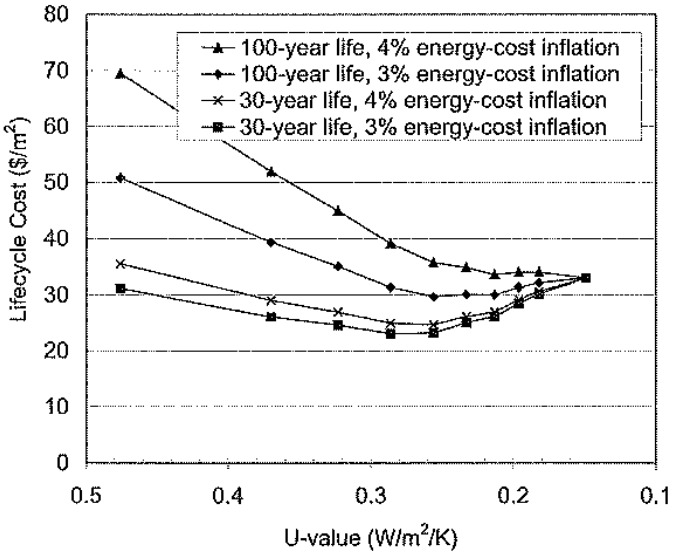


Figure 3.27: Comparison of incremental life-cycle costs of walls with increasing amounts of insulation for 30- and 100-year life spans. [TSU: source missing]

The main conclusion of these figures is that under the economic and other boundary conditions of the study, it is justified to require insulation levels substantially in excess of the level that is calculated to minimize life-cycle cost (Harvey, 2006).

The reduction in the cost of furnaces or boilers due to substantially better thermal envelopes is normally only a small fraction of the additional cost of the better thermal envelope. However, potentially larger cost savings can occur through downsizing or eliminating other components of the heating system, such as ducts to deliver warm air, or radiators. High-performance windows eliminate the need for perimeter heating. A very high-performance envelope can reduce the heating load to that which can be met by ventilation airflow alone. High-performance envelopes also lead to a reduction in peak cooling requirements, and hence, in cooling equipment sizing costs, and permit use of a variety of passive and low-energy cooling techniques.

If a fully integrated design takes advantage of all opportunities facilitated by a high-performance envelope, it is indeed possible for savings in the cost of mechanical systems to offset all or much of the additional cost of the high-performance envelope.

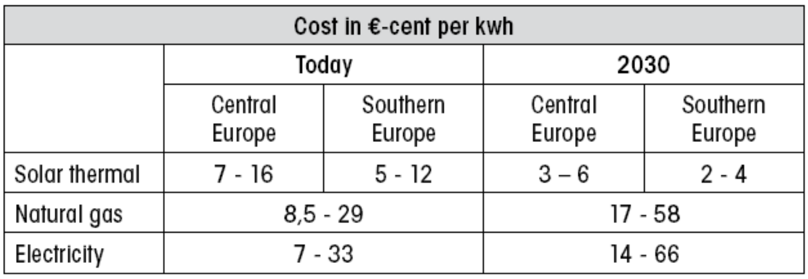
In considering daylighting, the economic benefit is enhanced by the fact that it reduces electricity demand the most when the sunlight is strongest. This is also when the daily peak in electricity demand tends to occur (Harvey, 2006). Several authors report measurements and simulations with annual electricity savings from 50% to 80%, depending on the hours and the location. Daylighting can lead to a reduction in cooling loads if solar heat gain is managed (Duffie and Beckman, 1991). This means that replacing artificial light with just the amount of natural light needed reduces internal heating. Savings in lighting plus cooling energy use of 22% to 86%, respectively, have been reported.

3.8.2 Active Solar Heating and Cooling

Solar processes are generally characterized by high first cost and low operating costs (Duffie and Beckman, 1991). Most solar energy processes require an auxiliary (i.e., conventional) energy source, so that the system includes both solar and conventional equipment and the annual loads are met by a combination of the energy sources.

Table 3.7 shows a range of prices for heat generated by a solar thermal system, compared to the current price of gas and electricity for the end user, and the price projected for 2030. Inflation is not considered according to the European Solar Thermal Technology Platform, "Solar Heating and Cooling for a Sustainable Energy Future in Europe."

Table 3.7: Cost per kWh for solar thermal, gas, and electricity - today and 2030. [TSU: source missing, reference year missing, table content and caption not clear], [TSU: convert to US $ 2005]



Cost in €-cent per kwh				
	Today		2030	
	Central Europe	Southern Europe	Central Europe	Southern Europe
Solar thermal	7 - 16	5 - 12	3 – 6	2 - 4
Natural gas	8,5 - 29		17 - 58	
Electricity	7 - 33		14 - 66	

The costs of solar heat include all taxes, installation, and maintenance. The range of costs is wide because the total costs vary greatly, depending on factors such as the following: quality of products and installation, ease of installation, available solar radiation (e.g., latitude, number of sunny hours, orientation and tilt of the collectors), ambient temperature, and use patterns determining the heat load.

By 2030, technological progress and economies of scale are assumed to lead to about a 60% reduction in costs (European Solar Thermal Industry Federation [ESTIF], 2009).

Although important cost reductions in solar thermal energy can be achieved through R&D and economies of scale, Table 3.7 shows why ESTTP's priority is to enable the large-scale use of solar thermal energy by developing a mass market of new applications, such as Active Solar Buildings, solar cooling, process heat, and desalination.

Over the last decade, for each 50% increase in installed capacity of solar water heaters, investment costs have fallen 20%. In particular, combination systems have benefited from these cost reductions and have increased their market share (European Solar Thermal Industry Federation [ESTIF], 2009). Further research, development, and demonstration (RD&D) investment can help to further drive down these costs. Cost reductions are expected to stem from the following: direct building integration (façade and roof) of collectors; improved manufacturing processes; and new advanced materials, such as polymers for collectors.

Furthermore, potential for cost reduction can be seen by the mass production of standardized (i.e., kit) systems, which reduce the need for on-site installation and maintenance work (Figure 3.28).

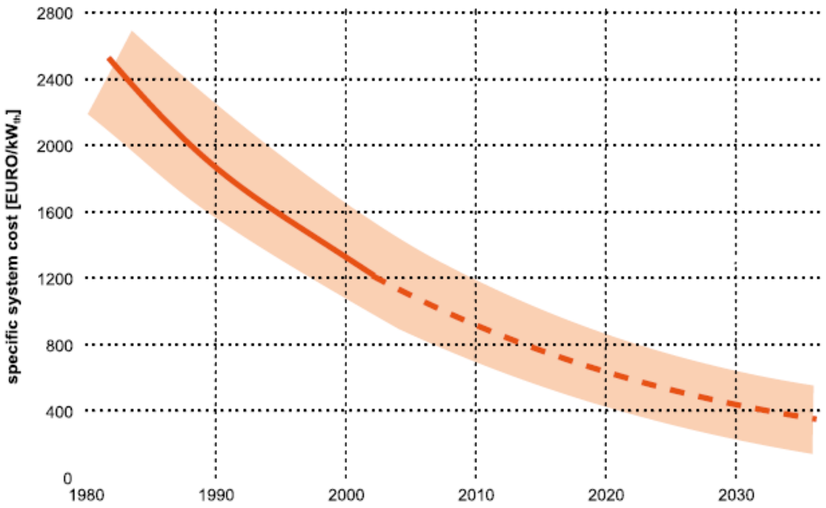


Figure 3.28: Costs of small solar thermal systems, past and projected to 2030 (Institut für Thermodynamik und Wärmetechnik (ITW), University of Stuttgart). [TSU: convert to US $ 2005, specify region]

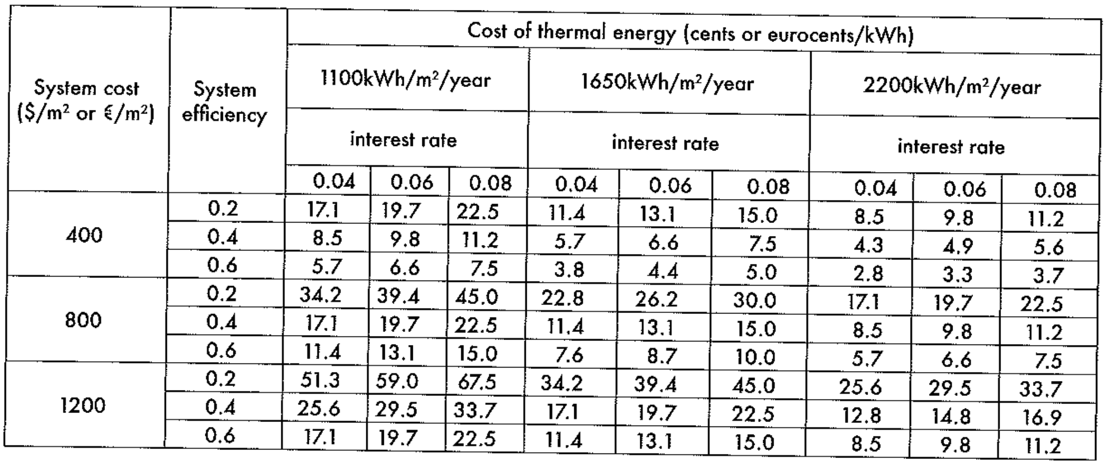
Advanced applications—such as solar cooling and air conditioning, industrial applications, and desalination/water treatment—are in the early stages of development, with only a few hundred first-generation systems in operation. Considerable cost reductions can be achieved if R&D efforts are increased over the next few years.

(Henning, 2004) indicates the following costs for solar collectors, support structures, and piping (excluding storage systems, heat exchangers, and pumps):

- Solar-air collectors, 200 to 400 €/m2
- Flat-plate or stationary compound parabolic collectors, 200 to 500 €/m2
- Evacuated-tube collectors, 450 to 1,200 €/m2

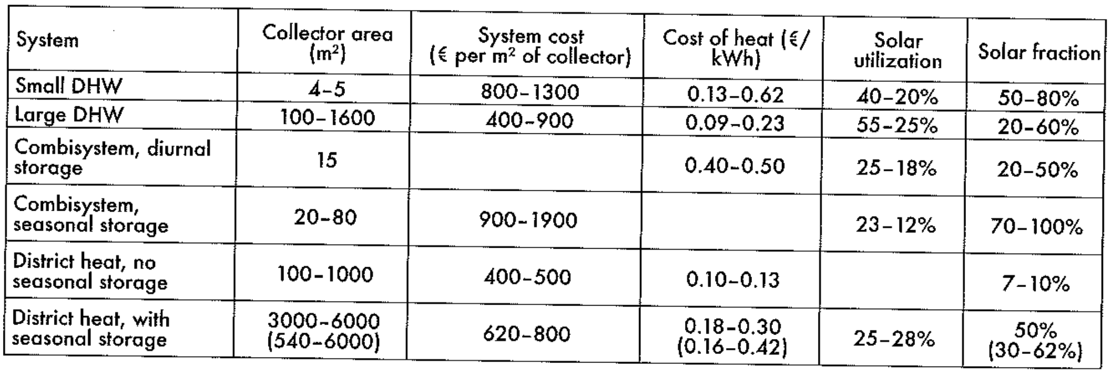
Table 3.8 gives illustrative costs of solar thermal energy, and Table 3.9 summarizes cost and performance data for a variety of solar thermal systems in Germany.

Table 3.8: Illustrative costs of solar thermal energy. [TSU: source missing]



System cost (\$/m^2 or €/m^2)	System efficiency	Cost of thermal energy (cents or eurocents/kWh)								
		1100kWh/m^2/year			1650kWh/m^2/year			2200kWh/m^2/year		
		interest rate			interest rate			interest rate		
		0.04	0.06	0.08	0.04	0.06	0.08	0.04	0.06	0.08
400	0.2	17.1	19.7	22.5	11.4	13.1	15.0	8.5	9.8	11.2
	0.4	8.5	9.8	11.2	5.7	6.6	7.5	4.3	4.9	5.6
	0.6	5.7	6.6	7.5	3.8	4.4	5.0	2.8	3.3	3.7
800	0.2	34.2	39.4	45.0	22.8	26.2	30.0	17.1	19.7	22.5
	0.4	17.1	19.7	22.5	11.4	13.1	15.0	8.5	9.8	11.2
	0.6	11.4	13.1	15.0	7.6	8.7	10.0	5.7	6.6	7.5
1200	0.2	51.3	59.0	67.5	34.2	39.4	45.0	25.6	29.5	33.7
	0.4	25.6	29.5	33.7	17.1	19.7	22.5	12.8	14.8	16.9
	0.6	17.1	19.7	22.5	11.4	13.1	15.0	8.5	9.8	11.2

Table 3.9: System costs, cost of heat, solar utilization, and solar fraction for solar thermal DHW or space heating systems in Germany. [TSU: source missing, reference year, convert to US $ 2005]



System	Collector area (m²)	System cost (€ per m² of collector)	Cost of heat (€/kWh)	Solar utilization	Solar fraction
Small DHW	4-5	800-1300	0.13-0.62	40-20%	50-80%
Large DHW	100-1600	400-900	0.09-0.23	55-25%	20-60%
Combisystem, diurnal storage	15		0.40-0.50	25-18%	20-50%
Combisystem, seasonal storage	20-80	900-1900		23-12%	70-100%
District heat, no seasonal storage	100-1000	400-500	0.10-0.13		7-10%
District heat, with seasonal storage	3000-6000 (540-6000)	620-800	0.18-0.30 (0.16-0.42)	25-28%	50% (30-62%)

Energy costs should fall with ongoing decreases in the costs of individual system components, and with better optimization and design. For example, (Furbo *et al.*, 2005) show that better design of solar domestic hot-water storage tanks when combined with an auxiliary energy source can improve the utilization of solar energy by 5% to 35%, thereby permitting a smaller collector area for the same solar yield.

With regard to complete solar domestic hot-water systems, the energy payback time requires accounting for any difference in the size of the hot-water storage tank compared to the non-solar system and the energy used to manufacture the tank (Harvey, 2006). It is reported that the energy payback time for a solar/gas system in southern Australia is 2 to 2.5 years, despite the embodied energy being 12 times that of a tankless system. For an integrated thermosyphon flat-plate solar collector and storage device operating in Palermo (Italy), a payback time of 1.3 to 4.0 years is reported.

3.8.3 PV Electricity Generation

PV prices decreased dramatically over the last 30 years—the average global PV module prices dropped from about 22 USD/W in 1980 to the current level of less than 4 USD/W. From 1990 to 2009, the average global price of PV modules used for power applications (modules > 75 W) dropped from 9.32 to less than 2 USD/W (2008 USD) (Liebreich, 2009). The PV module learning curve in Figure 3.29 indicates a progress ratio of 80%, and consequently, a learning rate (price experience factor) of 20%, which means that the price is reduced by 20% for each doubling of cumulative sales (Hoffmann, 2009; Hoffmann *et al.*, 2009). A compilation of other studies indicates that the learning rate for PV ranges between 11% and 26% (Maycock, 2002; Parente *et al.*, 2002; Neij, 2008; IEA, 2010b).

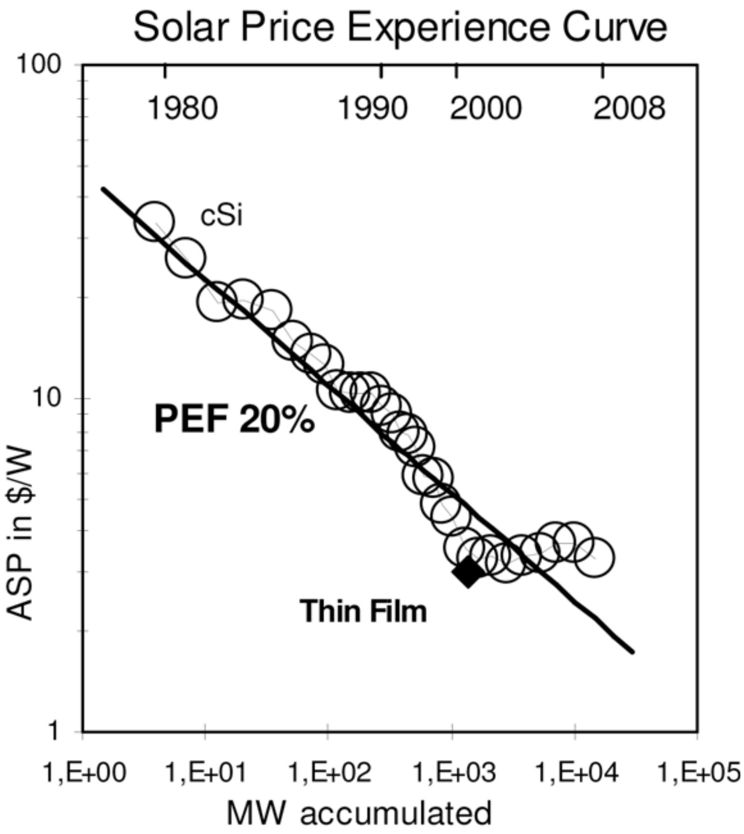


Figure 3.29: Solar price experience or learning curve for PV modules (Hoffmann *et al.*, 2009). [TSU: y-axis undefined (ASP), PEF undefined, convert to US $ 2005]

Figure 3.30 depicts the increase in production from 1990 through 2008, showing regional contributions. Even more dramatically, as module prices have decreased, production has increased and market penetration has increased.

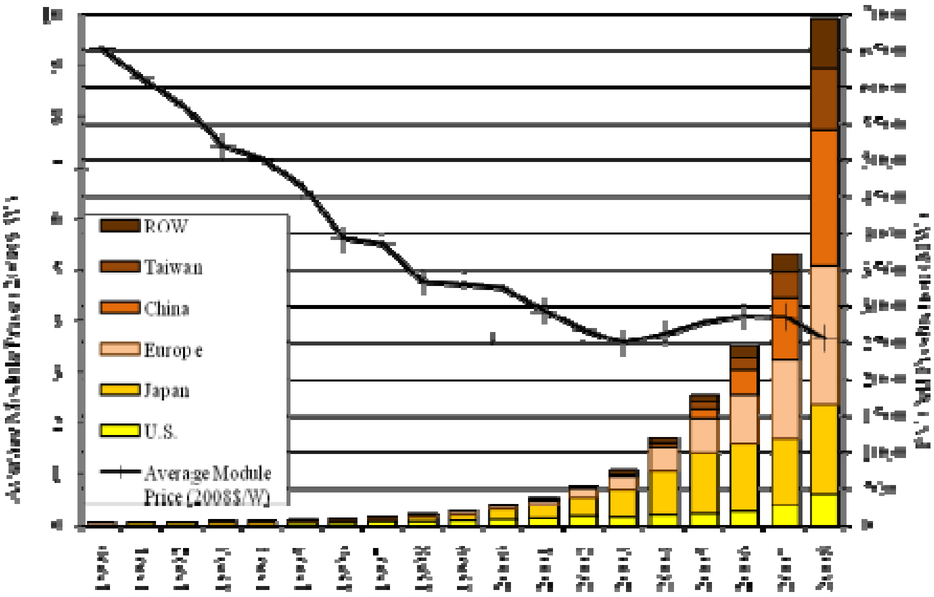


Figure 3.30: PV module prices have fallen as PV cell production has increased (Navigant Consulting Inc., 2008); (Maycock, 1993; Maycock, 2001b; Maycock, 2001a; Maycock, 2006; PV News, 2008; PV News, 2009; PV News, 2010) [TSU: convert to US $ 2005, axis label not readable, source not clear, rephrase caption]

PV module manufacturing costs are projected to continue to drop and are expected to be at or below 1.50 USD/W for all major technologies by 2015 (Table 3.10). Both thin-film and crystalline silicon technologies have numerous pathways for realizing continued technological innovation and cost reductions. In addition, third-generation technologies could come into the market in the longer term at even lower cost/price levels.

Table 3.10: Module manufacturing costs and price forecast per peak watt in 2008 US$ (Mehta and Bradford, 2009). [TSU: convert to US $ 2005, column definition not clear]

Technology	2008	2010	2012	2015
Crystalline Silicon				
Global vertically integrated multicrystalline silicon (mc-Si)	2.12 / 3.43	1.87 / 2.41	1.66 / 2.02	1.43 / 1.71
European mc-Si	2.74 / 3.43	2.17 / 2.41	1.81 / 2.02	1.54 / 1.71
Asian mc-Si	3.11 / 3.43	2.08 / 2.41	1.60 / 2.02	1.33 / 1.71
Supermono c-Si	2.24 / 3.83	1.89 / 2.89	1.65 / 2.47	1.41 / 2.03
Thin Films				
Amorphous silicon (a-Si)	1.80 / 3.00	1.45 / 1.79	1.21 / 1.47	1.02 / 1.33
Copper indium gallium diselenide (CIS/CIGS)	1.26 / 2.81	0.98 / 2.19	0.89 / 1.77	0.80 / 1.51
Cadmium telluride (CdTe)	1.25 / 2.51	1.13 / 2.10	1.00 / 1.72	0.89 / 1.48

The average installed cost of PV systems has also decreased significantly over the past couple of decades and is projected to continue decreasing rapidly as PV technology and markets mature. For example, Wiser et al. (2009) studied some 37,000 grid-connected, customer-sited PV projects in the United States, representing 363 MW of capacity. They found that the capacity-weighted average costs of PV systems installed in the USA declined from 10.5 USD/W in 1998 to 7.6 USD/W in 2007. This decline was primarily attributable to a drop in non-module (BOS) costs.

Figure 3.31 compares average installed costs in Japan (5.9 USD/W), Germany (6.6 USD/W), and the USA (7.9 USD/W) for residential PV systems completed in 2007. The lower costs in Japan and Germany can be attributed to their larger, more mature markets with lower non-R&D market barriers, including factors such as improved distribution channels, installation practices, interconnection, siting, and permitting.

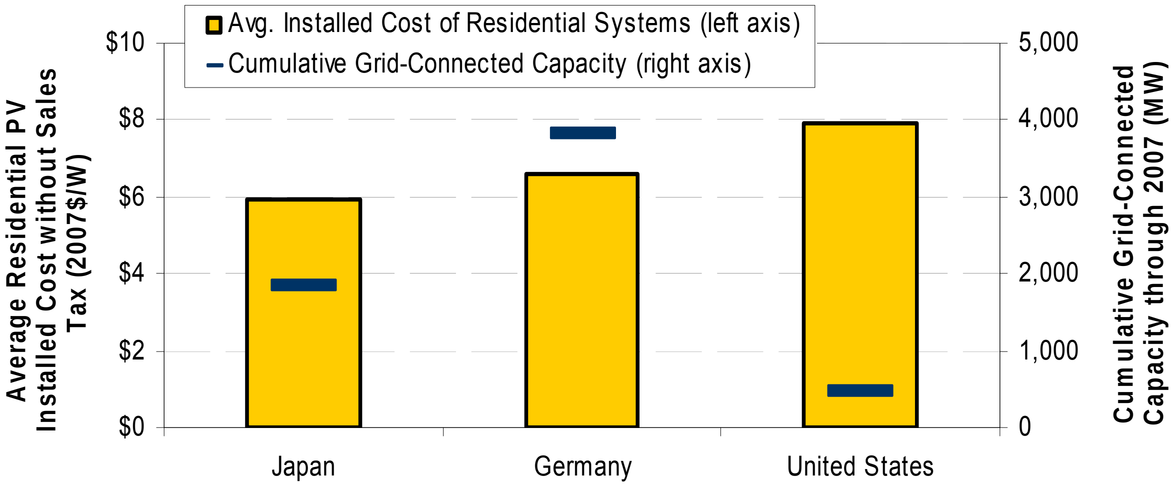


Figure 3.31: Average installed cost of residential PV systems completed in 2007, in Japan, Germany, and the USA (Wiser *et al.*, 2009) [TSU: convert to US $ 2005]

Since the second half of 2008, PV system prices have decreased considerably. This decrease is due to the increased competition between PV companies because of huge increases in production capacity and production overcapacities. The first-quarter 2010 average PV system price in Germany dropped to 2,864 €/kWp (2005 US $: 3,315 $/kWp) (Bundesverband Solarwirtschaft e.V., 2009). In 2009, thin-film projects were realized as low as 2.72 $/Wp (2005 US $; 3 $/Wp in 2009 $) (Liebreich, 2009). The resulting levelized cost of energy (LCOE) varied between 0.145 and 0.363 $/Wp (0.16 and 0.40 $/Wp in 2009 $).

Today, the cost of PV electricity generation in regions of high solar irradiance is already in the range of 17 to 20 €ct/kWh in Europe and the U.S. Until 2020, the cost is expected to be reduced more than 50% down to about 8 $ct/kWh (Breyer *et al.*, 2009) [TSU: convert to US $ 2005].

The goal of the U.S. Department of Energy (DOE) Solar Energy Technology Program expressed in its Technology Plan is to make PV-generated electricity cost-competitive with conventional energy sources in the USA by 2015. Specific energy cost targets for various market sectors are 0.08 to 0.10 USD/kWh for residential, 0.06 to 0.08 USD/kWh for commercial, and 0.05 to 0.07 USD/kWh for utilities.

Funding of PV R&D over the past decades has supported innovation and gains in PV cell quality, efficiencies, and price. Public budgets for R&D programs in the IEA Photovoltaic Power Systems Programme countries collectively reached about 330 million USD, with the USA, Germany, and Japan contributing 138, 61, and 39 million USD, respectively (IEA, 2008).

3.8.4 CSP Electricity Generation

Solar thermal electricity systems are a complex technology operating in a complex resource and financial environment, so many factors affect life-cycle cost calculations (Gordon, 2001). A study for the World Bank (World Bank Global Environment Facility Program, 2006) suggested four phases in cost reduction for CSP technology and that cost competitiveness with fossil fuel could be reached by 2025. [TSU: reference to Fig.3.32 missing]

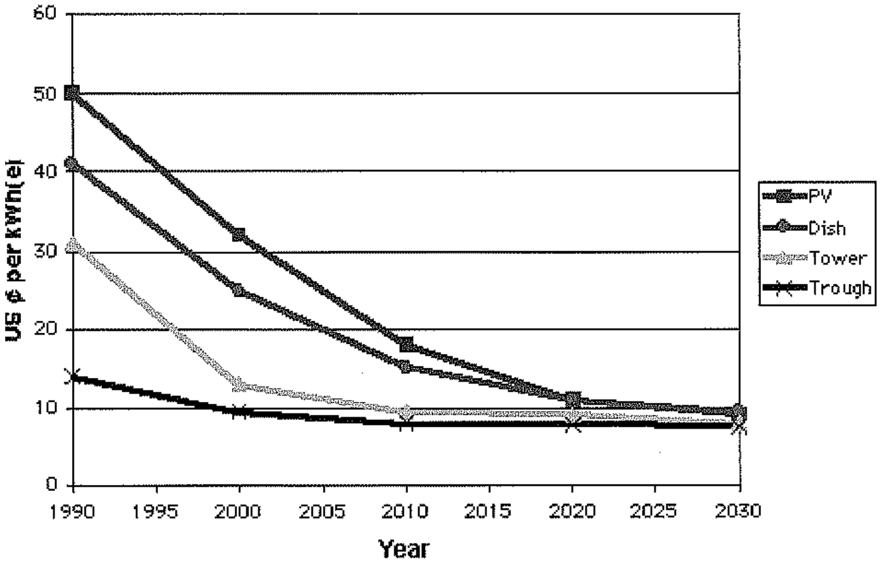


Figure 3.32: Energy cost (in U.S. cents per kWh) for PV and three CSP technologies from 1990 to 2030. [TSU: source missing]

The total investment for the nine stations making up the 354 MW_e of Solar Electric Generating Station plants in California (installed from 1985 to 1991) was 1.25 billion USD (nominal, not adjusted for inflation). For the nominal 64-MW_e Nevada Solar One plant installed in 2007, construction and associated costs amounted to 260 million USD.

The publicized capital costs of CSP plants are often confused when compared with other renewables, as varying levels of integrated thermal storage increase the capital cost, but also improve the annual output and capacity factor of the plant. The U.S. DOE CSP initiative that funds R&D projects with U.S. companies is focusing on thermal storage, concentrator component manufacturing, and advanced CSP systems and components (U.S. Department of Energy, 2008). The projects are aiming to reduce today's energy costs to 0.07 to 0.10 USD/kWh by 2015 and to less than 0.07 USD/kWh with 12 to 17 hours of storage by 2020. The European Union is pursuing similar goals through a comprehensive RD&D program.

The learning ratio for CSP, excluding the power block, is given as 10% ±5% by Neij (2008; IEA, 2010a). Other studies provide learning rates according to CSP components: Trieb et al. (2009) give 10% for solar field, 8% for storage, and 2% for power block, and NEEDS (2009) states 12% for solar field, 12% for storage, and 5% for power block.

3.8.5 Solar Fuels Production

Thermochemical cycles along with electrolysis of water are the most-promising processes for "clean" hydrogen production for the future. In a comparison study, both the hybrid-sulfur cycle and a metal-oxide-based cycle were operated by solar tower technology for multi-stage water-splitting (Graf *et al.*, 2008). The electricity required for the alkaline electrolysis was produced by a parabolic trough power plant. For each process, the investment, operating, and hydrogen production costs were calculated on a 50 MW_{th} scale. The study points out the economic potential of sustainable hydrogen production using solar energy and thermochemical cycles compared to commercial electrolysis. A sensitivity analysis was done for three different cost scenarios. Hydrogen production costs ranged from 3.9 to 5.6 €/kg for the hybrid-sulfur cycle, from 3.5 to 12.8 €/kg for the metal-oxide-based cycle, and 2.1 to 6.8 €/kg for alkaline electrolysis. [TSU: convert to US $ 2005] The weaknesses of these economic assessments are primarily related to the uncertainties in the viable efficiencies and investment costs of the various solar components due to their early stage of development and their economy of scale (Steinfeld and Meier, 2004).

A substitute natural gas can be produced by the combination of solar hydrogen and CO_2 in a thermochemical synthesis at cost ranges from 8 to 10 €cent/kWh$_{th}$ with renewable power costs of 2 to 4 €ct/kWh$_{el}$ (Sterner, 2009). [TSU: convert to US $ 2005] These costs are highly dependent on the operation mode of the plant and can be reduced by improving efficiency and reducing electricity costs.

3.9 Potential Deployment

The potential of direct solar energy is often underestimated. The reason is because 1) direct solar covers a wide range of technologies and applications, and 2) most scenarios only look into common indicators such as the share of primary energy, electricity, heat, or transport fuel from renewable energy sources. These indicators do not consider that a number of applications of direct solar energy may contribute only small numbers to these indicators, but that the value provided—and, consequently, the reason why people use them—is much higher. In addition, Martinot et al. (2007) explain that the different scenario targets use different accounting methods, which lead to quite different outcomes.

One example is the difference between the International Energy Agency (IEA) method and the British Petroleum (BP) method used for their Statistical Review of World Energy to account for primary energy (British Petroleum, 2008). This difference is discussed in Chap.1, as well as in a box in Chap. 10.

The issue is how one accounts for distributed stand-alone generation of solar electricity and low-temperature solar heat. In addition, storage is never considered in these studies. These indicators are rarely used in scenarios, but they are becoming more important as these applications grow in use. As pointed out in section 3.4, the IEA's Solar Heating & Cooling Programme, together with the European Solar Thermal Industry Federation and other major solar thermal trade associations, has decided to publish statistics in kW$_{th}$ (kilowatt thermal) and has agreed to use a factor of 0.7 kW$_{th}$/m^2 to convert square meters of collector area into kW$_{th}$. However, an unresolved issue is what statistical number to use for the primary energy part of heat—either the total produced or the actual used.

This section presents the near-term and long-term forecasts for solar energy deployment. Then we comment on the prospects and barriers to solar energy deployment in the longer-term scenarios, and the role of the deployment of solar energy in meeting different GHG mitigation targets. This discussion is based on energy-market forecasts and carbon and energy scenarios published in recent literature.

3.9.1 Near-Term Forecasts

Currently, the main market drivers are the various national support programs for solar-powered electricity systems or low-temperature solar heat installations. These programs either support the installation of the systems or the generated electricity. The scenarios for the potential deployment of the technology depend strongly on public support to develop markets, which can then drive down costs along the learning curves. It is important to remember that learning curves depend on actual production volume, not on time.

The markets for the different solar technologies vary significantly between the technologies. But they also vary regionally for the same technology. This fact leads to very different thresholds and barriers for becoming competitive with existing technologies.

Table 3.11 shows scenarios developed for solar capacities. It should be highlighted that passive solar gains are not included in these statistics, because this technology reduces the demand and is not part of the supply chain considered by the energy statistics. The same PV technology can be applied for stand-alone, mini-grid, or hybrid systems in remote areas without grid connection, as well as for distributed and centralized grid-connected systems. The deployment of CSP technology is limited by regional availability of good-quality direct-normal irradiance of 2,000 kWh/m^2 or more in Earth's "Sun Belt."

Table 3.11: Evolution of cumulative solar capacities (IEA, 2008; Teske, 2008) [TSU: source missing for row 7-8 (Shell)]

Name of Scenario and Year	Low temperature solar [GWh]		Solar PV electrical [GW]		CSP capacities [GW]	
	2000	2010	2000	2010	2000	2010
Greenpeace (reference scenario 2008)	---	112[1]	1.00	10	0.35	2
Greenpeace ([r]evolution scenario 2008)	---	300	1.00	21	0.35	5
Greenpeace (advanced scenario 2008)	---	---	---	21	0.35	5
IEA Reference Scenario (2008)	---	---	1.00	10	0.35	---
IEA ACT Map (2008)	---	---	1.00	22	0.35	---
IEA Blue Map (2008)	---	---	1.00	27	0.35	---
Shell (Scramble)	---	---	---	---	---	---
Shell (Blueprints)	0	163	---	---	---	---

[1] Calculated from heat supply in PJ/a and 850 full-load hours annually.

3.9.2 Long-Term Deployment in the Context of Carbon Mitigation

The IPCC Fourth Assessment Report estimated the available solar energy resource as 1,600 EJ/year for PV and as 50 EJ/year for CSP (however, this estimate was given as very uncertain, with sources reporting values with orders of magnitude higher) (IPCC, 2007).

On the other hand, the potential deployment of direct solar in the IPCC Fourth Assessment Report gives a potential contribution of direct solar to the world electricity supply by 2030 of 633 TWh (2.3 EJ), which is 7% of the world electricity supply (IPCC, 2007).

Chapter 10 provides a summary of the literature on the possible contribution of renewable energy supplies in meeting global energy needs under a range of CO_2 stabilization scenarios. Figure 3.33 shows the global solar energy contribution to global supply in carbon stabilization scenarios from a review of literature in primary energy units (EJ). Figure 3.34 shows the same data for PV and

Figure 3.35 as a proportion of the total electricity supply. Finally, Figure 3.36 presents these data for CSP.

The reference-case projections of solar energy role in the electricity global energy supply have a very wide range. Nevertheless, the average is 1 EJ in 2020, 5 EJ in 2030, and around 40 EJ in 2050. Both PV and CSP show spectacular growth after 2030, when it is expected that the technologies are mature enough to reach the market. The contribution of PV is similar to that of CSP in 2020 and 2030, but the projections of 2050 show a larger contribution for CSP (about 65%).

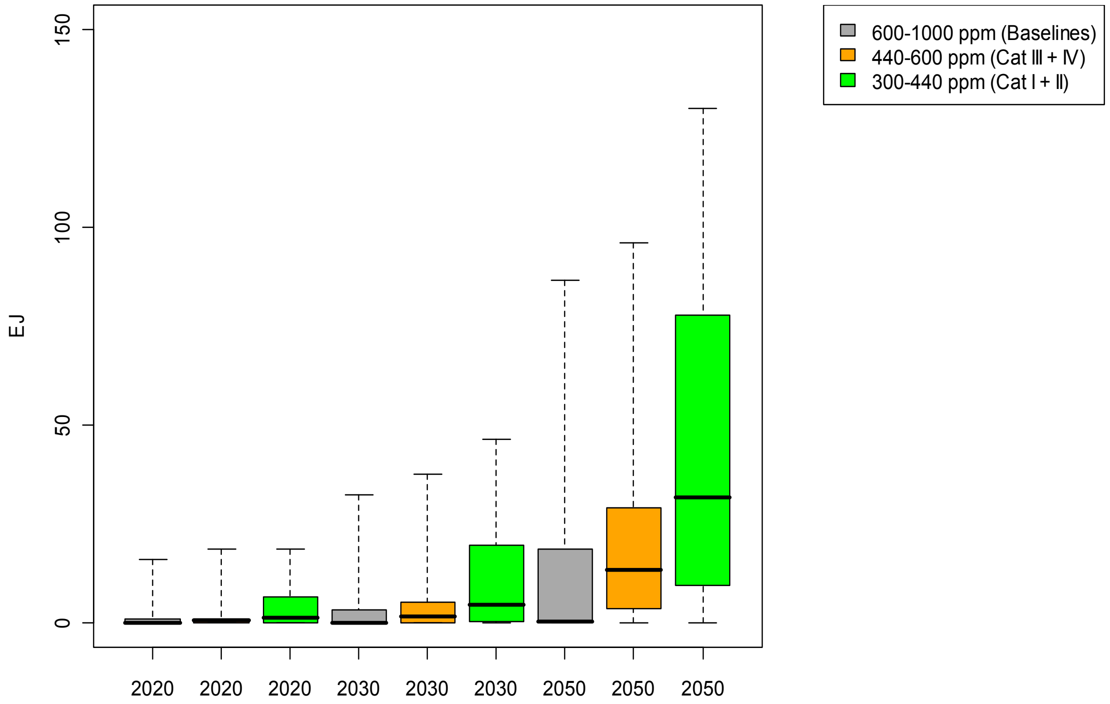


Figure 3.33: Global supply of solar energy in carbon stabilization scenarios. [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

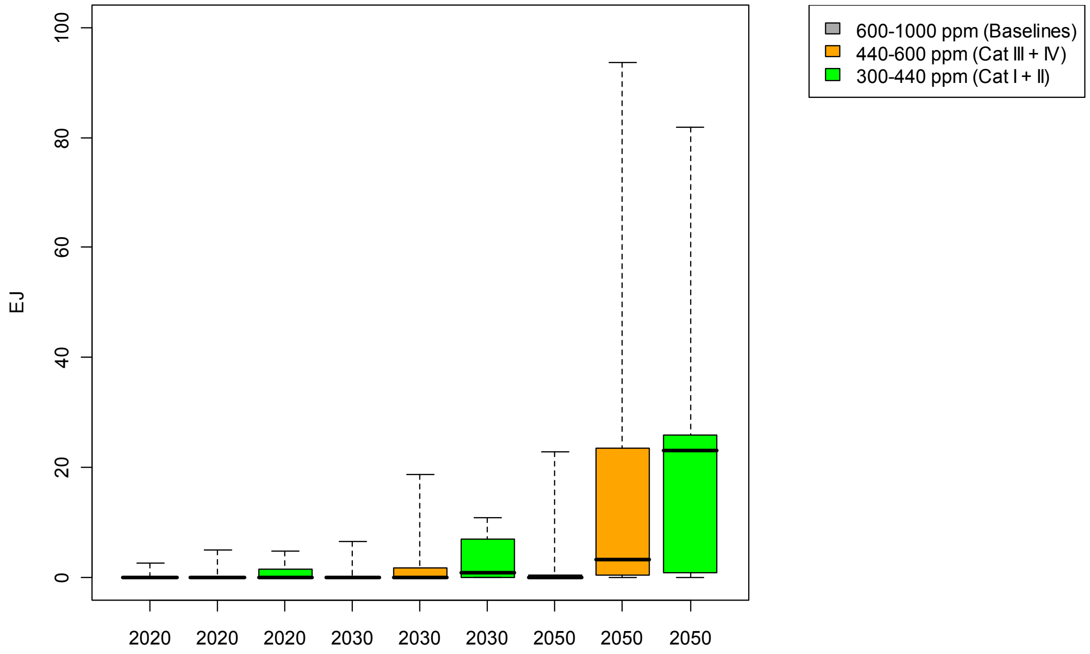


Figure 3.34: Global supply of solar PV energy in carbon stabilization scenarios [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

There is a huge difference in the potential contribution of solar energy in the global electricity supply when different stabilization ranges are considered. When the carbon limits are decreased, the solar contribution grows spectacularly. In fact, Figure 3.34 shows that the contribution of solar PV would be extremely low in the 600–1000 ppm-CO_2 stabilization scenario.

The growth is shown in 2050, when the solar PV median contribution is around 20 EJ (~10% of global electricity supply) in the 440–600 and 300–440 ppm-CO_2 stabilization ranges, while only 2 EJ (~0% of global electricity supply) in the 600–1000 ppm-CO_2 stabilization range. The contribution of solar PV found in 2020 and 2030 is very low in all scenarios, always lower than 7 EJ.

We emphasize the huge variation among the studies used in Figure 3.34. These variations are probably due to the different approaches used to generate these scenarios, but also to the difficulties encountered by the modelling tools used in these studies to address the technical and economic viability of solar energy. This variation is especially large in the solar PV contribution in 2050 for the 440–600 ppm-CO_2 stabilization scenario, which ranges from 7 to 70 EJ, depending on the study considered. In the most-stringent 300–440 ppm-CO_2 stabilization scenario, the solar PV supply in 2050 varies from 10 to 23 EJ, which is equivalent to 5% to 18% of global electricity supply.

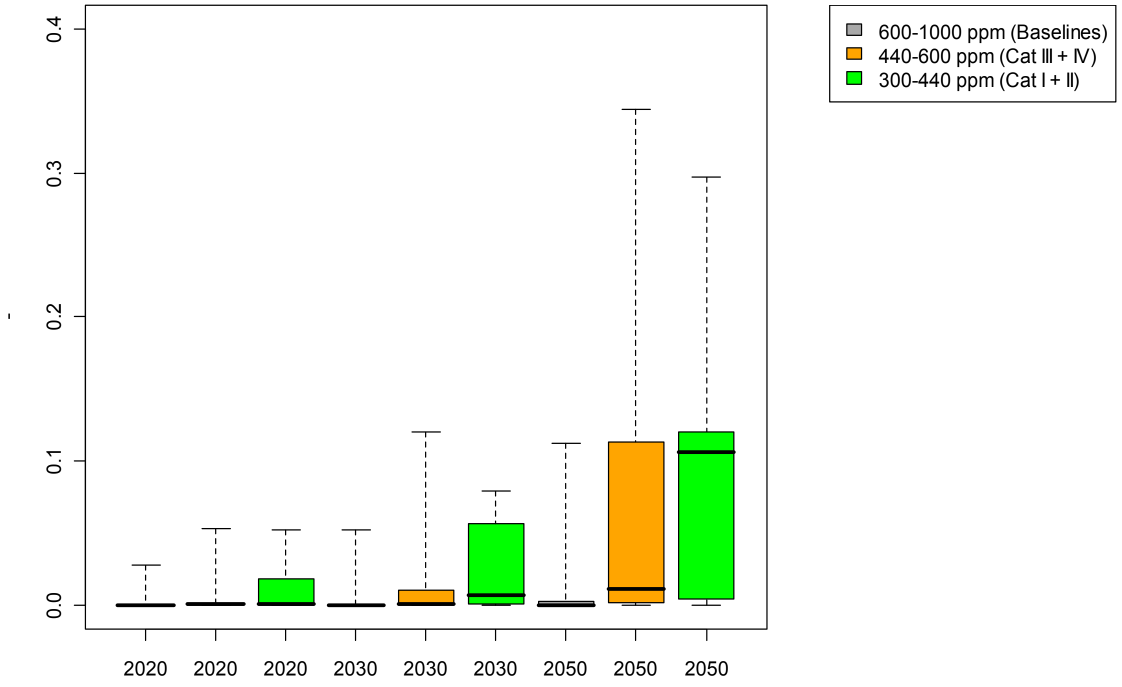


Figure 3.35: Solar PV electricity share in total global electricity supply. [TSU: Title on y-axis missing], [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

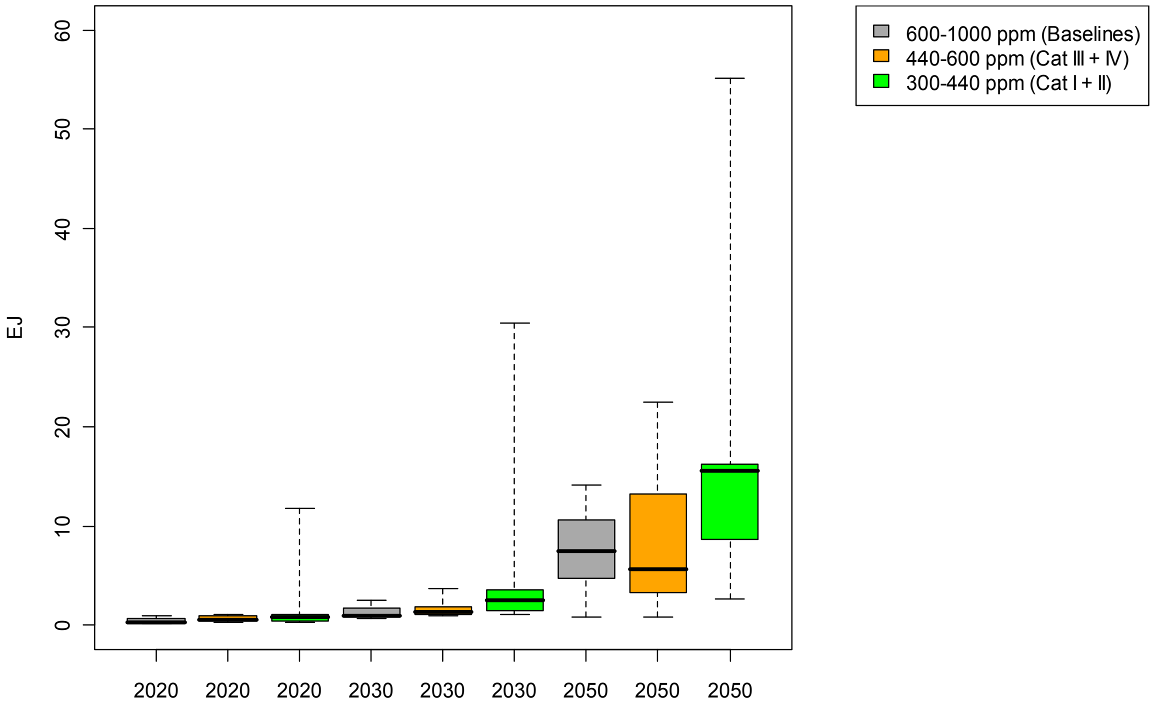


Figure 3.36: Global supply of solar thermal energy (CSP) in carbon stabilization scenarios[TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

When considering the potential contribution of thermal solar energy (CSP) in the global electricity supply with different stabilization ranges, the growth with time seems to have a better slope, already showing a contribution in 2030. Again, when the carbon limits considered are decreased, the solar contribution grows. In 2050, the median results of the different scenarios show a low contribution if the 600–1000 ppm-CO_2 stabilization scenario is considered, but the contribution is already around 20 EJ with the 440–600 ppm-CO_2 stabilization, and 35 EJ with the most-stringent scenario.

Once more, the variation among the studies included in Figure 3.36 is very important. For example, in the most-stringent scenario in 2050, the contribution of solar thermal to the global supply of electricity ranges from 18 to 55 EJ.

To achieve these levels of solar deployment, economic incentive policies to reduce carbon emissions and/or increase renewable energy will probably be necessary, and those incentives will need to be of adequate economic attractiveness and stability to motivate substantial private investment (see Chapter 11). Below, we describe a variety of possible challenges to the aggressive growth of solar energy [TSU: following paragraph does not correspond to this notification].

Resource Potential. The solar resource is inexhaustible, and it is available and able to be used in all countries and regions of the world.

The technical potential varies over the different regions of the Earth. The worldwide technical potential of solar energy is considerably larger than the current primary energy consumption (Nakićenović *et al.*, 1998). The economic potential for applying solar energy depends on a variety of factors such as theoretical availability of solar energy in a particular region, environmental constraints, resource availability, conversion efficiency of the available technology, competition with alternative energy sources, national and local supports policies for renewable power generation, coverage and structure of the electricity grid, capability of the power system to deal with power output intermittency, and energy consumption demand and patterns in various sectors of the economy and social life. The range of technologies using solar energy is wide and the respective markets have quite different growth rates, ranging between 10% and 50% per year.

Regional Deployment. Industry-driven scenarios with regional visions for up to 100% of renewable energy supply by 2050 are developed in various parts of the world.

The Semiconductor Equipment and Materials International Association (SEMI) developed PV roadmaps for China and India that go far beyond the targets of the national governments (Semiconductor Equipment and Materials International, 2009b; Semiconductor Equipment and Materials International, 2009a). These targets are about 20 GW by 2020 and 100 GW by 2050 for electricity generation in China and 20 GW and 200 GW in India (both PV and CSP) (Indian Ministry of New and Renewable Energy, 2010; Zhang *et al.*, 2010).

In Europe, the European Renewable Energy Council developed a 100% Renewable Energy vision based on the inputs of the various European industrial industry associations (Zervos *et al.*, 2010). 2010]. Assumptions for 2020 on final electricity, heat and cooling, as well as transport demand are based on the European Commission´s New Energy Policy (NEP) scenario with both a moderate and high price environment as outlined in the Second Strategic Energy Review (European Commission, 2008). The scenarios for 2030 and 2050 assume a massive improvement in energy efficiency to realise the 100% renewable energy goals. For Europe, this scenario assumes that solar thermal can contribute about 557 TWh and 1415 TWh heating and cooling in 2030 and 2050, respectively. For electricity generation, about 556 TWh from PV and 141 TWh from CSP are anticipated for 2030 and 1347 TWh and 385 TWh for 2050, respectively.

In Japan, the New Energy Development Organisation (NEDO), the Ministry for Economy, Trade and Industry (METI), the Photovoltaic Power Generation Technology Research Association (PVTEC), and Japan Photovoltaic Energy Association (JPEA) drafted the “PV Roadmap Towards 2030” in 2004 (Kurokawa and Aratani, 2004). In 2009, the roadmap was revised; the target year was extended from 2030 to 2050, and a goal was set to cover between 5% and 10% of domestic primary energy demand with PV power generation in 2050. The targets for electricity from PV systems range between 35 TWh for the reference scenario and 89 TWh for the advanced scenario in 2050 (Komiyama *et al.*, 2009).

In the USA, the industry associations—Solar Electric Power Association (SEPA) and Solar Energy Industry Association (SEIA)—are working together with the U.S. Department of Energy (DOE) and other stakeholders to develop scenarios for electricity from solar resources (PV and CSP) of 10% and 20% in 2030. The results of the Solar Vision Study are expected in the middle of 2010.

Supply Chain Issues. Passive solar is a purely local market because the building market is a local market. Globalizing the knowledge on passive solar technologies would increase its market penetration. Low-temperature solar thermal is implemented all over the world with local markets, local suppliers, and local industries, but a global market is starting to be developed. PV is a global industry with a global supply chain; some industries have more industry policies, but others not so much. CSP is starting to develop a global supply chain; currently, the market is driven by Spain and USA, but other countries such as India are helping to expand the market.

Technology and Economics. Passive solar has a well-established technology with room for improvement; however, the awareness of the building sector is not always available. The economics are understood, but they depend on local solar resources and local support and building regulations. Low-temperature solar thermal is a well-established technology ranging from lower to higher technological solutions with further room of improvement; the economics depends on solar resource and range of applications and local economy—some regions may need support programs to create markets and be competitive, but in other regions it is already competitive.

PV is already an established technology, but further development is under way; economics have a similar pattern, but depend on the local solar resource. Economics of PV technology depends on support programs; currently, there is a tendency that higher support and less competition leads to higher end-market prices. The CSP technology is developed, but still at an early stage of commercialisation; there is little competition yet, but it is growing rapidly. The economics are similar to those of PV.

Integration and Transmission. This is not an issue for passive solar applications. The integration issues in low-temperature solar are only important for large systems where integration to local district heating systems is needed. Due to the availability of the resource only during the day, improved transmission and storage systems are needed for a high penetration of PV systems. Integration and transmission issues for CSP are exactly the same as for any other power plant.

Social and Environmental Concerns. Direct solar energy has few social and environmental concerns. Rather, the main benefit of passive solar is in reducing energy demand of buildings. Similar to low-temperature solar, it has the benefit of reducing the energy demand for water heating and room heating.

The main concern of the PV technology is the availability of material. Water availability and consumption is the main environmental concern for CSP. However, this technology has the benefit of using dessert areas, of increasing environmental benefits of technologies such as desalination, and of producing dispatchable renewable electricity.

3.9.3 Concluding Remarks on Potential Deployment

Potential deployment scenarios range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of energy supply. Although it is true that direct solar energy provides only a very small fraction of the world energy supply, it is undisputed that this energy source has the largest potential and a promising future.

Reducing cost is a key issue in making direct solar energy more cost competitive. This can only be achieved if the solar technologies reduce their costs along their learning curves, which depend primarily on market volumes. In addition, continuous R&D efforts are required to ensure that the slope of the learning curves do not flatten too early.

The true costs of implementing solar energy are still unknown because the main implementation scenarios that exist today consider only a single technology. These scenarios do not take into account the co-benefits of a renewable/sustainable energy supply via a range of different renewable energy sources and energy-efficiency measures.

Potential deployment depends on the actual resources and availability of the respective technology. However, to a large extent, the regulatory and legal framework in place can foster or hinder the uptake of direct solar energy applications. Minimum building standards with respect to building orientation and insulation can reduce the energy demand of buildings significantly and can increase the share of renewable energy supply without increasing the overall demand. Transparent, streamlined administrative procedures to install and connect solar power source to existing grid infrastructures can further lower the cost related to direct solar energy.

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Chapter 4

Geothermal Energy

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Author(s):	CLAs:	Barry A. Goldstein, Gerardo Hiriart			
	LAs:	Ruggero Bertani, Christopher J. Bromley, Luis C.A. Gutiérrez-Negrín, Ernst Huenges, Hirofumi H.M. Muraoka, Arni Ragnarsson, Jefferson W. Tester, Vladimir I. Zui			
	CAs:	David Blackwell, Trevor N. Demayo, John W. Lund, Mike Mongillo, David Newell, Ladislaus Rybach, Subir Sanyal, Kenneth H. Williamson, Doone Wyborne [AUTHORS: to be finally completed].			
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Chapter 4: Geothermal Energy

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EXECUTIVE SUMMARY

Geothermal resources correspond to the accessible thermal energy stored in the Earth's interior, and are used to generate electric energy in a thermal power plant, or in other domestic and agro-industrial applications requiring heat. **Near-term (by 2015)** geothermal-electric **deployment** is estimated to be 121.6 TWh/y (0.44 EJ/y), and 250.4 TWh(thermal)/y (0.9 EJ/y) for heat applications. Forecast **long-term deployment (by 2050)** is 1266 TWh/y (4.56 EJ/y) for electricity and 2184 TWh(thermal)/y (7.86 EJ/y) for heat, representing 2.5%-4.1% of global electricity demand and 4.9% of global heat demand, with some countries obtaining most of their primary energy needs (heating, cooling and electricity) from geothermal energy. Global **technical potentials** are estimated to be between 91 EJ/y (to 3 km depth) and 1043 EJ/y (to 10 km depth) for electricity and between 10 EJ/y (minimum) and 322 EJ/y (maximum) for heat.

Geothermal heat is extracted using wells that produce hot fluids contained in hydrothermal reservoirs with naturally high permeability or by artificial fluids pathways in Enhanced (Engineered) Geothermal Systems (EGS). **Technology for electric generation from hydrothermal geothermal resources is mature, sustainable and reliable** since approximately 40% of the installed capacity has been operating for more than 25 years. Direct heating technologies using Geothermal Heat Pumps (GHP), district heating and EGS methods are available, with different degrees of maturity.

High availability is a comparative advantage of geothermal energy use. **Geothermal resources are currently used for base-load electric generation** in 24 countries with an installed capacity of 11 GW and a global average capacity factor of 71%, with newer installations above 90%, providing 10% to 30% of their electricity demand in six countries. Geothermal resources are also used directly for heating and cooling in 78 countries, accounting for 50 GW of thermal capacity with GHP applications having the widest market penetration.

Geothermal is a renewable resource as the extracted heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by injection of the depleted (cooled) fluids. **If managed properly, geothermal systems can be sustainable for the long term.** Direct CO_2 emissions average 120 g/kWh$_e$ for currently operating conventional flash and direct steam power plants and less than 1 g/kWh$_e$ for binary cycle plants with total injection. Corresponding figures for direct use applications are even lower. It should be emphasized that this emission is from natural CO_2 releases into the atmosphere, not created by any combustion process, since the exploitation of geothermal energy does not create any additional CO_2 production to the environment. Over its full life-cycle, the CO_2-equivalent emissions range from 23-80 g/kWh$_e$ for binary plants and 14-202 g/kWh$_t$ for district heating systems and GHP. **This means geothermal resources are environmentally advantageous and the net energy supplied more than offsets the environmental impacts of human, energy and material inputs.**

Like other RE, geothermal-electric projects have relatively high up-front capital costs, varying currently between 1800 and 5300 US$ (2005) per kilowatt, but with no recurring "fuel costs". **The levelised costs of electricity (LCOE) from conventional hydrothermal resources are competitive in today's electricity markets, ranging from 43 to 84 US$ (2005) per megawatt-hour (MWh).** LCOE projections for EGS electricity fall within a much wider range because of uncertainties regarding resource parameters (particularly sustainable flow-rate and heat recovery factor), and assumptions regarding future drilling costs. **Costs are expected to decrease – by about 15% for hydrothermal and by 50% for EGS by 2050**, assuming success in developing stimulation technology. Current costs of direct uses are generally competitive ranging from an average of <100 (pond heating) to 3900 (for building heating) US$ (2005) per installed thermal kilowatt and correspondingly low levelised costs for energy as they avoid inherent heat to power efficiency limitations.

Despite the present competitiveness of conventional geothermal energy for electric and non-electric applications, most operating systems today are utilizing the highest grade resources available. **Public and private support for research along with favourable deployment policies would assist the expanded utilisation of conventional geothermal resources and demonstration and commercialisation of EGS and other non-conventional geothermal resources.** This policy support could include subsidies, loan guarantees and tax write-offs to cover the risks of initial deep drilling and long term productivity. Feed-in tariffs with confirmed geothermal prices, and direct subsidies for district and building heating would also help to accelerate deployment.

Geothermal heat sources will not be impacted by climate change. Geothermal energy utilization is nearly climate neutral, and its many other positive environmental attributes enable it to operate in an environmentally sustainable manner. With its natural thermal storage capacity, geothermal is especially suitable for supplying dispatching base-load power. Thus **geothermal could function in a portfolio approach to increase the effectiveness of intermittent RE sources such as hydro, wind and solar, resulting in a much larger net impact for mitigating climate change.**

Although there are clear challenges to realizing the massive potential of geothermal energy, they are surmountable within 20 years with modest investments for research, development, and early deployment of advanced technologies. **Geothermal energy is uniquely positioned to play a key role in climate change mitigation strategies.**

4.1 Introduction

Geothermal resources consist of thermal energy stored at depth within the earth in both rock and trapped steam or liquid water. Geothermal systems occur in a number of geological environments where the temperatures and depths of the reservoirs vary accordingly. Many high-temperature (>180°C) hydrothermal systems are associated with recent volcanic activity and are found near plate tectonic boundaries (subduction, rifting, spreading or transform faulting), or at crustal and mantle hot spot anomalies. Intermediate (100-180°C) and low temperature (<100°C) systems are also found in continental settings, formed by above-normal heat production through radioactive isotope decay; they include aquifers charged by water heated through circulation along deeply penetrating fault zones. However, there are several notable exceptions, and under appropriate conditions, high, intermediate and low temperature geothermal fields can be utilised for both power generation and the direct use of heat.

Geothermal systems can be classified as convective, which includes liquid- and vapour-dominated hydrothermal as well as lower temperature aquifers, or conductive**,** which includes hot rock and magma over a wide range of temperatures. Lower temperature aquifers contain deeply circulating fluids in porous media or fracture zones, but lack a localized heat source. They are further sub-divided into systems at hydrostatic pressure and systems at pressure much higher than hydrostatic (geo-pressured). Resource utilisation technologies can be grouped under types for electrical power generation or for direct use of the heat. Geothermal Heat Pumps (GHP) are a subset of direct use, and Enhanced or Engineered Geothermal Systems (EGS), where fluid pathways are engineered by fracturing the rock, are a subset under both utilisation types. Currently, the most widely exploited geothermal systems for power generation are hydrothermal (of continental subtype). Table 4.1 summarizes all of these types.

Table 4.1 Type of geothermal resources, temperatures and uses.

Type	Natural fluids	Subtype	Temperature Range	Utilisation	
				Current	Potential
Convective (Hydrothermal)	Yes	Continental	H, I & L	Power, direct uses	
		Submarine	H	None	Power
Conductive	No	Shallow (<400 m)	L	Direct uses (GHP)	
		Hot rock (EGS)	H, I	Direct	Power, direct
		Magma bodies	H	None	Power, direct
Lower temperature Aquifers	Yes	Hydrostatic aquifers	I & L	Direct	Power, direct
		Geo-pressured		Direct	Power, direct

Temperature: H: High (>180°C), I: Intermediate (100-180°C), L: Low (ambient to 100°C). EGS: Enhanced (or Engineered) Geothermal Systems. Direct uses include GHP (Geothermal Heat Pumps).

In areas of magmatic intrusions, temperatures above 1000°C can occur at less than 10 km depth. Magma typically ex-solve mineralised fluids and gases, which then mix with deeply circulating groundwater. Heat energy is also transferred by conduction but in magmatic systems, convection is also important. Typically, a hydrothermal convective system is established whereby local surface heat-flow (through hot springs and steam vents) is significantly enhanced. Such shallow systems can last hundreds of thousands of years, and the gradually cooling magmatic heat sources can be replenished periodically with fresh intrusions from a deeper magma chamber. Finally, geothermal fields with temperatures as low as 5-10°C are also used for direct applications using heat pumps.

Subsurface temperatures increase with depth according to the local geothermal gradient, and if hot rocks within drillable depth can be stimulated to improve permeability, using hydraulic fracturing, chemical or thermal stimulation methods, they form a potential EGS resource that can be used for power generation and/or direct applications. EGS resources occur in all geothermal environments, but are likely to be economic in the medium term in geological settings where the heat flow is high enough to permit exploitation at depths of less than 5 km. Experiments have investigated the potential of such continental EGS settings in large areas of Europe, North America, Asia and Australia. In the longer term, and given the average geothermal gradients (25-30°C/km), EGS resources at relatively high temperature (≥180°C) may be exploitable in geological settings at depths up to 7 km, which is well within the range of existing drilling technology (~10 km depth). Geothermal resources of different types may occur at different depths. For example, fractured and water-saturated hot-rock EGS resources lie below hot sedimentary aquifer resources in the Australian Cooper Basin (Goldstein et al., 2009). These EGS resources include Hot Dry Rock (HDR), Hot Fractured Rock (HFR), Hot Wet Rock (HWR), among other terms.

Direct uses of geothermal energy have been practised at least since the Middle Palaeolithic when hot springs were used for ritual or routine bathing (Cataldi, 1999), and industrial utilisation began in Italy by exploiting boric acid from the geothermal zone of Larderello, where in 1904 the first kilowatts of electric energy were generated and in 1913 the first 250-kWe commercial geothermal power unit was installed (Burgassi, 1999).

For the last 100 years, geothermal energy has provided safe, reliable, environmentally benign energy used in a sustainable manner to generate electric power and provide direct heating services on both large and small scales. Approximately 40% of the present-day installed electricity capacity has been in operation for more than 25 years, demonstrating technical maturity and reliability. Geothermal typically provides base-load generation, but it can be dispatched and used for meeting peak demand. Today, geothermal represents a viable energy resource in many industrial and developing countries using a mature technology to access and extract naturally heated steam or hot water from natural hydrothermal reservoirs, and it has the potential to make a more significant contribution on a global scale through the development of advanced technology such as EGS that would enable energy recovery from a much larger fraction of the accessible stored thermal energy in the earth’s crust. In addition, GHP that can be utilized anywhere in the world for heating and cooling, have had significant growth in the past 10 years, and are expected to provide a significantly greater contribution to global energy savings in the future (Lund et al., 2003, 2010).

Today’s hydrothermal technologies have demonstrated very high average capacity factors (up to 90% in some plants) in electric generation with low carbon emissions. The capacity factor (CF) is the ratio of the actual generation of electricity (averaged across a year) to the installed electrical capacity, and is expressed as a percentage. Environmental and social impacts do exist with respect to land and water use and seismic risk, but these are site and technology specific and largely manageable. New opportunities exist to develop geothermal beyond power generation, particularly to use geothermal heat for district and process heating, along with GHP for space heating and cooling.

This chapter includes a brief description of the worldwide potential of geothermal resources (4.2), the current technology and applications (4.3) and the expected technological developments (4.6), the present market status (4.4) and its probable future evolution (4.8), the geothermal environmental and social impacts (4.5) and the cost trends (4.7) in using geothermal energy to contribute to reduce greenhouse gas (GHG) emissions and then mitigate climate change. As presented in this chapter, climate change has no major impacts on geothermal energy, but the widespread development of geothermal energy could considerably reduce the future emission of carbon dioxide into the atmosphere, and play a significant role in reducing anthropogenic effects on climate change by replacing fossil fuel burning plants.

4.2 Resource Potential

4.2.1 Global technical resource potential

The IPCC Fourth Assessment Report (AR4) estimated an available energy resource for geothermal (including potential reserves) of 5000 EJ/y (Sims et al., 2007; see Table 4.2).

The total thermal energy contained in the Earth is of the order of 12.6 x 10^{12} EJ and that of the crust the order of 5.4 x 10^{9} EJ to depths of up to 50 km (Dickson and Fanelli, 2003). The main sources of this energy are due to the heat flow from the earth's core and mantle, and that generated by the continuous decay of radioactive isotopes in the crust itself. Heat is transferred from the interior towards the surface, mostly by conduction, at an average of 0.065 W/m^2 on continents and 0.101 W/m^2 through the ocean floor. The result is a global terrestrial heat flow rate of around 1400 EJ/y. Considering that continents cover ~30% of the earth's surface and their lower average heat flow, the terrestrial heat flow under continents can be estimated at 315 EJ/y (Stefansson, 2005).

Under continents, the stored thermal energy within 10 km depth (reachable with current drilling technology) has been estimated between 400 x 10^6 EJ (EPRI, 1978) and 105 x 10^6 EJ (Tester et al., 2005, see Table 11.1), within 5 km depth between 140 x 10^6 EJ (WEC, 1994) and 65 x 10^6 EJ and at 3 km depth between 43 x 10^6 EJ (EPRI, 1978) and 35 x 10^6 EJ (Table 4.2). For the Australian continent alone, Budd et al. (2008) estimated that recovery of just 1% of the stored geothermal energy above 150°C to 5 km in the Australian continental crust corresponds to 190,000 EJ. Based on these estimates, available resource is clearly not a limiting factor for geothermal deployment globally.

Estimates of stored geothermal energy can be regarded as theoretical geothermal potentials, e.g. the physical upper limit of the energy available from a certain source, in this case geothermal. Technical potential however, includes practical limits to development, and is defined as the amount of RE output obtainable by full implementation of demonstrated and likely to develop technologies or practices, with no explicit reference to costs, barriers or policies.

Table 4.2 Global theoretical and technical geothermal potential (for electricity).

Depth (km)	Theoretical Potential (thermal)		Technical Potential (electric) (EJ/y)			
	10^6 EJ	Reference	Identified resources	Reference	Hidden resources	Total
10	400	EPRI, 1978	5.7	Stefansson, 2005	1036.9	1042.6
10	105	Tester et al., 2005			267.8	273.5
5	140	WEC, 1994			359.2	364.9
5	65	--			163.6	169.3
3	43	EPRI, 1978			106.4	112.1
3	35	--			85.1	90.8

Recovery of geothermal energy utilises only a portion of the stored thermal energy due to limitations in rock permeability that permit heat extraction through fluid circulation, and to the minimum temperature limits for utilisation at a given site. To calculate an effective technical potential it is also necessary to exclude the heat which cannot be accessed at drillable depths or is insufficiently hot for practical use. Global utilisation has so far concentrated on areas in which geological conditions, such as natural fractures and porous formations, permit water or steam to transfer heat nearer to the surface, thus giving rise to convecting hydrothermal resources where drilling to depths up to 4 km can access fluids at temperatures of 180°C to more than 350°C.

For electric generation, Stefansson (2005) calculated the world geothermal potential for identified hydrothermal resources at 200 GWe (equivalent to 5.7 EJ/y with a capacity factor of 90%) with a lower limit of 50 GWe (1.4 EJ/y). Assuming the unidentified, hidden resources are 5-10 times higher than the identified ones, based on correlations in the US and other countries, he estimated the upper limit for the worldwide geothermal technical potential between 1000 and 2000 GWe (28.3 and 56.8 EJ/y with the same 90% capacity factor). Largely based on those estimations, Krewitt et al. (2009) made their estimations for geothermal technical potentials, particularly for 2050 at 45 EJ/y.

However, a more recent estimation for unidentified geothermal resources indicates that within the US alone the stored geothermal energy to 10 km depth is 13.6 x 10^6 EJ in conduction-dominated EGS of crystalline basement and sedimentary rock formations (Tester et al., 2006, see Table 1.1). Assuming that 2% of the heat is recoverable and taking into account all the aspects for conversion of the recoverable heat into electricity (thermal efficiencies, temperature drops, ambient temperatures, cooling cycles and others), and for conversion of the electric energy to electric power assuming a lifespan of 30 years, it is possible to obtain 1249 GWe (Tester et al., 2006, see Table 3.3). With this electric installed capacity, 35.4 EJ/y of electric energy can be produced with the same capacity factor of 90%, and for the US represents a geothermal technical potential additional to the identified hydrothermal resources in this country.

Making similar assumptions for the world and keeping the same relationship between theoretical (stored heat) and electric technical potentials (1 EJ theoretical ~ 2.61 x 10^6 EJ/y of technical potential at 90% capacity factor for 30 years), it is possible to obtain different worldwide technical potentials for hidden geothermal resources at different depths, as presented in Table 4.2. Based on this assessment, the total worldwide geothermal technical potential for electricity varies from a minimum of about 91 EJ/y (down to 3 km depth) to a maximum of 1043 EJ/y (down to 10 km depth) (Fig. 4.1). While these estimates are lower than the earlier projection of 5000 EJ/y in the AR4 (Sims et al., 2007) they still correspond to a large and well distributed global technical potential for geothermal. The minimum value down to 10 km depth (274 EJ/y) is less than the assessed continental heat-flow (315 EJ/y, Stefansson, 2005), implying that this global rate of extraction although calculated for a 30 year project lifespan, would actually be sustainable long term by natural heat recharge.

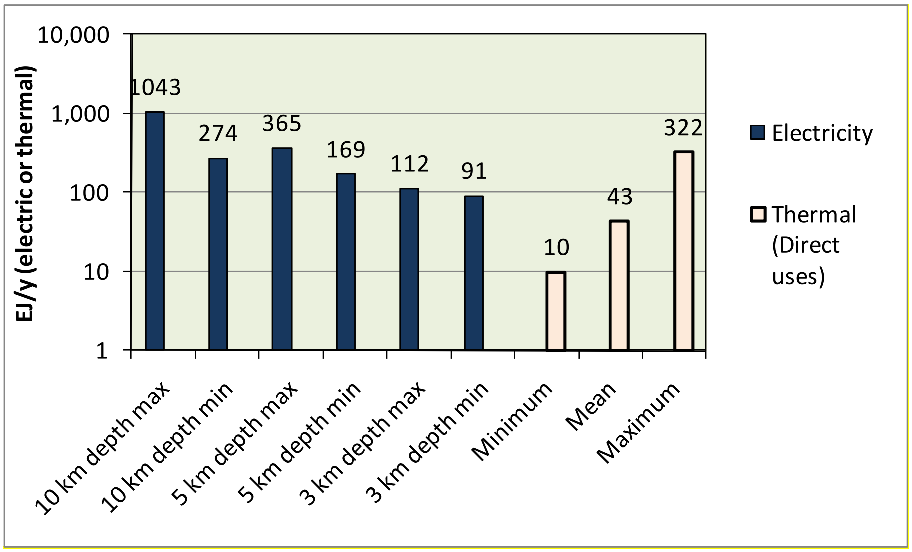

Figure 4.1 Geothermal technical potentials for electricity and direct uses (heat) (Prepared with data from Table 4.2 and 4.3)

Hidden or unidentified resources are mostly composed of low to mid grade conduction dominated environments. Estimating the technical potential of EGS recovery methods is uncertain because of the limited commercial experience to-date. Wide spread development is more likely to occur if commercial-scale demonstration plants successfully establish sustainable operation within the next decade. In particular, it is important to achieve sufficient reservoir heat exchange surface and volume, inter-well connectivity and production flow rates, with acceptable water consumption and pressure drops. Assuming successful resolution of these issues, EGS will become a leading technology for providing thermal energy and electricity globally because of its widespread accessibility.

For hydrothermal submarine vents, an estimation of >100 GWe (>2.8 EJ/y) offshore technical potential has been made (Hiriart et al., 2010). This is based on the 3900 km of ocean ridges confirmed as having hydrothermal vents, with the assumption that only 1% could be developed for electricity production using a recovery factor of 4%. This assumption is based on capturing part of the heat from the flowing submarine vent without any drilling. If offshore drilling becomes technically and economically feasible a technical potential of 1000 GWe (28 EJ/y) from hydrothermal vents may be possible.

For geothermal direct uses, Stefansson (2005) estimated 4400 GW_{th} for the world potential geothermal from resources <130°C, with a minimum of 1000 GW_{th} and a maximum, considering hidden resources, of 22,000-44,000 GW_{th}. Taking a worldwide average capacity factor for direct uses of 31%, the geothermal technical potential for heat can be estimated to be 43 EJ/y with a lower value of 9.8 EJ/y and an upper value of 322 EJ/y (equivalent to 33,000 GW_{th} of installed capacity) (Fig. 4.1). Krewitt et al. (2009) used the same values estimated by Stefansson (2005) in GW_{th}, but a capacity factor of 100% was assumed when converted into EJ/y, and then the average upper limit of 33,000 GW_{th} was converted into 1040 EJ/y.

4.2.2 Regional resource potential

The assessed geothermal technical potentials included in Table 4.2 and Fig. 4.1 are presented on a regional basis in Table 4.3.

Table 4.3 Geothermal technical potentials for the IEA regions (prepared with data from EPRI, 1978, and global technical potentials described in section 4.2.1).

IEA REGION	Technical potential in EJ/y (electric) at depths to:						Technical potential in EJ/y (heat for direct uses)		
	3 km		5 km		10 km				
	Min	Max	Min	Max	Min	Max	Min	Mean	Max
1. OECD North America	18.7	23.1	37.0	79.7	58.1	221.7	2.1	9.3	69.5
2. Latin America	10.4	12.8	21.3	45.9	32.9	125.5	1.2	5.5	40.9
3. OECD Europe	4.7	5.8	8.4	18.1	13.8	52.7	0.8	3.6	26.8
4. Africa	14.5	17.9	25.5	55.0	42.4	161.7	1.4	6.1	45.8
5. Transition Economies	17.2	21.2	29.5	63.6	49.6	189.1	1.5	6.8	51.1
6. Middle East	3.2	4.0	5.7	12.2	9.4	36.0	0.3	1.4	10.2
7. Developing Asia	7.3	9.1	14.6	31.5	22.9	87.2	0.8	3.7	27.6
8. India	2.4	3.0	4.0	8.7	6.9	26.1	0.2	1.0	7.2
9. China	6.4	7.9	12.9	27.7	20.1	76.6	0.7	3.3	24.5
10. OECD Pacific	5.9	7.3	10.4	22.4	17.3	65.9	0.6	2.5	19.0
Total	**90.8**	**112.1**	**169.3**	**364.9**	**273.5**	**1042.6**	**9.8**	**43.0**	**322.6**

The regional assessment of theoretical potential reported in Table 4.2 was conducted by the Electric Power Research Institute in 1978 (EPRI, 1978), based on a detailed estimation of the thermal energy stored inside the first 3 km under the continents accounting for regional variations in the average geothermal gradient and the presence of either a diffuse geothermal anomaly or a high enthalpy region, associated with volcanism or plate boundaries. The values in Table 4.3 followed the EPRI approach for each region and applied to the minimum and maximum technical potentials mentioned before at 3, 5 and 10 km depth. The separation into electric and thermal (direct uses) potentials is somewhat arbitrary in that most higher temperature resources could be used for either or both in combined heat and power applications depending on local market conditions.

4.2.3 Possible impact of climate change on resource potential

Geothermal energy is a renewable resource, but has unique sustainability characteristics. As thermal energy is extracted from the active reservoir, it creates locally cooler regions. Geothermal projects are typically operated at production rates that cause local declines in pressure and/or in temperature over the economic lifetime of the installed facilities. These cooler and lower pressure zones in the reservoir lead to gradients that result in continuous recharge by conduction from hotter rock, and convection and advection of fluid from surrounding regions. The time scales for thermal and pressure recovery are similar to those required for energy removal (Stefansson, 2000; Rybach and Mongillo, 2006). Detailed modelling studies (Pritchett, 1998; O'Sullivan and Mannington, 2005) have shown that this type of resource exploitation can be economically feasible, and still be renewable on a timescale useful to society, when non-productive recovery periods are considered.

Therefore, with proper well placement and reservoir management strategies, geothermal energy can be sustainably developed. In hydrothermal reservoirs sustainable production can be achieved by adjusting production rates and injection strategies, taking into account the local resource characteristics (field size, natural recharge rate, etc.).

Time scales for naturally recharging depleted geothermal reservoirs following the cessation of production have been determined using numerical model simulations for: 1) heat extraction by geothermal heat pumps, 2) the use of doublet (two wells) systems on a hydrothermal aquifer for space heating, 3) the generation of electricity from a high enthalpy hydrothermal or EGS reservoir (for details see Rybach and Mongillo, 2006; Axelsson et al., 2005; O'Sullivan and Mannington, 2005; Bromley et al., 2006). Models predict that replenishment will occur on time scales of the same order as the lifetime of the geothermal production cycle (Axelsson et al., 2005; Axelsson et al., 2010).

Geothermal resources are not dependent on climate conditions and climate change is not expected to have a significant impact on the geothermal resource potential. The operation of heat-pumps is not affected in any significant way by a gradual change in ambient temperature associated with climate change. On a local basis, the effect of climate-change on rainfall distribution may have a long-term effect on the recharge to specific groundwater aquifers, which in turn may affect discharges from some hot springs, and could have an effect on water levels in shallow geothermally-heated aquifers. Also a change in availability of cooling water from surface water supplies could be affected by changes in rainfall patterns, and this may affect the efficiency of cooling for power plant condensers. However, each of these effects, if they occur, can easily be remedied by simple adjustments to the technology.

4.3 Technology and applications (electricity, heating, cooling)

4.3.1 Geothermal energy utilisation

Geothermal energy is extracted from reservoir fluids by discharging various mixtures of hot water and steam through production wells. In high temperature reservoirs, as pressure drops, the water component boils or “flashes”. Separated steam is piped to a turbine to generate electricity and the remaining hot water may be flashed again two or three times at progressively lower pressures (and temperatures) to obtain more steam. The remaining brine is usually sent back to the reservoir through injection wells or first cascaded to a direct-use system before injecting. Few reservoirs produce “dry” steam, which can be sent directly to the turbine. In these cases, control of steam flow to meet power demand fluctuations is easier than in the case of two-phase production, where continuous upflow in the well-bore is required to avoid gravity collapse of the water phase. Intermediate temperature reservoirs are utilised by extracting heat from produced hot water through a heat exchanger generating power in a binary cycle or in heating and injecting the cooled water back into the reservoir.

Geothermal technologies belong to Category 1 (technologically mature with established markets in at least several countries). Key technologies for exploration and drilling, reservoir management and stimulation and energy recovery and conversion are described below.

4.3.2 Exploration and drilling

Since geothermal resources are underground, exploration methods (including geological, geochemical and geophysical surveys) have been developed to locate and assess them and these methods can be improved. The objectives of geothermal exploration are to identify and rank prospective geothermal reservoirs prior to drilling, and to provide methods of characterising reservoirs that enable estimations of geothermal reservoir performance and lifetime. Exploration of a prospective geothermal reservoir involves estimating its lateral extent and depth with geophysical methods and drilling exploration wells, minimising the risk.

Today, geothermal wells are drilled over a range of depths down to 5 km using conventional drilling methods similar to those used for oil and gas. Advances in drilling technology enable high temperature operation and provide directional capability. Typically, wells are deviated from vertical to about 30-50° inclination from a “kick off point” at depths between 200 m and 2000 m. Many wells can be drilled from the same pad, heading in different directions to access large resource volumes, target permeable structures and minimise the surface impact. Current geothermal drilling methods are presented in more detail in chapter 6 of Tester et al. (2006). In addition, for other geothermal applications such as GHP and direct uses, smaller and more flexible rigs have been developed to overcome accessibility limitations in built-up areas.

4.3.3 Reservoir engineering

The modern method of estimating reserves and sizing power plants is to apply reservoir simulation technology. Since it is not possible to gather all the data required to construct a comprehensive deterministic model, a conceptual model is built, using available data, then translated into a numerical representation, and calibrated to the unexploited, initial thermodynamic state of the reservoir. Future behaviour is forecast under selected load conditions using a heat and mass transfer algorithm (for example, Pruess, 2009), and optimum plant size selected.

Injection management is an important aspect of geothermal development. Cooling of production zones by injected water that has had insufficient contact with hot reservoir rock can result in severe production declines. Placement of wells should also aim to enhance deep hot recharge through production pressure drawdown, but suppress shallow inflows of peripheral cool water through injection pressure increase.

Given sufficient, accurate calibration with field measurements (surface and subsurface), geothermal reservoir evolution can be modelled and pro-actively managed. Hence, it is prudent to monitor and analyse the chemical and thermodynamic properties of geothermal fluids, along with mapping their flow and movement. This information combined with other geophysical data are fed back to re-calibrate models for better predictions (Grant et al., 1982).

4.3.4 Power plants

For electricity generation, dry steam, flash and binary plants are in use today. In all cases heat transfer and rejection are major considerations in the existing designs. Geothermal flash plants, the most common configuration, consist of pipelines, water-steam separators, vaporisers, de-misters, and different types of turbines. Steam turbines are driven by convective flow to a low pressure exhaust or a vacuum. In a condensing turbine (Figure 4.2, left), vacuum conditions are usually maintained by direct contact condenser.

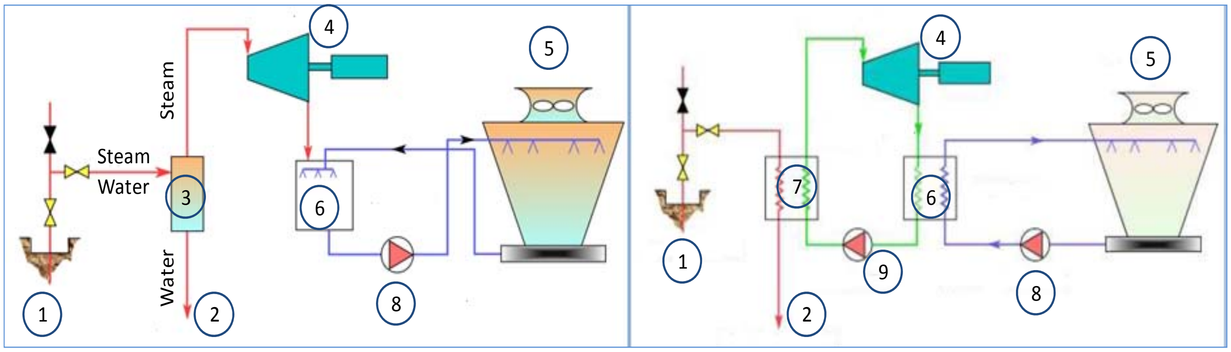

Figure numbers: 1: Production well, 2: Injection well, 3: Separator, 4: Turbo-generator, 5: Cooling tower, 6: Condenser, 7: Heat exchanger, 8: Water pump, 9: Feed pump.

Figure 4.2 Schematic diagram of a geothermal condensing steam power plant (left) and a binary-cycle power plant (right) (Adapted from Fridleifsson et al., 2008).

The unit sizes commonly range from 20-110 MWe (DiPippo, 2008). Design optimisation requires knowledge of reservoir behaviour. Double or triple flash cycles make use of excess brine separated at high pressure. A “triple flash” steam turbine can have three different inlets, operating at pressures and temperatures as low as 1.4 bar_a and 110°C. Dry steam plants do not need separators as geothermal fluids are steam (as in The Geysers, USA, Larderello, Italy, Matsukawa, Japan, and some Indonesian fields), and then their design is simpler. Back-pressure turbines are steam turbines that exhaust to the atmosphere, omitting the condenser and the cooling tower, and are frequently used as small plants to start the development of new fields. The efficiency is only about 50-60% of condensing turbines, but the cost is less. About 15 back-pressure units of 5 MWe have been successfully operating in Mexico since the 1980s (Hiriart and Gutiérrez-Negrín, 1994).

Binary cycle plants of Organic Rankine Cycle (ORC) type (Figure 4.2, right) utilise lower temperature geothermal fluids (ranging from about 70 to 170°C) than conventional flash and dry steam plants (from about 150°C to over 300°C). They are more complex since the geothermal fluid (water, steam or both) passes a heat exchanger heating another “working” fluid such as isopentane or isobutane with a low boiling point, which vaporizes and drives a turbine. The working fluid can then be air-cooled or condensed with water. Binary plants are often constructed as linked modular units of a few MWe in capacity or as bottoming cycle with flash steam plants.

Combined or hybrid plants comprise two or more of the above basic types to improve versatility, increase overall thermal efficiency, improve load-following capability, and efficiently would cover a wide (90-260°C) resource temperature range.

Cogeneration (Co-gen) plants, or Combined or Cascaded Heat and Power plants (CHP), produce both electricity and hot water for district heating or direct use at significantly higher utilisation efficiency than can be achieved for just generating electricity or supplying heat. Relatively small industries and communities of a few thousand people provide sufficient markets for combined heat and power applications. Iceland has two geothermal cogeneration plants with a combined capacity of 300 MWt in operation; the distance of the plants to the towns ranges from 12 to 25 km, over which cooling losses using large insulated pipes and high flow-rates, are negligible. At the Oregon Institute of Technology (OIT) with 3000 students, faculty and staff a CHP provides most of the electricity needs and all the heat demand (Lund and Boyd, 2009). Combined heat and power using low temperature geothermal resources have also been developed in Germany and Austria.

4.3.5 Technologies needed for EGS development

The principle of Enhanced Geothermal Systems (EGS) is as follows: in the subsurface where temperatures are high enough for effective utilisation, a fracture network is created or enlarged to act as fluid pathways. Water is passed through this deep reservoir using injection and production wells, and heat is extracted from the circulating water at the surface. The extracted heat can be used for power generation and for district heating.

EGS projects are currently at a demonstration and experimental stage. The key technical and economic challenges for EGS over the next two decades will be to achieve and maintain efficient and reliable stimulation of multiple reservoirs with sufficient volumes to sustain long term production at acceptable rates, with low flow impedance, limited short-circuiting fractures, and manageable water loss (Tester et al., 2006), and managing seismic risks.

Conforming research priorities for EGS and magmatic resources as determined in Australia (DRET, 2008), USA, the EU (ENGINE, 2008) and the International Partnership for Geothermal Technologies (IPGT, 2008) are summarised in Table 4.4. Successful deployment of the associated services and equipment is also relevant to many conventional geothermal projects.

Table 4.4 Priorities for advanced geothermal research (HTHF: high temperature & high flow-rate).

Complementary research & share knowledge	Education / training
Standard geothermal resource & reserve definitions	Improved HTHF hard rock drill equipment
Predictive reservoir performance modelling	Improved HTHF multiple zone isolation
Predictive stress field characterisation	Reliable HTHF slim-hole submersible pumps
Mitigate induced seismicity / subsidence	Improve resilience of casings to HTHF corrosion
Condensers for high ambient-surface temperatures	Optimum HTHF fracture stimulation methods
Use of CO_2 as a working fluid for heat exchangers	HTHF logging tools and monitoring sensors
Improve power plant design	HTHF flow survey tools
Technologies & methods to minimise water use	HTHF fluid flow tracers
Predict heat flow and reservoirs ahead of the bit	Mitigation of formation damage, scale and corrosion

4.3.6 Technology for submarine geothermal generation

Offshore, there are some 67,000 km of mid-ocean ridges, of which 13,000 km have been studied, and more than 280 sites with submarine geothermal vents have been discovered (Hiriart et al., 2010). Some discharge thermal energy of up to 60 MWt (Lupton, 1995) but there are others, such as ‘Rainbow’, with an estimated output of 1-5 GWt (German et al., 1996). The abundance of submarine hydrothermal systems indicates that technology for their future exploitation should be investigated further, providing such projects become economically feasible.

In theory, electric energy could be produced directly from a hydrothermal vent (without drilling) using an encapsulated plant, like a submarine, containing an ORC binary plant, as described by

Hiriart and Espíndola (2005). The operation would be similar to other binary cycle power plants using evaporator and condenser heat exchangers, with internal efficiency of the order of 80% (Hiriart et al., 2010). Overall efficiency for a submarine vent at 250°C of 4% (electrical power generated / thermal power) is a reasonable estimate for such an installation (Hernández, 2008). Other critical challenges for these resources include the distance from shore, water depth, grid-connection costs and the potential impact on unique marine life around hydrothermal vents.

Adaptation of off-shore drilling technology to tap into off-shore hydrothermal resources also has the potential of significantly increasing global technical geothermal resource potential. Integrated development, to share infrastructure with other renewable energy sources (such as offshore wind and wave power), may provide an economic platform for utilisation in the long term.

4.3.7 Direct use

Direct use provides heating and cooling for buildings including district heating, fish ponds, greenhouses and swimming pools, water purification/desalination and industrial and process heat for agricultural products and mineral extraction and drying.

For space heating, closed loop (double pipe) systems are commonly used. In this case, heat exchangers are utilised to transfer heat from the geothermal water to a closed loop that circulates heated freshwater through the radiators. This is often needed because of the chemical composition of the geothermal water. The spent water is disposed of into injection wells. Open loop systems do not inject produced geothermal fluids. However, in both cases a conventional backup boiler (as shown in Figure 4.3) may be provided to meet peak demand, to reduce the overall investment, and to conserve the geothermal resource.

In Iceland, the geothermal water is transported up to 63 km from the geothermal fields to towns. Transmission pipelines are mostly of steel insulated by rock wool (surface pipes) or polyurethane (subsurface). However, several small villages and farming communities have successfully used plastic pipes (polybutylene), with polyurethane insulation, as transmission pipes. The temperature drop is insignificant in large diameter pipes with a high flow rate.

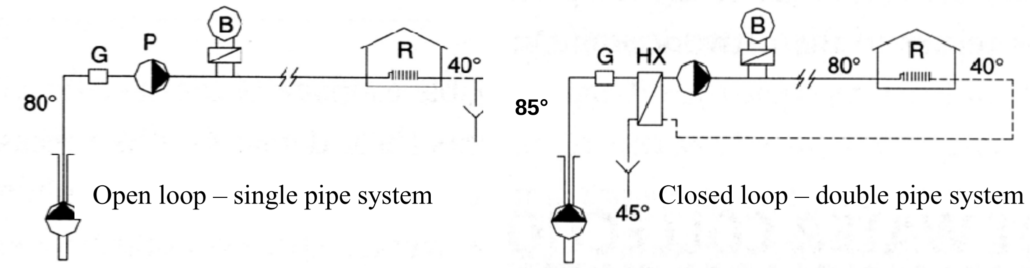

Figure 4.3 Two main types of district heating systems (Dickson and Fanelli, 2003). G=gas separator, P=pump, B=backup boiler, R=radiation heating, HX=heat exchanger.

4.3.8 Geothermal heat pumps

Geothermal Heat Pumps (GHP) have experienced one of the fastest growing applications of renewable energy in the world (Rybach, 2005; Lund et al., 2010). This form of direct use of geothermal energy is based on the relatively constant ground or groundwater temperature in the range of 4°C to 30°C readily available almost anywhere, to provide space heating, cooling and domestic hot water for all types of buildings. Extracting energy cools the ground, which creates temperature gradients, enhancing recharge thus, heating and cooling loads need to be balanced or mitigated.

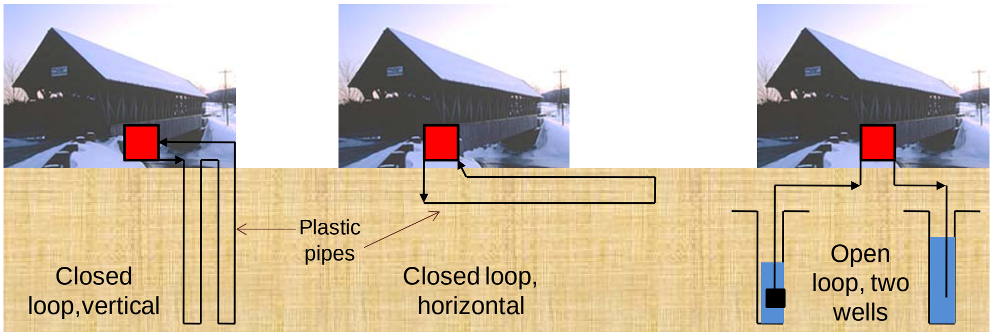

Figure 4.4 Closed loop and open loop heat pump systems. The heat pump that includes a compressor and heat exchangers is shown in red (Adapted from Lund et al., 2003).

There are two main types of geothermal heat pumps (Figure 4.4). In ground-coupled systems a closed loop of plastic pipe is placed in the ground, either horizontally at 1-2 m depth or vertically in a borehole down to 50-250 m depth. A water-antifreeze solution is circulated through the pipe. Thus heat is collected from the ground in the winter and optionally heat is rejected to the ground in the summer. An open loop system uses groundwater or lake water directly as a heat source in a heat exchanger and then discharges it into another well or into the same water-reservoir.

In essence heat pumps are nothing more than refrigeration units with the heat rejected in the condenser used for heating or heat extracted in the evaporator used for cooling. Their efficiency is described by a coefficient of performance (COP) which is the heating or cooling output divided by the electrical energy input. Typically this value lies between 3 and 4 (Lund et al., 2003; Rybach, 2005).

4.4 Global and regional status of market and industry development

Electricity has been generated commercially by geothermal steam since 1904. Presently the geothermal industry has a wide range of participants, including major energy companies, private and public utilities, equipment manufacturers and suppliers, field developers and drilling companies. Current industrial participants can be found by searching the IGA, IEA-GIA, GEA, GRC, and other national websites featuring energy attributes. [TSU: Full names missing.]

4.4.1 Status of geothermal electricity from conventional geothermal resources

In 2009, electricity was being produced from conventional geothermal resources in 24 countries with an installed capacity of 10.7 GWe (Fig. 4.5). The worldwide use of geothermal energy for power generation (predominantly from conventional hydrothermal resources) was 67.2 TWh/y in 2008 with a worldwide CF of 71% (Bertani, 2010). Many developing countries are amongst the top 15 in geothermal electricity production.

Conventional geothermal resources currently used to produce electricity are of high-temperature (>180°C), typically utilised through steam turbines (condensing or back-pressure, flash or dry-steam), and of low-intermediate temperature (<180°C) commonly utilised using binary-cycle power plants.

Currently the world’s top geothermal producer is the US with almost 29% of the global installed capacity (3094 MWe, Fig. 4.5). The US geothermal resurgence is due to increased RE penetration in the US power generation market. State Renewable Portfolio Standards (RPS) demand and the Federal Production Tax Credit (PTC), increased natural gas price fluctuation, and a rapid acceleration of pushback against the permitting of new coal-fired power plants have all opened a clear market opportunity for geothermal growth. US geothermal activity is concentrated in a few western states, but only a fraction of the geothermal potential has been developed so far.

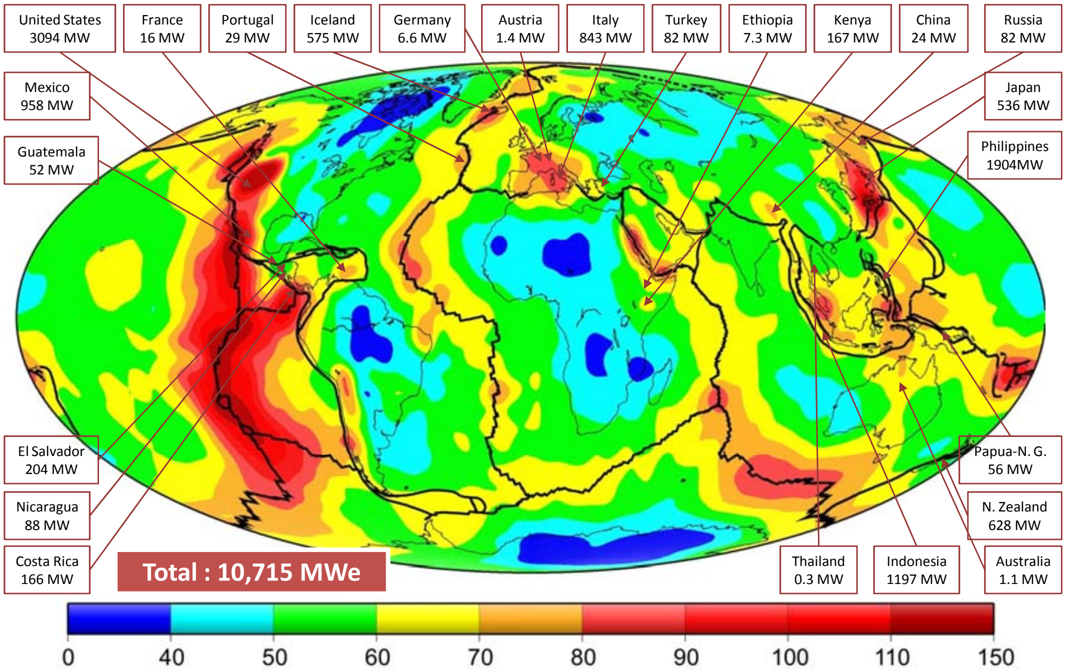

Figure 4.5 Geothermal-electric installed capacity by country in 2009. Figure shows worldwide average heat flow in mW/m2 and tectonic plates boundaries (Figure from Hamza et al., 2008; data from Bertani, 2010).

Outside of the US, about 29% of the global installed geothermal capacity resides in the Philippines and Indonesia, and then the markets of Mexico, Italy, Japan, Iceland, and New Zealand account for one third of the global installed geothermal capacity (Fig. 4.5). Although some of these markets have seen relatively limited growth over the past few years, in others, greater urgency to advance low-carbon base-load power generation is helping re-start new capacity growth (for example, installed capacity in New Zealand and Iceland has doubled in the past five years, IEA-GIA, 2009). Moreover, attention is turning to new markets like Chile, Germany, and Australia, and other more established markets as in East Africa, Turkey, Nicaragua and Russia.

The majority of existing geothermal assets are operated by state-owned utilities and Independent Power Producers (IPP). Currently, more than 30 companies globally have an ownership stake in at least one geothermal deployed project. Altogether the top 20 owners of geothermal capacity control approximately 90% of the entire installed global market.

At the end of 2009, the geothermal-electric capacity (10.7 GWe) represented only 0.21% of the total worldwide electric capacity, which was about 5,000 GWe. However, taken separately, six of those 24 countries shown in Figure 4.6 (El Salvador, Kenya, Philippines, Iceland, Costa Rica and New Zealand) obtain more than 10% of their national electricity production from high temperature, conventional geothermal resources (Bromley et al., 2010).

Worldwide evolution of geothermal power and geothermal direct uses during the last 40 years are presented in Table 4.5, including the annual average rate of growth over each period. The average annual growth of geothermal-electric installed capacity over the last 40 years is 7.2% [TSU to authors: Value inconsistent with value in table 4.5. Please clarify.], and for geothermal direct uses (heat applications) is 11% in the last 35 years.

Table 4.5 Average annual growth rate in geothermal power capacity and direct uses in the last 40 years. (Prepared with data from Bertani, 2010; Lund et al., 2005, 2010; Gawell and Greenberg, 2007; Fridleifsson and Ragnarsson, 2007.)

Year	Electric capacity		Direct uses capacity	
	MWe	%	MWt	%
1970	720	—	N.A.	—
1975	1,180	13.1	1,300	—
1980	2,110	15.6	1,950	10.7
1985	4,764	22.6	7,072	38.0
1990	5,834	5.2	8,064	3.3
1995	6,833	4.0	8,664	1.8
2000	7,972	3.9	15,200	14.4
2005	8,933	2.9	27,825	16.3
2010	10,715	4.7	50,583	16.1
Total annual average:		7.0		11.0

%: Average annual growth in percent over the period.

N.A.: Reliable data not available.

4.4.2 Status of Enhanced Geothermal Systems

EGS demonstration is active in Europe, the US and Australia. Since 2005 Australia has seen rapid acceleration in activity. By 2010, 18 stock market-registered enterprises held Australian geothermal licences. Cumulative investment amounted to US$ 248 M (to end of 2008) and was underpinned by government grants of US$ 267 M (to end of 2009) (Goldstein et al., 2010). In France the EU project "EGS Pilot Plant" at Soultz-sous-Forêts, started in 1987 and has recently commissioned the first power plant (1.5 MWe) to utilise the enhanced fracture permeability at 200°C. In Landau, Germany, the first EGS-plant, with 2.5 to 2.9 MWe, went into operation in late 2007 (Baumgärtner *et al.*, 2007). Deep sedimentary aquifers are tapped at the geothermal test site in Groß Schönebeck using two research wells (Huenges *et al.*, 2009).

The US in its recent clean energy initiatives has included large EGS research, development, and demonstration components as part of a revived national geothermal program. One of the main goals for EGS in the short term is to upscale to several tens of MWe.

The availability of financing, water, transmission and distribution infrastructure and other factors will play major roles in regional growth trends of EGS projects. In the US, Australia, and Europe, EGS concepts are being field tested and deployed, providing advantages for accelerated deployment in those regions as risks and uncertainties are reduced. In other rapidly developing regions in Asia, Africa, and South America, factors that would affect deployment are population density, distance to market, electricity and heating and cooling demand.

4.4.3 Status of direct uses of geothermal resources

Direct heat supply temperatures are typically close to actual process temperatures in district heating systems which range from approximately 60 to 120°C. As a result, only a small degradation of the thermodynamic quality of the geothermal heat occurs. The main types (and relative percentages) of direct applications in annual energy use are: space heating of buildings (63%, of which three quarters are from heat pumps), bathing and balneology (25%), horticulture (greenhouses and soil heating) (5%), industrial process heat and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%) (Lund et al., 2010).

Heating of building spaces, including district heating schemes, is among the most important direct applications. When the resource temperature is too low for direct use, it is possible to use a geothermal heat pump (GHP). Also space cooling can be provided by geothermal resources, and GHP devices can heat and cool with the same equipment.

Bathing, swimming and balneology utilizing geothermal water have a long history and are globally wide-spread. In addition to the thermal energy the chemicals dissolved in the geothermal fluid are also important for treating various skin and health diseases.

Geothermally heated greenhouses allow cultivation of flowers and vegetables in colder climates where commercial greenhouses would not normally be economical. Heating soil in outdoor agricultural fields has also been applied at several places such as Iceland and Greece.

A variety of industrial processes utilise heat applications, including drying of forest products, food, and minerals industries as in the United States, Iceland and New Zealand. Other applications are process heating, evaporation, distillation, sterilisation, washing, CO_2 and salt extraction.

Aquaculture using geothermal heat allows better control of pond temperatures, which is of great importance for optimal growth. Tilapia, salmon and trout are the most common fish raised, but unusual species such a tropical fish, lobsters, shrimp or prawns, and alligators are also reported.

Snow melting or de-icing by using low temperature geothermal water is applied in some colder climate countries. City streets, sidewalks, and parking lots are equipped with buried piping systems carrying hot geothermal water. In some cases, this is return water from geothermal district heating systems as in Iceland, Japan and the United States.

The world installed capacity of geothermal direct use is currently estimated to be 50.6 GWt (Table 4.5), with a total thermal energy usage of about 121.7 TWh_t/y (0.438 EJ/y), distributed in 78 countries, with an annual average capacity factor of 27.8%. Geothermal heat pumps (GHP) contributed with 70% (35.2 GWt) of the worldwide installed capacity (Lund et al., 2010).

4.4.4 Impact of policies

To bring geothermal to its full capacity in climate change mitigation it is necessary to address the following main barriers, described according to the taxonomy of barriers used in this report.

I1 (Clarity in concepts [knowledge, understanding]). Lack of clarity in understanding geothermal is often a barrier. Improvements could include programmes to standardise on reliable and efficient geothermal technologies, to enhance public knowledge, to encourage more informed acceptance of geothermal energy use, and to conduct further research towards the avoidance or mitigation of induced hazards and adverse effects.

I2 (RE know-how systems). Efficient deployment of geothermal technologies relies on the availability of skilled installation and service companies with well-trained personnel. For deep geothermal drilling and reservoir management, such services are currently concentrated in a few countries. For GHP installation and district heating, there is also a correlation between local availability and awareness of service companies, and technology uptake. To increase development rates, this constraint could be overcome by improved global infrastructure of services.

T3 (Transport and accessibility). Distributions of potential geothermal resources vary from being almost site-independent (for GHP technologies and EGS) to being much more site-specific (for hydrothermal sources). The distance between electricity markets or centres of heat demand and geothermal resources, as well as the availability of transmission capacity, can be a significant factor in the economics of power generation and direct use.

E2 (Cost structure and accounting) & E3 (Project appraisal and financing). Reducing costs and increasing the efficiency of supplying geothermal energy will enhance its market competitiveness. Policies set to drive uptake of geothermal energy work better if local demand and risk factors are taken into account. For example, large numbers of small domestic heat customers can be satisfied using GHP technologies, requiring relatively small budgets. For other countries, district heating systems and industrial heat applications are more efficient and provide greater mitigation of CO_2 emissions, but these markets typically require larger scale investments and a different policy framework.

P3 (Energy subsidy, taxing, other support policies). Policies that support improved applied research and development would benefit all geothermal technologies, but especially emerging technologies such as EGS. Public investment in higher-risk geothermal research and exploration drilling is likely to lead to a significant acceleration in follow-up commercial deployment. Specific incentives for geothermal development can include subsidies, guarantees, and tax write-offs to cover the risks of initial deep drilling. Policies to attract energy-intensive industries to known geothermal resource areas can also be useful. Feed-in tariffs with confirmed geothermal prices have been very successful in attracting commercial investment in some countries (e.g. Germany). Direct subsidies for new building heating, refurbishment of existing buildings with GHP, and for district heating systems, may be more applicable in other settings.

P4 (Regulations and rules impeding RE). Experience has shown that the relative success of geothermal development in particular countries is closely linked to their government's policies, regulations, incentives and initiatives. Successful policies have taken into account the benefits of geothermal energy, such as its independence from weather conditions and its suitability for base-load power. Another important policy consideration is the opportunity to subsidize the price of geothermal kWh (both power and direct heating and cooling) through the mechanism of direct or indirect CO_2 emission taxes. A funding mechanism that subsidizes the commercial upfront exploration costs, including the higher-risk initial drilling costs, would also be useful. In this regard, a tax write-off provision for unsuccessful exploration drilling costs can, and has been, a useful incentive. Government legislation, regulations, policies and programs that target increased use of RE and lower greenhouse gas emissions will generally provide support to the increased use of geothermal resources.

4.5 Environmental and social impacts

One of the strongest arguments for using geothermal energy is its limited environmental impact. Sound practices protect natural thermal features that are valued by the community, and minimise any adverse effects from disposal of geothermal fluids and gases, induced seismicity and ground subsidence. Good practice can also optimize water and land use, while improving long-term sustainability of production. The following sub-sections address these issues in more detail.

4.5.1 CO_2 and other gas and liquid emissions while operating geothermal plants

Geothermal systems involve natural phenomena, and typically discharge gases mixed with steam from surface features, and minerals dissolved in water from hot springs. Apart from CO_2, geothermal fluids can, depending on the site, contain a variety of other gases, such as H_2S, H_2, CH_4,

NH_3 and N_2. Mercury, arsenic, radon and boron may be present. The amounts depend on the geological, hydrological and thermodynamic conditions of the geothermal field[1].

In high temperature hydrothermal fields, measured direct CO_2 emission from the operation of conventional power or heating plants is widely variable, from 0 to 740 g/kWh_e, but averages about 120 g/kWh_e (weighted average of 85% of the world power plant capacity, according to Bertani and Thain, 2002, and Bloomfield et al., 2003). The gases are often extracted from a steam turbine condenser or two-phase heat exchanger and released through a cooling tower. CO_2, on average, constitutes 90% of these non-condensable gases (Bertani and Thain, 2002).

Of the remaining gases, H_2S is toxic, but is rarely sufficiently concentrated to be harmful after venting to the atmosphere and dispersal. Removal of H_2S released from geothermal power plants is practiced in parts of the US and Italy. Elsewhere, H_2S monitoring is a standard practice to provide assurance that concentrations after venting and atmospheric dispersal are not harmful. CH_4 is also present in relatively small concentrations (typically a few percent of the CO_2 concentration).

In low-temperature applications (<100°C), direct CO_2 emission from geothermal fluid is about 0-1 g/kWh (electric) depending on the carbonate content of the water. If the extracted geothermal fluid is passed through a heat exchanger and then completely injected (such as in a closed-loop pumped system), then CO_2 emission is nil. Other gas emissions from low-temperature geothermal resources are normally much less than the emissions from the high-temperature fields.

In Enhanced Geothermal Systems power plants are likely to be designed as closed-loop circulation systems, with zero direct emissions. (If boiling occurs within the circulation loop, then some non-condensable gas extraction and emission is likely.)

The possibility of using CO_2 as a working fluid in geothermal reservoirs is also under investigation. The fact that the rock volume of active commercial sized geothermal reservoirs is of the order of a cubic kilometre per well would enable storage of a large volume of supercritical CO_2 underground. If this method is successfully developed, it could provide a means for enhancing the effect of geothermal energy deployment for lowering CO_2 emissions beyond just generating electricity with a carbon-free renewable resource.

In direct uses (heating) emissions of CO_2 from low-temperature geothermal fluids are usually negligible (Fridleifsson et al., 2008). In Reykjavik (Iceland), the CO_2 content of thermal groundwater used for district heating (0.05 mg/kWh_t) is lower than that of the cold groundwater. In China (Beijing, Tianjin and Xianyang) it is less than 1 g CO_2/kWh. In the Paris Basin (a sedimentary basin), the geothermal fluid is kept under pressure within a closed circuit (the geothermal ‘doublet’) and injected into the reservoir without any degassing taking place. Conventional geothermal district heating schemes (such as Klamath Falls, Oregon, US) commonly produce brines which are also injected into the reservoir and thus never release CO_2 into the environment. CO_2 is also used in greenhouses to improve plant growth and extracted for use in carbonated beverages –such in Iceland.

Most hazardous chemicals in geothermal fluids are concentrated in the water phase. If present, boron and arsenic are likely to be harmful to ecosystems if released at the surface, so geothermal brine is usually injected into the reservoir. This avoids contamination of surface waterways. In the past, surface disposal of separated water has occurred at a few fields, but today it happens only in exceptional circumstances such as equipment failure. If the discharge is significantly in excess of

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[1] Note that SO_2, unlike H_2S, is a common source of acid rain, but is not usually present in geothermal emissions.

natural hot spring discharges, and is not strongly diluted, then the net effects on ecology of rivers, lakes or marine environments can be adverse. Shallow groundwater aquifers of potable quality may also need to be protected from contamination by injected fluids or from soakage ponds by using cemented casings or impermeable liners. Monitoring is undertaken to investigate, and if necessary mitigate, such adverse effects (Bromley et al., 2006).

After separation and condensation, surplus steam condensate may be suitable for stock drinking water or irrigation purposes instead of injection. At Wairakei, New Zealand, the steam condensate has been approved by environmental regulating agencies for irrigation purposes, but each case will be chemically different and must be judged on its own merits.

4.5.2 Life-cycle assessment

Life-cycle assessment (LCA) analyses the whole life cycle of a product "from cradle to grave". For geothermal power plants all gas emission impacts directly and indirectly related to the construction, operation and deconstruction of the plant are considered in LCA.

Kaltschmitt et al. (2006) calculated CO_2-equivalent emissions of between 59 and 79 g/kWh for closed loop binary power plants. Pehnt (2006) calculated a LCA CO_2-equivalent of 41 g/kWh. Nill (2004) analysed the learning curve effects on the life cycle and predicts a reduction in CO_2-equivalent from binary plants from 80 g/kWh to 47 g/kWh between 2002 and 2020. Frick et al. (2010) compare two binary plants of the same capacity (1.75 MWe) with resources at different depths and temperatures, and calculated a CO_2-equivalent between 23 and 66 g/kWh. Binary closed loop systems are expected to have a greater use in future. They also presented other LCA environmental indicators, which are compared to those of a central European reference mix in Table 4.6, where it is observed that the geothermal CO_2-equivalent is between 4 and 12% of this reference mix. At sites with above-average geological conditions, CO_2-equivalent emissions can be less than 1%. The breakdown of the reference mix is: 26% lignite coal, 26% nuclear power, 24% hard coal, 12% natural gas, 4% hydropower, 4% wind power, 1% crude oil, 3% other fuels (Frick et al., 2010).

Table 4.6 Environmental impact indicators for a reference electricity mix and for typical geothermal binary power plants (Prepared with data from Frick et al., 2010).

LCA indicator	Reference electricity mix	Binary geothermal plants (1.75 MWe)
Finite energy resources	8.9 MJ/kWh	0.4-1.0 MJ/kWh
CO_2-equivalent	566 g/kWh	23-66 g/kWh

Using life cycle assessments for geothermal direct uses, Kaltschmitt (2000) published figures of 4-16 tonnes CO_2-equivalent /TJ (14.3-57.6 g/kWh_t) for low-temperature district heating systems, and 50-56 tonnes CO_2-equivalent/TJ (180-202 g/kWh_t) for heat pumps.

The life cycle of intermediate- to low-temperature geothermal developments is dominated by large initial material and energy inputs during the construction of the wells, power plant and pipelines. To maximize net-energy output and minimize emissions these can be optimised during the construction period. For hybrid electricity/district heating applications, more direct use of the heat optimizes the environmental benefits.

In conclusion, the LCA assessments show that geothermal is similar to other RE (hydro and wind) in total life-cycle emissions, and it has significant environmental advantages relative to a reference electricity mix dominated by fossil fuel sources.

4.5.3 Potential hazards of induced seismicity and others

Local hazards arising from natural phenomena, such as micro-earthquakes, hydrothermal steam eruptions and ground subsidence may be influenced by the operation of a geothermal field. Pressure or temperature changes induced by stimulation, production or injection of fluids can lead to geo-mechanical stress changes and these can then affect the subsequent rate of occurrence of these natural phenomena. A geological risk assessment can help avoid or mitigate these hazards.

With respect to induced seismicity, felt ground vibrations or noise have been an environmental and social issue associated with some EGS demonstration projects, particularly in populated areas (e.g. Soultz in France, Basel in Switzerland [subsequently suspended] and Landau in Germany). Such events have not lead to human injury or major property damage, but routine seismic monitoring is used as a diagnostic tool and management and protocols have been prepared to measure, monitor, and manage systems pro-actively as well as to inform the public of any hazards (Majer et al., 2008). Collaborative research initiated by the IEA-GIA (Bromley and Mongillo, 2008), and in Europe (GEISER, 2010), the US and Australia, is aimed at better understanding and mitigating induced seismicity hazards, and providing risk-management protocols.

During 100 years of development, although turbines have been tripped off-line, no buildings or structures within a geothermal operation or local community have been significantly damaged (more than superficial cracks) by shallow earthquakes originating from either geothermal production or injection activities. The process of high pressure injection of cold water into hot rock, which is the preferred EGS method of stimulating fractures to enhance fluid circulation, generates local stress changes which usually trigger small seismic events through hydro-fracturing or thermal stress redistribution. Proper management of this issue will be an important step to facilitating significant expansion of future EGS projects.

Hydrothermal steam eruptions have, in the past, been triggered at a few locations by shallow geothermal pressure changes (both increases and decreases). Such eruptions are generally caused by rapid boiling in a near-surface water body generating expansion forces that lift rock out of an expanding crater. These risks can be mitigated by prudent field design and operation.

Land subsidence has been an issue at a few high temperature geothermal fields, particularly in New Zealand. Pressure decline can affect some poorly consolidated formations (e.g. high porosity mudstones or clay deposits) causing them to compact anomalously and form local subsidence ‘bowls’. Management by targeted injection to maintain pressures at crucial depths and locations has succeeded in minimizing subsidence effects in the Imperial Valley (US) where maintaining levels to allow for irrigation drainage is important.

4.5.4 Benefits and impacts – economic, environmental, social

A potential economic benefit for geothermal power projects is the possibility to access the United Nations’ Clean Development Mechanism (CDM). The CDM provides a clear, market-driven valuation for the very low GHG emissions of geothermal power plants, and the revenue from certified emission reductions (CER) –carbon credits generated by CDM projects– can be used to reduce the price that would otherwise be charged to consumers of the electricity. The CERs, where each credit represents a reduction of one tonne of CO_2 or equivalent, are calculated by comparing the CO_2 emissions factor for the electricity generator, in tonnes per MWh, with that of the grid to which the electricity will be supplied. A recent, actual example of that is the Darajat III geothermal project, which was developed by a private company in Indonesia under prevailing international market conditions. This project started to operate in 2007 with 110 MWe and was registered by the CDM. The Darajat III plant is currently producing about 650,000 CERs per year. After factoring in the uncertainties of the CER market and the risks of continued CER revenue in the post-Kyoto (post-2012) period, the CDM reduces the life-cycle cost of geothermal energy by about 2 to 4% (Newell and Mingst, 2009).

A good example of the environmental benefits of geothermal direct use is the city of Reykjavik, Iceland, which has eliminated heating with fossil fuels, significantly reducing air pollution, and avoided about 100 Mt of cumulative CO_2 emissions (i.e., around 2 Mt annually) (Fridleifsson et al., 2008). Other examples are at Galanta in Slovakia (Fridleifsson et al., 2008), Pannonian Basin in Hungary (Arpasi, 2005), and Paris Basin in France (Laplaige et al., 2005).

The successful realization of geothermal development projects often depends on the level of acceptance by the local people. Prevention or minimization of detrimental impacts on the environment, and on land occupiers, as well as the creation of benefits for local communities, is indispensable to obtain social acceptance. Local people are often aware of the risks and benefits of geothermal projects and of their rights to protect their environment by participating in the management of resources in their territory. The necessary prerequisites to secure agreement of local people are: i) Prevention of adverse effects on people's health, ii) Minimization of environmental impacts, iii) Creation of direct and ongoing benefits for the resident communities.

Geothermal development often creates job opportunities for locals. This can be helpful for poverty alleviation in developing countries. Geothermal developments, particularly in Asian, Central and South American, and African developing nations, are often located in remote mountainous areas. Because drilling and plant construction must be done at the site of a geothermal resource, use of a local workforce can lead to better employment opportunities. Some geothermal companies and government agencies have approached social issues by improving local security, building roads, schools, medical facilities and other community assets, which may be funded by contributions from profits obtained from operating the power plant.

Multiple land-use arrangements that promote employment by integrating subsurface geothermal energy extraction with labour-intensive agricultural activities are also useful. In many developing countries, geothermal is also an appropriate energy source for small-scale distributed generation, helping accelerate development through access to energy in remote areas.

4.5.5 Land use

Environmental impact assessments for geothermal developments consider a range of land and water use impacts during both construction and operation phases that are common to most energy projects (e.g. noise, vibration, dust, visual impacts, surface and ground water impacts, ecosystems, biodiversity) as well as specific geothermal impacts (e.g. effects on outstanding natural features such as springs, geysers and fumaroles).

Land use issues in many settings (e.g. Japan, the US and New Zealand) can be a serious impediment to further expansion of geothermal development. National Parks, for example, have often been established in remote volcanic tourist areas where new geothermal prospects also exist. Despite good examples of unobtrusive, scenically-landscaped developments (e.g. Matsukawa, Japan), and integrated tourism/energy developments (e.g. Wairakei, New Zealand and Blue Lagoon, Iceland), land use issues still seriously constrain new development options in some countries. Potential pressure and temperature interference between adjacent geothermal developers or users can be another issue that affects all types of heat and fluid extraction, including heat pumps and EGS power projects. Regional planning takes this into account, through appropriate simulation models, when allocating permits for energy extraction.

Another measure of optimum land use that is relevant in some settings is the 'footprint' occupied by geothermal installations. Table 4.7 presents the typical footprint for common conventional geothermal power plants, taking into account surface installations (drilling pads, roads, pipelines, fluid separators and power-stations). The subsurface resource that is accessed by directional or vertical geothermal boreholes typically occupies an area equivalent to about 10 MWe/km^2.

Therefore, about 95% of the land above a typical geothermal resource is not needed for surface installations, and can be used for other purposes (e.g., farming, horticulture and forestry at Mokai and Rotokawa in New Zealand, and a game reserve at Olkaria, Kenya).

Table 4.7 Land requirements for typical geothermal power generation options.

Type of power plant	Land Use	
	m^2/MWe	m^2/GWh/year
110-MWe geothermal flash plants (excluding wells)	1260	160
56-MWe geothermal flash plant (including wells, pipes, etc.)	7460	900
49-MWe geothermal FC-RC plant (excluding wells)	2290	290
20-MWe geothermal binary plant (excluding wells)	1415	170

FC: Flash cycle, RC: Rankine cycle (Data from Tester et al., 2006).

4.6 Prospects for technology improvement, innovation, and integration

4.6.1 Technological and process challenges

Successful development and deployment of improved geothermal technologies will mean significantly higher energy recovery, longer field lifetimes and much more widespread availability of geothermal energy. Achieving that success will require sustained support and investment into technology development from governments and the private sector for the next 10 to 20 years.

With time, better technical solutions are expected to improve power plant performance and reduce maintenance down-time. More advanced approaches for resource development, including advanced geophysical surveys, reinjection optimization, scaling/corrosion inhibition, and better reservoir simulation modelling, will help reduce the resource risks by better matching installed capacity to sustainable generation capacity.

While conventional, high-temperature, naturally-permeable geothermal reservoirs are profitably deployed today for power production and direct uses, the success of the EGS-concept would lead to widespread utilization of lower grade resources. EGS requires innovative methods for exploring, stimulating and exploiting geothermal resources at any commercially viable site. Development of these methods will likely improve conventional geothermal technologies. The challenges facing EGS developers encompass several tracks (Tester et al., 2006):

1. Development of exploration technologies and strategies to reliably locate prospective EGS.
2. Improvement and innovation in well drilling, casing, completion and production technologies for the exploration, appraisal and development of deep geothermal reservoirs (as generalised in Table 4.4).
3. Improvement of methods to hydraulically stimulate reservoir connectivity between injection and production wells to attain sustained, commercial production rates.
4. Development/adaptation of data management systems for interdisciplinary exploration, development and production of geothermal reservoirs, and associated teaching tools to foster competence and capacity amongst the people who will work in the geothermal sector.
5. Improvement of numerical simulators for production history matching and predicting coupled thermal-hydraulic-mechanical-chemical processes during developing and exploitation of reservoirs.
6. Improvement in assessment methods to enable reliable predictions of chemical interaction between geo-fluids and geothermal reservoirs rocks, geothermal plant and geothermal equipment, enabling optimised, well-, plant- and field-lifetimes.

7. Performance improvement of thermodynamic conversion cycles for a more efficient utilisation of the thermal heat sources in district heating and power generation applications.

The required technology development would clearly reflect assessment of environmental impacts including land use and induced micro-seismicity hazards or subsidence risks (see section 4.5).

4.6.2 Improvements in exploration technologies

In exploration, R&D is required for hidden geothermal systems and EGS prospects. Rapid reconnaissance geothermal tools will be essential to identify new prospects, especially those with no surface manifestations such as hot springs and fumaroles. Satellite-based hyper-spectral, thermal infra-red, high-resolution panchromatic and radar sensors are most valuable at this stage, since they can provide data inexpensively over large areas.

Once a regional focus area has been selected, success will depend upon the availability of cost-effective reconnaissance survey tools to detect as many geothermal indicators as possible. Airborne-based hyper-spectral, thermal infra-red, magnetic and electromagnetic sensors are valuable at this stage, providing rapid coverage of the geological environment being explored, at an appropriate resolution. Ground-based verification, soil sampling and geophysical surveys (magneto-telluric, resistivity, gravity, seismic and/or heat flow measurements) should follow.

4.6.3 Accessing and engineering the reservoirs

Special research is needed in large diameter drilling through plastic, creeping or swelling formations such as salt or shale. Abnormally high fluid pressure in such formations causes abnormal stresses that differ considerably from those found in hydrostatic pressure gradients. To provide long-life completion systems in ductile formations, new cementing technologies regarding the geo-mechanical behaviour of plastic rock need to be defined, especially for deviated wells.

Drilling must minimise formation damage that occurs as a result of a complex interaction of the drilling fluid (chemical, filtrate and particulate) with the reservoir fluid and formation. The objectives of new-generation geothermal drilling and well construction technologies are to reduce the cost and increase the useful life of geothermal production facilities through an integrated effort (see Table 4.4).

The international Iceland Deep Drilling Project (IDDP) is a long-term program to improve the efficiency and economics of geothermal energy by harnessing deep unconventional geothermal resources (Fridleifsson *et al.*, 2010). Its aim is to produce electricity from natural supercritical hydrous fluids from drillable depths. Producing supercritical fluids will require drilling wells and sampling fluids and rocks to depths of 3.5 to 5 km, and at temperatures of 450-600°C.

All tasks related to the engineering of the reservoir require sophisticated modelling of the reservoir processes and interactions to be able to predict reservoir behaviour with time, to recommend management strategies for prolonged field operation, and to minimize potential environmental impacts.

In the case of EGS, reservoir stimulation procedures need to be refined to significantly enhance the hydraulic productivity, while reducing the risk of seismic hazard. Imaging fluid pathways induced by hydraulic stimulation treatments through innovative technology would facilitate this. New visualisation and measurement methodologies (imaging of borehole, permeability tomography, tracer technology, coiled tubing technology) should become available for the characterisation of the reservoir.

4.6.4 Efficient production of geothermal power, heat and/or cooling

Technical equipment needed to provide heating/cooling and/or electricity from geothermal wells is already available on the market. However, the efficiency of the different system components can still be improved, especially for low-enthalpy power plant cycles, cooling systems, heat exchangers and production pumps for the brine.

Thermodynamic cycles can be improved, and thermal heat sources utilised more efficiently, both in district heating and in conversion to electrical power. For power generation, a modular low-temperature cycle could be set up allowing for conventional and new working fluids to be examined.

New and cost-efficient materials are required for pipes, casing liners, pumps, heat exchangers and for other components to be used in geothermal cycles to reach higher efficiencies and develop cascade uses.

The potential development of valuable by-products may improve the economics of geothermal development, such as recovery of the condensate for industrial applications after an appropriate treatment, and in some cases recovery of valuable minerals from geothermal brines (such as lithium, zinc, high grade silica, and in some cases gold).

4.7 Cost trends

Geothermal projects have typically high up-front capital costs (mainly due to the cost of drilling wells and constructing surface power plants) and low operational costs. These operational costs vary from one project to another due to size and quality of the geothermal fluids, but are relatively predictable in comparison with power plants of traditional energy sources which are usually subject to market fluctuations in fuel price. This section describes the capital costs of geothermal-electric projects, the levelised cost of geothermal electricity and the historic and probable future trends, and also presents costs for direct uses of geothermal energy. It should be noted that that the following costs may have wide variations (up to 20-25%) between countries (e.g. between Indonesia, US and Japan).

4.7.1 Costs of geothermal-electric projects and factors that affect it

One of the main factors affecting the cost of a geothermal-electric project is the type of project: field expansion projects may cost 10-15% less than a new (greenfield) project, since investments have already been made in infrastructure and exploration and valuable resource information is available (learning effect) (Stefansson, 2002; Hance, 2005).

The cost structure of a geothermal-electric project is composed of the following components: a) exploration and resource confirmation, b) drilling of production and injection wells, c) surface facilities and infrastructure, and d) power plant.

The first component (a) includes lease acquisition, permitting, prospecting (geology and geophysics) and drilling of exploration and test wells. Drilling of this type of wells has a success rate typically about 50-60% (Hance, 2005), even though some sources reduce the percentage success to 20-25% (GTP, 2008). Confirmation costs are affected by: well parameters (depth and diameter), rock properties, well productivity, rig availability, time delays in permitting or leasing land, and interest rates. This first component represents between 10 and 15% of the total capital cost (capex) (Bromley et al., 2010) but for expansion projects may be as low as 1-3%.

Drilling of production and injection wells (component b) has a success rate of 60 to 90% (Hance, 2005; GTP, 2008). Factors influencing the cost include: well productivity (permeability and temperature), well depths, rig availability, vertical or directional design, the use of air or special circulation fluids, the use of special drilling bits, number of wells and financial conditions in a drilling contract (Hance, 2005; Tester et al., 2006). This component (b) represents 20-35% of the total capex (Bromley et al., 2010).

Surface facilities and infrastructure (component c) includes gathering steam and process brine, separators, pumps, pipelines and roads. Vapour-dominated fields have lower facilities costs since brine handling is not required. Factors affecting this component are: reservoir fluid chemistry, commodity prices (steel, cement), topography, accessibility, slope stability, average well productivity and distribution (pipeline diameter and length), and fluid parameters (pressure, temperature, chemistry) (Hance, 2005). Surface facilities and infrastructure represent 10-20% of the capex (Bromley et al., 2010).

The power plant (component d) includes turbines, generator, condenser, electric substation, grid hook-up, steam scrubbers, and pollution abatement systems. Power plant design and construction costs depend upon type (flash, back-pressure, binary, dry steam, or hybrid), as well as the type of cooling cycle used (water or air cooling). Other factors affecting power plant costs are: fluid enthalpy (resource temperature) and chemistry, location, cooling water availability, and the economies of scale (larger size is cheaper). This component varies between 40 and 81% of the capex (Hance, 2005; Bromley et al., 2010).

In the Table 4.8 are referred capital costs for typical geothermal-electric projects.

Table 4.8 Historic and current capital costs for typical turnkey (installed) geothermal-electric projects (2005 US$).

Type of project and plant	Capacity (MWe)	Year	Total Capex (2005 US$/kW)	References
Condensing flash plants:				
1. Greenfield (New)	n.s.	1997	1743	EPRI, 1997 (a)
2. Greenfield (New)	n.s.	2000	1631	Kutscher, 2000 (a)
3. Greenfield (New)	n.s.	2002	1143-2114	Stefansson, 2002 (a)
4. Greenfield (New)	n.s.	2003	1579-2053	Several included in (a)
5. Greenfield (New)	25-50	2004	2315-2666	California Energy Commission, 2004 (a)
6. Greenfield (New)	100	2006	~2200	Hjartarson & Einarsson, 2010
7. Greenfield (New)	50	2008	3244	Taylor, 2009 (b)
8. Greenfield (New) (worldwide average)	n.s.	2008	1778-3556	Bromley et al., 2010.
9. Expansion project	25	2009	2486	CFE internal data.
Binary cycle plants:				
10. Greenfield (New)	n.s.	1997	2548	EPRI, 1997 (a)
11. Greenfield (New)	n.s.	2000	2362	Kutscher, 2000 (a)
12. Greenfield (New)	n.s.	2002	2274	Owens, 2002 (a)
13. Greenfield (New)	n.s.	2003	1829-2906	Several included in (a)
14. Greenfield (New)	10-30	2004	3076-3383	California Energy Commission, 2004 (a)
15. Greenfield (New)	20	2008	3556	GTP, 2008
16. Greenfield (New) (worldwide average)	n.s.	2008	2133-5244	Bromley et al., 2010.

n.s.: Not specified. (a) References cited in: Hance, 2005. (b) Reference cited in: Cross and Freeman, 2009.

Labour and material costs are estimated to account for 40% each of total project construction costs. Labour costs can increase by 10% when a resource is remotely located. In addition to raw materials and labour, choice of power plant size is a key factor in determining the ultimate cost of a plant, but the optimum size of single units on a per-MW basis varies (Dickson and Fanelli, 2003; Entingh and Mines, 2006).

4.7.2 Levelised cost of geothermal electricity

The levelised cost of geothermal power corresponds to the sum of two major components: levelised cost of capital investment (LCCI) and operation and maintenance costs (O&M). The LCCI corresponds to the cost of the initial capital investment (i.e. site exploration and development & power plant construction) and its related financial costs, divided by the total output of the facility throughout the entire payback period (typically 25-30 years). Note, however, that payback period allows for refurbishment or replacement of aging surface plant, but is not equivalent to economic resource lifetime, which is typically more than 50 years, e.g. Larderello, Wairakei, The Geysers. In most cases, the LCCI represents a major part (about 65-80%) of the levelised cost of energy (LCOE) of geothermal projects.

Operating and maintenance (O&M) costs consist of fixed and variable costs directly related to the electricity production phase. O&M per annum costs include field operation (labour and equipment), well operation and work-over and facility maintenance. For geothermal plants, an additional factor is the cost of make-up wells, i.e. new wells to replace failed wells and restore lost production or injection capacity. Make-up wells can be considered equivalent to O&M costs since the purpose of make-up drilling is to maintain the full production capacity of the power plants (Hance, 2005). Costs of these wells are typically lower than those for the original wells, and their success rate is higher. Make-up drilling typically increases with time, but if distributed across the economic lifetime of a development, its cost, on average, amounts to an increase of about 30% in O&M costs per MWh.

Geothermal-electric O&M costs, including make-up wells, have been calculated for the US to be between 18.5 and 22.6 US$/MWh (Lovekin, 2000; Owen, 2002), and Hance (2005) proposed an average cost of 24.6 US$/MWh. Current O&M costs are ranged between 152 and 187 US$/kW per year, and then with an annual capacity factor of 71% (current worldwide average) those costs vary between 24.4 and 30.0 US$/MWh, but with an annual capacity factor of 90% can be as low as 19.3 and 23.7 US$/MWh. In other countries, O&M costs can be significantly lower than these figures. For example, in New Zealand operating experience shows that total costs are 10-14 US$/MWh for 20-50 MWe plant capacity (Barnett and Quinlivan, 2009).

Current LCOE (i.e., including LCCI and O&M costs) in 2005 US$/MWh for some of the typical geothermal-electric plants listed in Table 4.8 were calculated according to the methodology described in Chapter 1 [TSU: Annex II], using version 6 of the calculator developed by Verbruggen and Nyboer (2009), and are presented in Figure 4.6. In all cases the project lifetime was calculated to be 25 years and the capacity factor (plant performance) was 80%, which is the expected for new projects. For greenfield projects it was estimated that the plant starts to operate at the beginning of the fifth year after exploration starts, and for expansion projects the plant is commissioned by the third year. “Average flash” is the current worldwide average for greenfield projects and flash plants, and correspond to the middle value of the Case 8 rank in Table 4.8 (2667 US$/kWe); it was considered a plant of 100 MWe. “Average binary” is the correspondent middle value for binary plants in Case 16 in Table 4.7 (capex 3689 US$/kWe), considering a plant of 10 MWe.

There are significant variations in LCOE depending on the discount rate used, yet in general terms the LCOE for flash plants in high temperature fields is lower than for binary cycle plants in low to intermediate temperature fields. LCOE for expansion projects is also lower than for new projects and the larger the project (in MWe) the lower LCOE.

There are no actual LCOE data for EGS, but some projections have been made using two different models for several cases with diverse temperatures and depths (Table 9.5 in Tester et al., 2006). The obtained LCOE values for the MIT EGS model range from 100-175 US$/MWh for relatively high-grade EGS resources (250-330°C, 5 km depth wells) assuming a base-case present-day productivity of 20 kg/s per well. Assuming, however, that 20 years of technology development results in a 4-fold improvement in productivity by 2030 to 80 kg/s per well, then LCOE values for the same geological settings decrease by 65% to a range of 36-52 US$/MWh, and some less attractive geological settings (180-220°C, 5-7 km depth wells) become more economically viable at about 59-92 US$/MWh. Another model for a hypothetical EGS project in Europe considers two wells at 4 km depth, 165°C reservoir temperature, 33 kg/s flow-rate and a binary power unit of 1.6 MWe running with an annual capacity factor of 85.6% (data taken from Huenges, 2010). By applying the calculator (Verbruggen and Nyboer, 2009) the LCOE values are 139, 181 and 217 US$/MWh for discount rates of 3%, 7% and 10%, respectively.

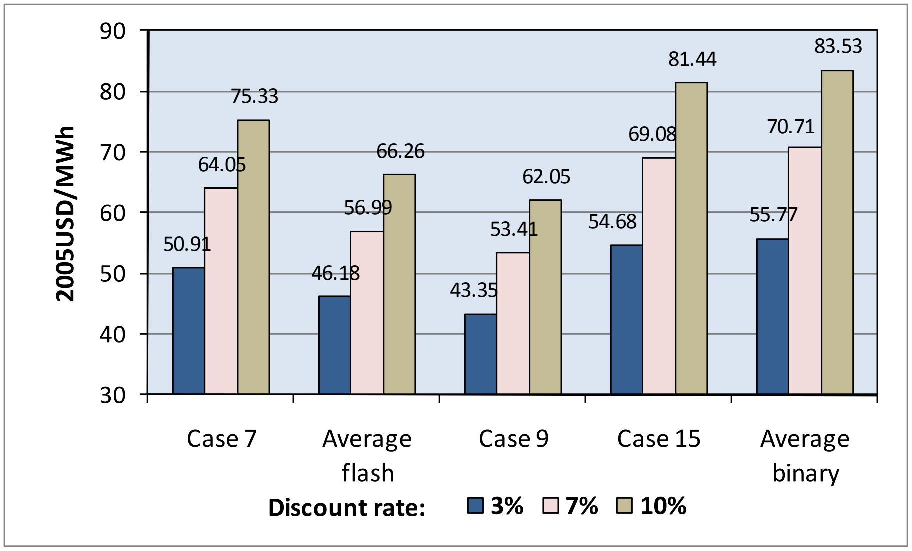

Figure 4.6. Current LCOE (LCCI plus O&M costs) in 2005 US$ per MWh for typical geothermal-electric plants using three different discount rates (3%, 7% and 10%). Cases 7, 9 & 15 are the same as in Table 4.8. “Average flash” is the Case 8 and “Average binary” the Case 16 in the Table 4.8.

4.7.3 Historical trends of geothermal electricity

From the 1980’s until about 2004, project development costs remained flat or even decreased (Kagel, 2006; Mansure and Blankenship, 2008). However, in 2006-2008 project costs sharply increased due to increases in the cost of commodities such as steel and cement, and drilling rig rates and engineering. This cost trend was not unique to geothermal and was mirrored across most other power sectors. Capex costs have since started to decrease due to the current economic downturn and reduced demand (Table 4.8).

On the other hand, the evolution of the worldwide average performance of geothermal-electric power plants is provided in Table 4.9 in the form of average capacity factor (CF) since 1995 and the projections to year 2100, calculated from installed capacity and average annual generation. The average capacity factor (CF) increased significantly between 1995 and 2000, and has since remained above 70%. The CF value incorporates a wide range of generation issues (unrelated to resource availability), including: grid connection failures (e.g. from storm damage), load following on smaller grids, and turbine failures. (Some operating geothermal turbines have exceeded their economic lifetime, so require longer periods of shut-down for maintenance or replacement.) Furthermore, a lack of make-up drilling to sustain long-term steam supply is sometimes due to financial constraints. Also, a substantial number of new power plants started during 2009, but their generation contributed for only part of the year.

Table 4.9 World installed capacity, electricity production and capacity factor of geothermal power plants 1995-2010 and forecasts for 2015-2050 (adapted from data from Bertani, 2010).

Year	Installed Capacity (GWe) actual or mean forecast	Electricity Production (GWh/y) Actual or mean forecast	Capacity Factor (%)
1995	6.8	38,035	64
2000	8.0	49,261	71
2005	8.9	56,786	73
2010	10.7	67,246	71
2015	18.5	121,600	75
2020	25.9	181,800	80
2030	51.0	380,000	85
2040	90.5	698,000	88
2050	160.6	1,266,400	90

Therefore, by projecting a further increase in CF, and assuming no such grid or load constraints for new developments, long-term CF of 80% to 95% can be expected (Fridleifsson et al., 2008). Several geothermal power plants are currently operating at CF of 90% and more.

4.7.4 Future costs trends

The future costs for geothermal electricity are likely to encompass a wide range because future deployment will probably include an increasing percentage of unconventional development types (such as EGS), which are currently in commercial demonstration mode and only limited cost data are presently available. However, considering the projected average capacity factor shown in Table 4.9 by 2020, 2030 and 2050, future LCOE for the cases before mentioned were calculated using the same calculator developed by Verbruggen and Nyboer (2009). The results are shown in Figure 4.7 using a discount rate of 7%, as used for all RE future cost trends in this report.

Some assumptions remained the same: the commissioning year for greenfield projects is the fifth year after exploration starts, while for expansion projects it is in the third year. However, the project lifetime was considered 27 years, considering improvements in materials, operation and maintenance and the fact that some actual plants currently in operation have achieved that lifetime. Figures for 2009 are those already presented in Figure 4.6. For 2020 it was assumed that the drilling cost (which represents between 20 and 45% of total capital costs) does not change but by 2030 this cost was estimated to be 7% lower and by 2050 15% lower than present costs, in all cases at 2005 US$. These decreasing costs are expected to occur due to better technologic practices in the drilling industry and to competition resulting from a greater availability of drilling rigs. Worldwide average capacity factor for 2020, 2030 and 2050 was assumed to be 80%, 85% and 90%, respectively, according to Table 4.9. All the remaining aspects and costs were considered, on balance, to be unchanging. Improvements in exploration, surface installations, materials and power plants are likely, and should lead to reduced costs, but these are expected to balance against increased commodity costs (especially steel and cement).

LCOE costs are therefore expected to decrease in an average of 1.7% by 2020, 8.5% by 2030 and 14.7% by 2050 (Fig. 4.7).

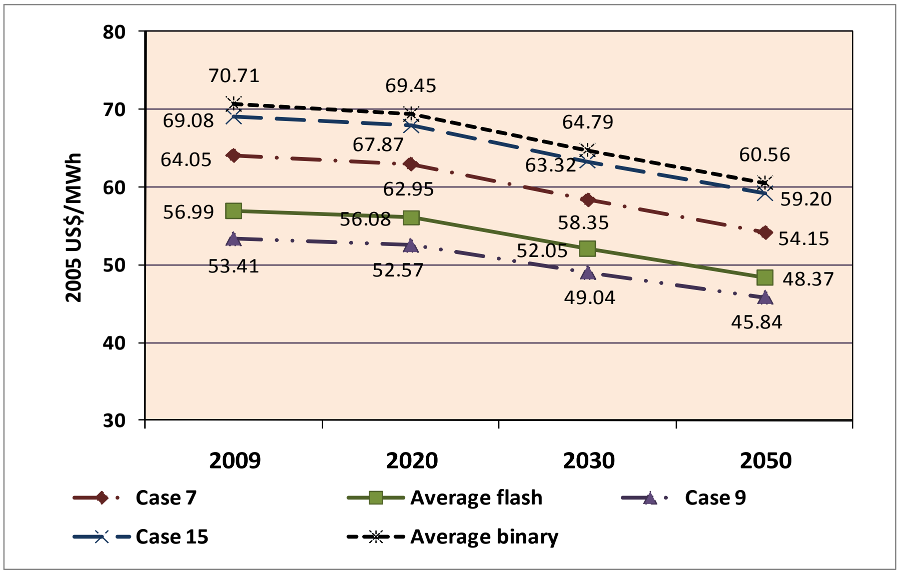

Figure 4.7 Present and projected LCOE in 2005 US$ for typical geothermal-electric plants at discount rate of 7%. Cases 7, 9 & 15 are the same as in Table 4.8. "Average flash" is the Case 8 and "Average binary" the Case 16 in the Table 4.8.

4.7.5. Economics of direct uses and geothermal heat pumps

Direct-use project costs have a wide range, depending upon the specific use, the temperature and flow rate required, the associate O&M and labor costs, and the income from the product produced. In addition, costs for new construction are usually less than cost for retrofitting older structures. The cost figures given in Table 4.10 are based on a temperature climate typical of the northern half of the United States or Europe, and obviously the heating loads would be higher for more northern climates such as Iceland, Scandinavia and Russia. Most figures are based on cost in the United States (expressed in 2005 US$), but would be similar in developed countries and lower in developing countries (Lund and Boyd, 2009).

Table 4.10 Capex and calculated LCOE for several geothermal direct applications (capex data taken from Lund, 1995; Balcer, 2000; Radeckas and Lukosevicius, 2000; Reif, 2008; Lund and Boyd, 2009).

Heat application	Capex (2005) US$/kW$_{th}$	LCOE in (2005) US$/kWh$_{th}$ at discount rate of		
		3%	7%	10%
Space heating (buildings)	1595-3940	0.115	0.144	0.168
Space heating (districts)	571-1566	0.063	0.079	0.093
Greenhouses	500-1000	0.033	0.043	0.050
Uncovered aquaculture ponds	50-100	0.036	0.037	0.038
GHP (residential)	938-1400	0.072	0.088	0.101
GHP (commercial)	938-3751	0.088	0.114	0.135

LCOE of the several direct uses included in Table 4.10 were calculated with the calculator by Verbruggen and Nyboer (2009). For building heating it was assumed a load factor of 0.30 and 20 years as the lifetime. For district heating was used the same load factor but 25 years of lifetime. District heating may be provided in the form of either steam or hot water and may be utilised to meet process, space or domestic hot water requirements. Often fossil fuel peaking is used to meet the coldest period, rather than drilling additional wells or pumping more fluids, as geothermal can usually meet all the load most of the time, thus improving the efficiency and economics of the system (Bloomquist et al., 1987). Thermal load density (heating load per unit of land areas) is critical to the feasibility of district heating because it is one of the major determinants of the distribution network capital and operating costs. Thus, downtown, high rise buildings are better candidates than single family residential area. Generally a thermal load density about 1.2 x 10^9 J/hr/ha is recommended.

For LCOE calculation of greenhouses it was assumed a load factor of 0.50 and for aquaculture ponds and tanks of 0.60, with the same lifespan of 20 years. Covered ponds and tanks would have higher capital cost than uncovered, but lower heating requirements.

Geothermal (ground-source) heat pump projects costs vary between residential installation and commercial/institutional installations, as the larger the building to be heated and/or cooled, the lower the unit (US$/kWt) investment and operating costs. In addition, the type of installation, closed loop (horizontal or vertical) or open loop using ground water, has a large influence on the installed cost (Lund and Boyd, 2009). The LCOE reported in Table 4.10 assumed 0.30 as load factor and 20 years as operational lifetime.

Industrial applications are more difficult to quantify, as they vary widely depending upon the energy requirements and the product to be produced. These plants normally require higher temperatures and often compete with power plant use; however, they do have a high load factor of 0.40 to 0.70, which improves the economics. Industrial applications vary from large food, timber and mineral drying plants (US and New Zealand) to pulp and paper plant (New Zealand). As an example, a large onion dehydration plant in the US (Nevada) uses 210 x 10^{12} J/year for drying 4500 kg/hour of wet onions over a 250 day period. This plant cost MUS$ 12.5 with the geothermal system, including wells adding MUS$ 3.37. The annual operation cost is MUS$ 5.63 and annual energy savings of MUS$ 1.5. With annual sales of MUS$ 5.63, a positive cash flow is realised in about two years (Lund, 1995).

4.8 Potential Deployment

Geothermal energy can contribute to near- and long-term carbon emissions reduction. In 2008 the worldwide geothermal-electric generation was 67.2 TWh_e (Sections 4.4.1 and 4.7.3) and the heat generation from geothermal direct-uses was 121.7 TWh_t (Section 4.4.3). These amounts of energy are equivalent to 0.24 and 0.44 EJ/y, respectively, for a total of 0.68 EJ/y (direct equivalent method). This represents only ~0.13% of the global primary energy demand in 2007. However, on a global basis, by 2050 geothermal could supply 2.5-4.1% of the global electricity demand and almost 5% of the global demand of heat-cooling, as it is shown in section 4.8.2.

This section starts by presenting the near-term (2015) global and regional deployments expected for geothermal energy (electricity and heat) based on current geothermal-electric projects under construction or planned, observed historic growth rates, as well as the forecast generation of electricity and heat. Subsequently, this section presents the long-term (2020, 2030, 2050) global and regional deployments comparing it to the IPCC AR4 estimate, includes results from scenarios provided by Chapter 10 of this report, and discusses their feasibility in terms of technical potential, regional conditions, supply chain aspects, technological-economic conditions, integration-transmission issues and environmental and social concerns. Finally, the section presents a short conclusion regarding the potential deployment.

4.8.1 Near-term forecasts

Historic growth rates of geothermal-electric capacity in the world over the past 40 years were presented in Table 4.5, as well as the growth rates of geothermal direct uses (heat) in the last 35 years. For power, the historic average annual rate is 7.0% and for direct uses 11%.

On the other hand, according to the latest country-update reports, the capacity of geothermal-electric projects stated as under construction or planned is expected to reach 18,500 MWe by 2015 (Bertani, 2010). This represents an annual average growth of 11.5%, higher than the historic rate, but is based on the present (BAU) conditions and expectations of geothermal markets.

For geothermal direct uses (heat applications) it is expected that the annual growth rate will be between the historic average rate (11%) and the rate over the last 5 years (2005-2010: 16.1%, Table 4.5). The average is 13.5% resulting in 95,300 MW_t by 2015. The expected deployments and generation by 2015 and by regions are presented in Table 4.11.

Table 4.11 Regional current and forecast installed capacity for geothermal power and direct uses (heat) and forecast generation of electricity and heat in the near-term.

REGION	Current capacity (2010)		Forecast capacity (2015)		Forecast generation (2015)	
	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)	Direct (TWh_t)	Electric (TWh_e)
1. OECD North America	13.893	4.052	30.7	6.5	80.8	43.1
2. Latin America	0.808	0.509	1.2	1.1	3.2	7.2
3. OECD Europe	20.357	1.551	36.6	2.1	96.2	13.9
4. Africa	0.13	0.174	2.5	0.6	6.5	3.8
5. Transition Economies	1.063	0.082	1.8	0.2	4.8	1.3
6. Middle East	2.362	0	3.1	0.0	8.2	0.0
7. Developing Asia	0.052	3.158	2.1	6.1	5.4	39.9
8. India	0.265	0	1.2	0.0	3.2	0.0
9. China	8.898	0.024	12.3	0.1	32.3	0.4
10. OECD Pacific	2.755	1.165	3.7	1.8	9.7	11.9
TOTAL	**50.583**	**10.715**	**95.3**	**18.5**	**250.4**	**121.6**

Notes: Current and forecast data for electricity taken from Bertani, 2010, and for direct uses from Lund et al., 2010. Average annual growth rate in 2010-2015 is 11.5% for power and 13.5% for direct uses.

For power, practically all the new power plants expected by 2015 will be conventional (flash and binary) in hydrothermal resources, with only a marginal contribution of EGS projects. In general terms, the worldwide trends in development of EGS are estimated to be slow in the next 5-10 years, and then present an accelerated growth.

On a regional basis, the deployment potential for harnessing identified and prospective conventional hydrothermal resources varies significantly. In Europe and Central Asia, there are a few countries that have well-developed high temperature resources (e.g. Italy and Turkey, see Figure 4.2). Many other European and Asian countries have huge under-developed hot water resources, of lower temperature, located within sedimentary basins at various depths (e.g. Paris, Pannonian, and Beijing basins). In the African continent, Kenya was the first country to utilise its rich hydrothermal resources for both electricity generation and direct use, and several other countries along the East African Rift Valley may follow suit.

The existing installed capacity in North America (US and Mexico) of 4 GWe, mostly from mature developments, is expected to increase by almost 60% in the short term, mainly in the US (from 3094 to 5400 MWe, according to Bertani, 2010). In the Central American countries the geothermal potential for electricity generation has been estimated to be 4 GWe (Lippmann, 2002) of which 12% has been harnessed so far (~0.5 GWe). South American countries, particularly along the Andes mountain chain, also have significant untapped --and under-explored-- hydrothermal resource potentials (at least 2 GWe).

For island nations with mature histories of geothermal development, such as New Zealand, Iceland, Philippines, and Japan, identified geothermal resources imply a future expansion potential of 2 to 5 times existing installed capacity, although constraints such as limited grid capacity, existing or planned generation (from other renewable energy sources) and environmental factors (such as National Park status of some resource areas), may limit the conventional geothermal deployment. Indonesia is one of the world's richest countries in geothermal resources, and other volcanic islands in the Pacific Ocean (Papua-New Guinea, Solomon, Fiji, etc.) and the Atlantic Ocean (Azores, Caribbean, etc.), have significant potential for growth from known hydrothermal resources, but are also grid constrained in growth potential.

Remote parts of Russia (Kamchatka) and China (Tibet) contain identified high temperature hydrothermal resources, the use of which could be significantly expanded given the right incentives and access to load. Parts of other South-East Asian nations (including India) contain numerous hot springs, inferring the possibility of potential, as yet unexplored, hydrothermal resources.

Taking the projected capacity factor (CF) for electric generation by 2015 (75% in Table 4.9), the expected generation of electricity for every region is also shown in Table 4.11. Of course, there will be variations in the CF for each region, but with the projected worldwide average it is expected that total electric generation will reach 121,590 GWh/y (Table 4.9) or 121.6 TWh/y (Table 4.11), equivalent to 0.44 EJ/y.

For geothermal direct uses projection on an annual growth rate of 13.5% results in 95,280 MWt (95.3 GWt) by 2015 with the regional contribution presented in Table 4.11. Using an average worldwide CF of 30% the expected generation of heat by 2015 will be 250,385 GWh_t/y or 250.4 TWh_t/y, equivalent to 0.9 EJ/y.

Expected high average annual growth of 13.5% in the geothermal direct use market is closely linked to the fact that space and water heating are significant parts of the energy budget in large parts of the world. In industrialised countries, 35 to 40% of the total primary energy consumption is used in buildings. In Europe, 30% of energy use is for space and water heating alone, representing 75% of total building energy use (Lund et al., 2010). The high potential deployment is due in large part to the ability of GHP to utilise groundwater or ground-coupled heat exchangers anywhere in the world. This use has large potential for replacing current energy-use in buildings.

4.8.2 Long-term deployment in the context of carbon mitigation

The IPCC Fourth Assessment Report (AR4) estimated a potential contribution of geothermal to the world electricity supply by 2030 of 633 TWh/y (2.28 EJ/y), equivalent to ~2% of the total (Sims et al., 2007; see Chapter 4.4.3). Other forecasts for 2020, 2030 and 2050 are presented in Table 4.12. As shown in this table, the IPCC AR4 estimate is a little higher than the maximum scenario of electric generation by 2030 (ETP 2008, Blue map scenario).

Table 4.12 Available scenarios of geothermal-electric installed capacity and generation of electricity in the long-term.

Year	Forecast installed capacity (GWe)			Forecast electric generation (TWh/y)		
	Min	Mid	Max	Min	Mid	Max
2020 (Reference)	19 (a)	33 (b)	57 (c)	128 (a)	231 (b)	392 (c)
2030 (Reference)	28 (a)	71 (b)	87 (c)	199 (a)	488 (b)	611 (c)
2050 (Reference)	38 (d)	134 (e)	152 (c)	264 (d)	934 (e)	1059 (c)

References: (a): IEA-WEO 08 (550 ppm policy scenario), (b): EREC-GPI 08, (c): ETP 2008 (Blue map scenario); (d): ETP 2008 (Base scenario); (e): ETP 2008 (ACT scenario).

A number of different scenarios with the contribution of geothermal resources have been modelled from the integrated assessment models presented in Chapter 10 of this report, taking into account the stabilization categories of CO_2 emissions regarded by the IPCC AR4 and grouping them into three: categories I+II (300-440 ppm), III+IV (440-600 ppm) and V+VI (600-1000 ppm). Results are presented in Figure 4.8; Primary Energy is provided as direct-equivalent, i.e. each unit of heat or electricity from RE (except from biomass) is accounted for as one unit at the primary energy level.

Projections of geothermal energy contribution to the global primary energy supply span a very broad range: up to 11.9 EJ/y in 2020, 21.3 EJ/y in 2030 and 50.1 EJ/y in 2050, taking the more stringent carbon mitigation policies (300-440 ppm in all years), and are sensitive to the carbon policy assumed by each projected year. Medians of all those scenarios are also sensitive to the carbon policy, ranging 0.39-0.68 EJ/y by 2020, 0.22-1.2 EJ/y by 2030 and 1.09-3.85 EJ/y by 2050, in all cases considering the baseline (600-1000 ppm) and the 300-440 ppm scenarios (Fig. 4.8).

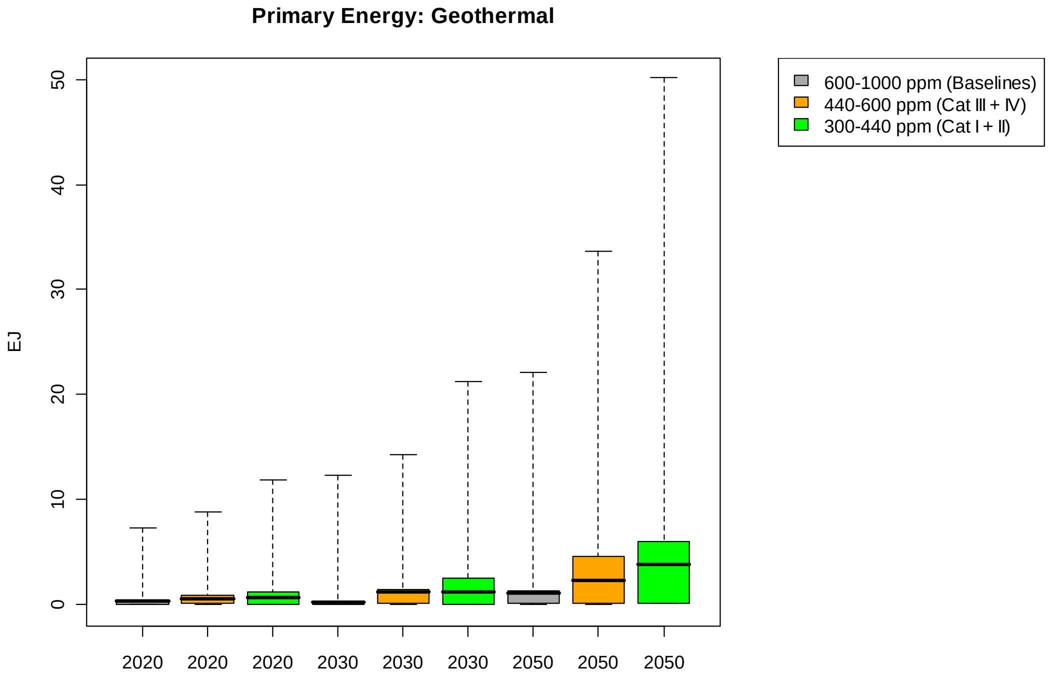

Figure 4.8 Primary energy from geothermal resources in the context of carbon mitigation for 2020, 2030 and 2050. Thick black line is the median, the coloured box corresponds to interquantile range 25th-75th percentile, and whiskers correspond to the total range across all scenarios. [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

These amounts are not completely comparable with the IPCC AR4 estimate by 2030, since this included only geothermal-electric generation without reference to the geothermal contribution for heat supply. But even so, it is clear that the 2.28 EJ/y of electric generation estimated by the IPCC AR4 by 2030 results well above the medians considered by 2030, but lies in the 25-75% percentile for the more restricted scenario (Fig. 4.8).

Based on the current geothermal-electric and direct uses installed capacity and the near-term projections presented in Table 4.11, the long-term regional deployments presented in Table 4.13 were obtained. For electric power deployment, it was assumed that the average annual rate growth for 2015-2030 will be the historic rate (7%), and for 2030-2050 an annual rate growth of 5.9% is expected. Both rates are lower than the near-term rate (2010-2015) of 11.5%. All of these forecasts include EGS projects deployment.

For direct uses deployment, the assumed average annual rate growths were: 11% for 2015-2020 (historic rate, see Table 4.5), 9% for 2020-2030, 5.5% for 2030-2040 and 2.5% for 2040-2050, reflecting an expected decrease in the average annual rate of growth.

Table 4.13 Regional long term forecasts of installed capacity for geothermal power and direct uses (heat) and global forecast of electric and direct uses (heat) generation.

REGION	**2020**		**2030**		**2050**	
	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)
1. OECD North America	51.8	9.2	121.6	16.7	234.5	45.4
2. Latin America	2.1	1.5	5.1	3.0	10.2	8.5
3. OECD Europe	62.2	3.0	151.0	5.8	305.9	25.3
4. Africa	4.1	0.8	11.1	1.6	18.4	7.0
5. Transition Economies	3.1	0.3	5.1	0.6	10.2	4.8
6. Middle East	4.1	0.0	5.2	0.1	7.1	2.2
7. Developing Asia	4.2	8.5	10.0	15.3	20.4	35.2
8. India	2.1	0.0	5.1	0.2	10.2	2.8
9. China	20.7	0.1	50.7	2.8	127.5	13.7
10. OECD Pacific	6.2	2.5	15.2	5.0	86.7	15.7
TOTAL	**160.5**	**25.9**	**380.1**	**51.0**	**831.1**	**160.6**
Expected global generation (thermal and electric) in:	TWh$_t$/y	TWh$_e$/y	TWh$_t$/y	TWh$_e$/y	TWh$_t$/y	TWh$_e$/y
	421.9	181.8	998.8	380.0	2184.0	1266.4
	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y
	1.52	0.65	3.60	1.37	7.86	4.56

Comparing the global forecasts for electric power with those presented in Table 4.12, one can see they are located between the minimum and medium estimates for 2020 and 2030, but are higher than the maximum estimates for 2050. For 2030, the projected electric generation (380 TWh/y or 1.37 EJ/y) is lower than the IPCC AR4 estimate of 633 TWh/y or 2.28 EJ/y.

Considering that the world electricity demand is projected to be between 25,743 (IEA-WEO 08) and 27,708 TWh/y (EREC-GPI 08) by 2020, geothermal would share around 0.7%of the total. For 2030 projections go from 28,997 to 33,265 TWh/y (IEA-WEO 08), and thus geothermal would share between 1.1% and 1.3% of the total electric demand. For 2050 estimates are between 30,814

(EREC-GPI 08) and 50,606 TWh/y (IEA-WEO 08), and then geothermal electricity would contribute with 2.5%-4.1% of the global electricity demand.

On the other hand, ERC-GPI 08 projects the global demand of heating-cooling by 2020 to be 156.8 EJ/y, by 2030 to be 162.4 EJ/y and by 2050 to be 161.7 EJ/y. Then, geothermal generation of heat by direct applications would supply about 1% of the total demand by 2020, 2.2% by 2030, and 4.9% by 2050.

According to the estimates in Table 4.13, total contribution (thermal and electric) of geothermal energy would be 2.17 EJ/y by 2020, 4.97 EJ/y by 2030, and 12.42 EJ/y by 2050. Considering each unit of heat or electricity accounted for as one unit at the primary energy level, these estimates are placed in the 75th-100th percentile of the Figure 4.8. Therefore, the estimates included in that figure in the 25th-75th percentile, including the mean, are feasible for 2020, 2030 and 2050.

To achieve the potential deployments presented in Table 4.13 and even the more conservative deployments shown by Fig. 4.8, economic incentive policies to reduce GHG emissions and increase RE will probably be necessary. Policy support for research and development would assist some geothermal technologies to demonstrate and commercialise EGS and other non-conventional geothermal resource development. This policy support could include subsidies, guarantees and tax write-offs to cover the risks of initial deep drilling and long term productivity. Feed-in tariffs with confirmed geothermal prices, and direct subsidies for district and building heating would also help to accelerate deployment. In addition, the following issues are worth to be highlighted.

Resource potential: Even the highest estimates for long-term contribution of geothermal energy to the global primary energy supply (50.1 EJ/y by 2050, Fig. 4.8), are well within the technical potentials described in section 4.2 (91 up to 1043 EJ/y for electricity and 10 up to 322 EJ/y for heat, Fig. 4.1). Thus, technical resource potential is not likely to be a barrier to reach the most aggressive levels of geothermal deployment (electricity and direct uses) in a global or regional basis.

Regional deployment: Forecast long-term (2020, 2030 and 2050) deployments for the IEA regions are presented in Table 4.13. The worldwide average annual rates of growth estimated for electricity deployment and for direct uses deployments are not the same for every region. Availability of financing, water, transmission and distribution infrastructure and other factors will play major roles in regional deployment rates. For instance, in the US, Australia, and Europe, EGS concepts are already being field tested and deployed, providing advantages for accelerated deployment in those regions as risks and uncertainties are reduced. In other rapidly developing regions in Asia, Africa, and South America, factors that would affect deployment are population density, market distance, electricity and heating and cooling demand.

Supply chain issues: Regional differences in technology development (for instance, deep drilling and reservoir management) may affect the adequate supply of labour and materials for geothermal deployment, but no relevant middle- or long-term constraints to materials supply, labour availability or manufacturing capacity are foreseen from a global perspective.

Technology and economics: Direct heating technologies using GHP, district heating and EGS methods are available, with different degrees of maturity. GHP systems have the widest market penetration, and an increased deployment will be supported by improving the coefficient of performance and installation efficiency. The direct use of thermal fluids from deep aquifers, and heat extraction using EGS, can be increased by further technical advances associated with accessing and engineering fractures in the geothermal reservoirs. Reducing sub-surface exploration risks will contribute to more efficient and sustainable development. Better reservoir management will optimize reinjection strategy, avoid excessive depletion, and plan future make-up well requirements, to achieve sustainable production. Improvement in energy utilisation efficiency from cascaded use of geothermal heat is an important deployment strategy. Evaluating the performance of geothermal plants, including heat and power EGS installations, will consider heat quality of the fluid by differentiating between the energy and the exergy or availability content (that part of the energy that can be converted to electric power). All of these technological improvements will lead to significantly reduce the capital costs and the LCOE of geothermal energy.

Integration and transmission: Due to the site-specific geographic location of conventional hydrothermal resources, there are some current transmission constraints for further deployments. However, no integration problems have been observed once transmission issues are solved, due to the base-load characteristic of geothermal electricity. In a long-term perspective, no transmission constraints are foreseen since EGS developments are less geography-dependant, even though the EGS's resource grades can vary substantially on a regional basis.

Social and environmental concerns: Concerns expressed about geothermal energy development include the possibility of induced local seismicity associated with hydro-fracturing in EGS, water usage by geothermal power plants in arid regions, land subsidence in some circumstances, fear of water and soil contamination, and potential impacts of facilities on scenic quality and use of natural areas and features (as geysers) that might otherwise be used for tourism. However, sound practices protect natural thermal features valued by the community, minimise any adverse effects from disposal of geothermal fluids and gases, induced seismicity and ground subsidence, and can optimize water and land use.

4.8.3 Conclusions regarding deployment

Overall, the geothermal-electric market appears to be accelerating compared to previous years, as indicated by the trends in both the number of new megawatts of power capacity installed and under development (Bertani, 2010). The gradual introduction of new technology improvements including EGS is expected to boost the growth rate exponentially after 10-20 years, reaching an expected global target of ~160 GWe by 2050 (Table 4.13). Some of the new technologies are entering the field demonstration phases to prove commercial viability (EGS), or early investigation stages to test practicality (utilization of supercritical temperature and submarine hydrothermal vents or off-shore resources). Power generation with binary plants opens up the possibility of producing electricity in countries which do not have high-temperature resources or may have requirements for total injection.

Direct use of geothermal energy for heating and cooling is currently commercially competitive, using accessible, hydrothermal resources. A moderate increase is expected in the future development of such hydrothermal resources for direct use, but a sustained compound annual growth is expected with the deployment of GHP and direct use in lower grade regions, which can be used for heating and/or cooling in most parts of the world, reaching up to 815 GWt by 2050 (Table 4.13). Marketing the cost/benefit advantages of direct use, including the inclusion of GHPs in programs, will support the uptake of RE and increase efficiencies of using existing electricity supplies by creating necessary infrastructure for widespread deployment.

Projections suggest that geothermal energy can provide 1.2% of the total electric demand by 2030 and between 2.5% and 4.1% by 2050. It also can provide 2.2% of the global demand for heat-cooling in 2030 and 4.9% by 2050.

Evidence suggests that the global and regional availability of geothermal resources is enough to meet the results of the modelled scenarios, and also that projected market penetration seems to be reasonable. With its natural thermal storage capacity, geothermal is especially suitable for supplying base-load power, and thus is uniquely positioned to play a key role in climate change mitigation strategies.

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 5

Hydropower

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Author(s):	CLAs:	Arun Kumar, Tormod A. Schei				
	LAs:	Alfred K. Ofosu Ahenkorah, Jesus Rodolfo Caceres, Jean-Michel Devernay, Marcos Freitas, Douglas G. Hall, Ånund Killingtveit, Zhiyu Liu				
	CAs:	Emmanuel Branche, Karin Seelos				
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All monetary values provided in this document will need to be adjusted for inflation/deflation and converted to US$ for the base year 2005.

Chapter 5: Hydropower

CONTENTS

EXECUTIVE SUMMARY

Hydropower is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable and price competitive technology. Hydropower has the best conversion efficiency of all known energy sources (about 90% efficiency, water to wire). It also has the highest energy payback ratio. Hydropower requires relatively high initial investment, but has the advantage of very low operation costs and a long lifespan. Life-cycle costs are deemed low.

The total worldwide technically feasible potential for hydropower generation is 14,368 TWh per year with a corresponding estimated total capacity potential of 3,838 GW; five times the current installed capacity. Undeveloped capacity ranges from about 70 percent in Europe and North America to 95 percent in Africa indicating large opportunities for hydropower development worldwide. The distribution and magnitude of the resource potential for hydropower could change due to a changing climate however the total amount of water in the hydrologic cycle will remain the same. Global effects on existing hydropower systems will however probably be small, even if individual countries and regions could have significant changes in positive or negative direction.

Hydropower has been a catalyst for economic and social development of many countries. According to the World Bank, large hydropower projects can have important multiplier effects creating an additional 40-100 cents of indirect benefits for every dollar of value generated. Hydropower can serve both in large centralized and small isolated grids. Nearly two billion people in rural areas of developing countries do not have electricity. Small scale hydro can easily be implemented and integrated into local ecosystems and might be one of the best options for rural electrification through stand alone or local grids, while large urban areas and industrial scale grids need the flexibility and reliability of reservoir and pumped storage hydro.

Hydropower is available in a broad range of projects scales and types. Projects are usually designed to suit particular needs and specific site conditions. Those can be classified by project type, head or by purpose. There is no consensus on size wise categories. Classifications by size are different worldwide due to varying development policies in different countries. The hydropower project types are: run-of-river, reservoir based and pumped storage.

Typical impacts ranging from negative to positive are well known both from environmental and social aspects. Good experience gained during past decades in combination with continually advancing sustainability guidelines, innovative planning based on stakeholder consultations and scientific know-how is promising with respect to securing a high sustainability performance in future hydropower projects. Transboundary water management, including hydropower projects, establishes an arena for international cooperation which can contribute to promote peace, security and sustainable economic growth. Ongoing research on technical (e.g. variable speed generation), silt erosion resistive material and environmental issues (e.g. fish friendly turbines) may ensure continuous improvement and enhanced outcomes for future projects.

Renovation, modernisation & uprating (RM&U) of old power stations is cost effective, environment friendly and requires less time for implementation. There is a substantial potential for adding hydropower generation components to existing infrastructure like weirs, barrages, canals and ship locks. About 75% of the existing 45,000 large dams in the world were built for the purpose of irrigation, flood control, navigation and urban water supply schemes. Only 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multipurpose reservoirs.

Hydropower is providing valuable energy services as the generating units can be started or stopped almost instantly. It is the most responsive energy source for meeting peak demands and balancing unstable electricity grids, which enhances energy security. Storage hydropower therefore is ideal for backing up and regulating the intermittent renewable sources like wind, solar and waves, thus allowing for a higher deployment of these sources in a given grid. Also the flexibility and short response time may facilitate nuclear and thermal plants to operate at their optimum steady state level thereby reducing their fuel consumption and emissions. Life cycle analysis indicates that hydropower is among the cleanest electricity options with a low carbon footprint. In March 2010, 2062 hydropower projects where in the CDM pipeline, representing 27% of CDM applications.

In addition to mitigate global warming, hydropower with storage capacity can also mitigate freshwater scarcity by providing water security during lean flows and drought in dry regions of the world. By 2035, it is projected that 3 billion people will be living in conditions of severe water stress. Water, energy and climate change are inextricably linked. Water storage facilities have an important role in providing energy and water for sustainable development. It is anticipated that climate change will lead to modifications of the hydrological regimes in many countries, introducing additional uncertainty into water resources management. In order to secure water and energy supply in a context of increasing hydrological variability, it will be necessary to increase investment in infrastructure sustaining water storage and control.

Creating reservoirs is often the only way to adjust the uneven distribution of freshwater in space and time. Freshwater is an essential resource for human civilisation. For this reason freshwater storage is a mean to respond to manifold needs, such as water supply, irrigation, flood control and navigation. Sitting at the nexus of water and energy, multipurpose hydropower projects may have an enabling role beyond the electricity sector as a financing instrument for reservoirs, helping to secure freshwater availability.

5.1 Introduction

This chapter describes hydropower technology. It starts with a brief historical overview of how the technology has evolved, the resource base and how it is affected by climate change, and gives a description of the technology and its social and environmental impacts. Also included is a summary of the present global and regional status of market and the hydropower industry, and projections for future development of technology and deployment of hydropower, both in the near (2015), medium (2030) and long term (2050). In this chapter the focus is solely on the generation of electrical energy from water. Mechanical energy generation for mills, water pumps, sawmills etc is not treated here.

5.1.1 Source of energy

The source of hydropower is water moving in the hydrological cycle. The source of hydropower therefore comes from the sun, since it is the solar radiation and absorbed solar energy that keeps the hydrological cycle active. Incoming solar radiation is absorbed at the land or sea surface, heating the surface and creating evaporation of water where water is available. A very large percentage, close to 50% of all the solar radiation input to the earth, is used to evaporate water and drive the hydrological cycle. The potential energy from tapping this cycle is therefore huge, but only a very limited amount may be practically harvested. Evaporated water moves into the atmosphere and increases the water vapour content in the air. Global, regional and local wind systems, generated and maintained by spatial and temporal variations in the solar energy input, will move the air and its vapour content over the surface of the earth, up to thousands of kilometres from the origin of evaporation. Finally, the vapour will condense and fall as precipitation, about 78% on oceans and 22% on land. This creates a net transport of water from the oceans to the land surface of the earth, and an equally large flow of water back to the oceans as river and groundwater runoff. It is the flow of water in the rivers that can be used to generate hydropower, or more precisely the potential energy of water moving from higher to lower ground on its way back to the ocean, driven by the force of gravity. Since most precipitation usually falls in mountainous areas, where also the elevation differences (called head by hydropower engineers) is largest, we usually find the largest potential for hydropower development in mountainous regions, or in rivers coming from such regions. The total surface runoff has been estimated to be 47 000 km^3, with a theoretical potential for hydropower generation of ca 41,000 TWh/year (UNDP/UNDESA/WEC, 2000; 2004).

Hydropower is both renewable and sustainable, it is not possible to deplete the resource as long as the sun keeps the hydrological cycle running. In fact, hydropower, wind power and ocean wave power (but not tidal power) are all generated by solar energy, and their distribution and magnitude are determined by the global climate and wind systems, water distribution and the topography. Using these sources is therefore equivalent to a direct harvesting of solar power.

5.1.2 History of hydropower development

Hydropower, hydraulic power or water power is power that is derived from the force or energy of moving water, which may be harnessed for useful purposes. Prior to the widespread availability of commercial electric power, hydropower was used for irrigation and operation of various machines, such as watermills, textile machines and sawmills etc. By using water for power generation, people have worked with nature to achieve a better lifestyle. The mechanical power of falling water is an age-old tool. It was used by the Greeks to turn water wheels for grinding wheat into flour, more than 2,000 years ago. In the 1700's mechanical hydropower was used extensively for milling and pumping. During the 1700s and 1800s, water turbine development continued. In 1880, a brush arc light dynamo driven by a water turbine was used to provide theatre and storefront lighting in Grand Rapids, Michigan; and in 1881, a brush dynamo connected to a turbine in a flour mill provided street lighting at Niagara Falls, New York. The breakthrough came when the electric generator was coupled to the turbine, which resulted in the world's first hydroelectric station was commissioned on September 30, 1882 on Fox River at Vulcan Street Plant Appleton, Wisconsin, USA (United States Bureau of Reclamation USBR).

Hydropower was the first technology to generate electricity from a renewable source and is presently the only renewable where the largest plants produce between 80-100 TWh/year (Itaipu-Brazil and Three Gorges-China). Hydropower projects are always site-specific and thus designed according to the river system they inhabit. Its great variety in size gives the ability to meet both large centralized urban energy needs as well as decentralized rural needs. In addition to mitigating climate change, hydropower's flexibility in size also creates opportunities towards meeting an increasing need for freshwater, especially when reservoirs are constructed.

Contemporary hydropower plants generate anywhere from a few kW, enough for a single residence, to several thousands of MW, power enough to supply a large city and region. Early hydropower plants were much more reliable and efficient than the fossil fuel fired plants of the day. This resulted in a proliferation of small to medium sized hydropower stations distributed wherever there was an adequate supply of moving water and a need for electricity. As electricity demand grew, coal and oil fuelled power plants increased. Several hydropower plants involved large dams which submerged land to provide water storage. This has caused great concern for environmental impacts. Historic regional hydropower generation during 1965 to 2007 is shown in figure 5.1.

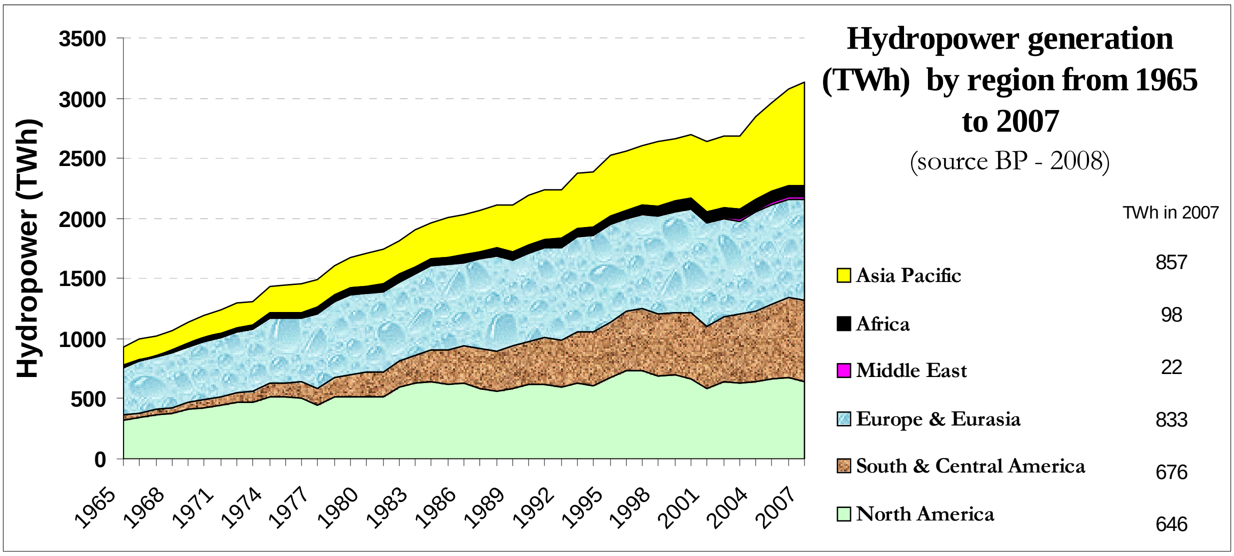

Figure 5.1: Hydropower generation (TWh) by region (BP, 2008).

5.1.3 Classification of hydropower projects

Hydropower projects can be classified by a number of ways which are not mutually exclusive:

- By size (large, medium, small, mini, micro, pico)
- By head (high or low)
- By purpose (single or multipurpose)
- By storage capacity (run-of-river, pond, seasonal, multi-year)
- By function (generation, pumping, reversible)
- By service type (base load, peaking, intermittent)
- By system design (Stand-alone or cascading)

The classification according to size (installed capacity) is the most frequent form of classification used. Yet, there is no worldwide consensus on definitions regarding size categories, mainly because of different development policies in different countries. Small scale hydropower plants have the same components as large ones. Compared to large scale hydropower, it takes less time and efforts to construct and integrate small hydro schemes into local environments. It has therefore been increasingly used in many parts of the world as an alternative energy source, especially in remote areas where other power sources are not viable. These power systems can be installed in small rivers or streams with little or marginal environmental effect.

Impacts on ecosystems will vary, however, not so much according to installed capacity or whether or not there is a reservoir, but by the design, where intakes, dams and waterways are situated and how much water flow is used for power generation compared to how much that is left as instream flow. The concept of small versus large hydro gives an impression of small or large negative impacts. This generalization will not hold as it is possible to construct rather large power plants with moderate impacts while the cumulative effects of several small power plants may be more adverse than one larger plant in the same area. It is more fruitful to evaluate hydropower based on its sustainability performance and based on the type of service provided as opposed to a classification based on technical units with little or no relevance for nature or society.

How high the water pressure on the turbines is will be determined by the difference between the upper water level (Intake) and the outlet. This difference is called head (the vertical height of water above the turbine). Head, together with discharge, are the most important parameter for deciding the type of hydraulic turbine to be used. Generally, for high heads, Pelton turbines are used, whereas Francis turbines are used to exploit medium heads. For low heads Kaplan and bulb turbines are applied. The classification of what is “High head” and “Low head” unfortunately varies widely from country to country, and no generally accepted rules can be found.

5.1.4 Multipurpose projects

As hydropower does not consume the water that drives the turbines, the water resource is available for various other uses essential for human subsistence. In fact, a significant proportion of hydropower projects are designed for multiple purposes. Accordingly to Lecornu (1998) about the third of all hydropower projects takes on various other functions aside from generating electricity. They prevent or mitigate floods and droughts, they provide the possibility to irrigate agriculture, to supply water for domestic, municipal and industrial use as well as they can improve conditions for navigation, fishing, tourism or leisure activities. One aspect often overlooked when addressing hydropower and the multiple uses of water is that the power plant, as a revenue generator, in some cases pays for the facilities required to develop other water uses, which might not generate sufficient direct revenues to finance their construction.

5.1.5 Maturity of technology

Hydropower is a proven and well advanced technology based on more than a century of experience. Hydropower schemes are robust, highly efficient and good for long-term investments with life spans of 40 years or more. Hydropower plants are unique, the planning and construction is expensive and the lead times are long. The annual operating and maintenance costs are very low compared with the capital outlay. Hydropower is an extremely flexible power technology. Hydro reservoirs provide built-in energy storage, and the fast response-time of hydropower enables it to be used to optimise electricity production across power grids, meeting sudden fluctuations in demand and helping to compensate for the loss of power from other sources (IEA-ETP, 2008). Hydropower provides an extraordinary level of services to the electric grid. The production of peak load energy from hydropower allows for the optimisation of base-load power generation from other less flexible sources such as nuclear and thermal power plants.

Hydropower has the best conversion efficiency of all known energy sources (~90%, water to wire) due to its direct transformation of hydraulic energy to electricity. It has the most favourable energy payback ratio considering the amount of energy required to build, maintain and fuel of a power plant compared with the energy it produces during its normal life span (see 5.4).

5.1.6 Policy

Hydropower infrastructure development is closely linked to more global national and regional development policies. Beyond its core role in contributing to energy security and reducing the country's dependence on fossil fuels, hydropower offers important opportunities for poverty alleviation and sustainable development. Hydropower also has a powerful contribution to make to regional cooperation, as good practice in managing water resources demands a river basin approach, regardless of national borders. In addition, multipurpose hydropower can strengthen a country's ability to adapt to climate change induced hydrological variability (World-Bank, 2009).

Hydropower development is not limited by physical or engineering potential. The main barriers are linked to a number of associated risks such as poor identification and management of environmental and social impacts, insufficient hydrological data, unexpected adverse geological conditions, lack of comprehensive river basin planning and regional collaboration, shortage of financing, scarcity of local skillful human resources. Those barriers are being addressed at policy level by a number of governments, international financing institutions (IFIs), professional associations and NGOs. Some examples of such policy initiatives impacting hydropower development are:

- The United Nations "Beijing Declaration on Hydropower and Sustainable Development" (2004) which underscores the strategic importance of hydropower for sustainable development, calling on governments and the hydropower industry to disseminate good practice, policy frameworks and guidelines and build on it to mainstream hydropower development that is economically, socially and environmentally sustainable, in a river basin context. The Declaration also calls for tangible action to assist developing countries to finance sustainable hydropower (United-Nations, 2004).

- The Action Plan elaborated during the African Ministerial Conference on Hydropower held in Johannesburg in 2006 (ADB 2006). This Action Plan aims inter alia at strengthening the regional collaboration, fostering the preparation of feasibility studies, streamlining legal and regulatory frameworks to build human capacity, promoting synergies between hydropower and other renewables, ensuring proper benefit sharing, expanded the use of CDM for hydropower projects in Africa.

- In 2009, the World Bank Group (WBG) has released its "Directions in Hydropower" which outline the rationale for the hydropower sector expansion and describes the WBG portfolio and renewed policy framework for tackling the challenges and risks associated with scaling up hydropower development. WBG's lending to hydropower has increased from less than US$ 250 million per year from 2002-04 to over US$ 1 billion in 2008 (World-Bank, 2009). [TSU: state US$2005 instead of US$; depending on origin consider converting this figure]

- In March 2010, the International Hydropower Association (IHA) has produced a policy statement on "Hydropower and the Clean Development Mechanism", supporting the current CDM reform being implemented by the CDM Executive Board as decided upon in Copenhagen (2009). Hydropower is the CDM's leading deployed renewable energy and CDM remains a key mechanism for fostering the mobilisation of private sector capital worldwide (Saili et al., 2010).

- The inter-governmental agreements signed between Laos and its neighbouring countries (Thailand, Vietnam, Cambodia) which create the necessary institutional framework for the development of major trans-boundary projects such as the 1088 MW Nam Theun 2 project developed under a Public-Private Partnership model (Viravong, 2008). The support of the World Bank and other IFIs has greatly helped mobilizing private loans and equity. The sales of electricity to Thailand have started in March 2010. Over the 25-year concession period, the revenues for the Government of Laos will amount to US$ 2 billion [TSU: state US$2005 instead of US$; depending on origin consider converting this figure], which will be used to serve the countries development objectives through a Poverty Reduction Fund (Fozzard, 2005).

- In India, following the announcement of a 50,000 MW hydro initiative by the Prime Minister in 2003, the Central Government has taken a number of legislative and policy initiatives, including preparation of a shelf of well-investigated projects and streamlining of statutory clearances and approval, establishment of independent regulatory commissions, provision for long-term financing, increased flexibility in sale of power, etc. India is also cooperating with Bhutan and Nepal for the development of their hydropower potential (Ramanathan et al., 2007).
- The U.S. Energy Secretary Chu said in November 2009 that hydropower capacity in the USA could “double with minimal impact to the environment”, largely by making better use of existing infrastructure. In March 2010, the U.S. Department of Energy, the U.S. Department of the Interior, and the U.S. Army Corps of Engineers signed a memorandum of understanding designed to foster development of hydropower resources that will serve the country's energy, environmental, and economic goals.

5.2 Resource potential

5.2.1 Worldwide Hydropower Potential

The International Journal of Hydropower & Dams *2005 World Atlas & Industry Guide* (IJHD, 2005) probably provides the most comprehensive inventory of current installed capacity, annual generation, and hydropower potential. The Atlas provides three measures of hydropower potential: gross theoretical, technically feasible, and economically feasible all as potential annual generation (TWh/year). The technically feasible potential values for the six regions of the world have been chosen for this discussion considering that gross theoretical potential is of no practical value and what is economically feasible is variable depending on energy supply and pricing which vary with time and by location.

The total worldwide generation potential is 14,368 TWh/yr (IJHD, 2005) with a corresponding estimated total capacity potential of 3,845 GW[1]; five times the current installed capacity. The generation and capacity potentials for the six world regions are shown in Figure 5.2. Pie charts included in the figure provide a comparison of the capacity potential to installed capacity for each region and the percentage that the potential capacity (undeveloped capacity) is of the combination of potential and installed capacities. These charts illustrate that undeveloped capacity ranges from about 70 percent in Europe and North America to 95 percent in Africa indicating large opportunities for hydropower development worldwide.

There are several notable features of the data in Figure 5.2. North America and Europe, that have been developing their hydropower resources for more than a century still have the sufficient potential to double their hydropower capacity; belying the perception that the hydropower resources in these highly developed parts of the world are “tapped out”. However, economically feasible

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[1] Derived value based on regional generation potentials **IJHD**, 2005: World Atlas & Industry Guide. International Journal of Hydropower and Dams, Wallington, Surrey, 383 pp. and average capacity factors shown in Figure 5.3.

potentials are subject to time dependent economic conditions and the sustainability policy choices given societies make. Most notably Asia and Latin America have outstandingly large potentials and along with Australasia/Oceania they have very large potential hydropower growth factors (potential capacity as a percentage of existing capacity are 440 to 640%). Africa has higher potential than either North America or Europe, which is understandable considering the comparative states of development. However, compared to its own state of hydropower development, Africa has the potential to develop 19 times the amount of hydropower currently installed.

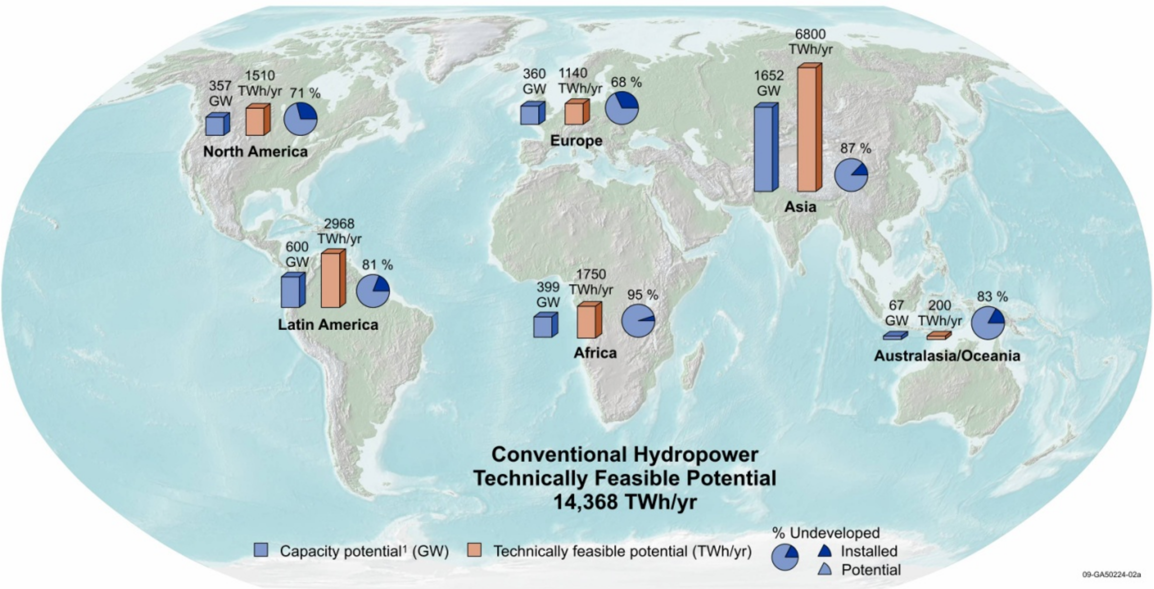


Figure 5.2: Regional hydropower potential in annual generation and capacity potential with comparisons of installed and potential capacities including undeveloped percentage of the total capacity (Source: (IJHD, 2005).

An understanding and appreciation of hydropower potential is best obtained by considering current total regional installed capacity (IJHD, 2005) and annual generation (2005/2006) (IJHD, 2007) shown in Figure 5.3. The 2005 reported worldwide total installed hydropower capacity is 746 GW producing a total annual generation of 3,032 TWh/yr averaged over 2005 and 2006. Figure 5.3 also includes regional average capacity factors calculated using regional total installed capacity and annual generation [capacity factor = generation/(capacity x 8760hrs)].

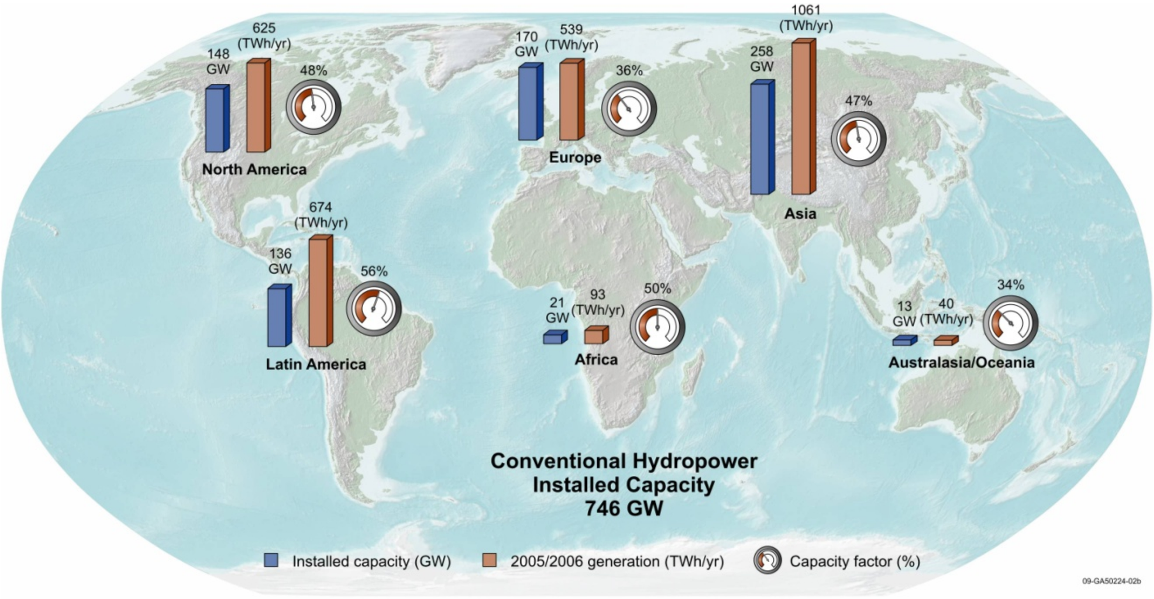


Figure 5.3: Total regional installed capacity (Source: (IJHD, 2005) 2005/2006 annual generation Source: IJHD (2007), and average capacity factor (derived as stated).

It is interesting to note that North America, Latin America, Europe, and Asia have the same order of magnitude of total installed capacity and not surprisingly, Africa and Australasia/Oceania have an order of magnitude less – Africa due to underdevelopment and Australasia/Oceania because of size, climate, and topography. The average capacity factors are in the typical range for hydropower (≈ 35 to 55%). Capacity factor can be indicative of how hydropower is employed in the energy mix (e.g., peaking vs base-load generation), water availability, or an opportunity for increased generation through equipment upgrades and operation optimization. Potential generation increases achievable by equipment upgrades and operation optimization have generally not been assessed.

The regional potentials presented above are for conventional hydropower corresponding to sites on natural waterways where there is significant topographic elevation change to create useable hydraulic head. Hydrokinetic technologies that do not require hydraulic head but rather extract energy in-stream from the current of a waterway are being developed. These technologies increase the potential for energy production at sites where conventional hydropower technology cannot operate. Non-traditional sources of hydropower are also not counted in the regional potentials presented above. Examples are constructed waterways such as water supply systems, aqueducts, canals, effluent streams, and spillways. Applicable conventional and hydrokinetic technologies can produce energy using these resources. While the generation potential of in-stream and constructed waterway resources have not been assessed, they are undoubtedly significant sources of emissions-free energy production based on their large extent.

Worldwide, hydropower has sufficient undeveloped potential to significantly increase its role as a full scale energy source. It can produce electricity with negligible green house gas emissions compared to the fossil energy sources currently in wide spread use. For this reason, hydropower has an important future role to play in mitigating climate change.

5.2.2 Impact of climate change on resource potential

The resource potential for hydropower is currently based on historical data for the present climatic conditions. With a changing climate, this potential could change due to:

- Changes in river flow (runoff) related to changes in local climate, particularly on precipitation and temperature in the catchment area. This may lead to changes in runoff volume, variability of flow and in the seasonality of the flow, for example by changing from spring/summer high flow to more winter flow, directly affected the potential for hydropower generation;
- Changes in extreme events (floods and droughts) may increase the cost and risk for the hydropower projects:
- Changes in sediment loads due to changing hydrology and extreme events. More sediment could increase turbine abrasions and decrease efficiency. Increased sediment load could also fill up reservoirs faster and decrease the live storage, reducing the degree of regulation, and decreasing storage services.

The most recent IPCC study of climate change, Assessment Report 4 (AR4), was published in 2007 (IPCC, 2007a). Possible impacts were studied by Working group II (WGII) and reported in ((IPCC, 2007a) which also included discussions on impact on water resources. Later, a Technical paper on Water was prepared based on the work in WGII and other sources (Bates *et al.*, 2008). The information presented in Chapter 5.2.2 is mostly based on these two sources, with a few additions from papers and reports published in 2008 and 2009 in order to assure that it is as up to date as possible.

5.2.3 Projected changes in precipitation

Climate change projections for the 21st century were developed in AR4. The projections were based on four different scenario families or "Storylines": A1, A2, B1 and B2, each considering a plausible scenario for changes in population and economic activity over the 21st century (IPCC, 2007b). The different storylines were used to form a number of emission scenarios, and each of these were used as input to a range of climate models. Therefore, a wide range of possible future climatic projections have been presented, with corresponding variability in projection of precipitation and runoff (IPCC, 2007a; Bates *et al.*, 2008).

Climate projections using multi-model ensembles show increases in globally averaged mean water vapour, evaporation and precipitation over the 21st century. A summary of results are shown in Figure 5.4. The figure shows % change in precipitation during 100 years, from 1990-99 to 2090-99. At high latitudes and in part of the tropics, all or nearly all models project an increase in precipitation, while in some sub-tropical and lower mid-latitude regions precipitation decreases in all or nearly all models. Between these areas of robust increase or decrease, even the sign of precipitation change is inconsistent across the current generation of models (Bates *et al.*, 2008).

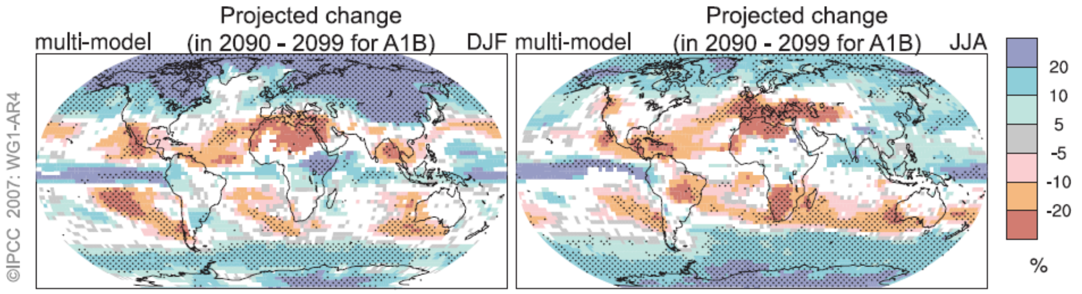


Figure 5.4: Projected multi-model mean changes in global precipitation for the SRES A1B Emission scenario. December to February at left, June to August at right. Changes are plotted only where more than 66% of the models agree on the sign of the change. The stippling indicates areas where more than 90% of the models agree on the sign of the change (IPCC, 2007b).

5.2.4 Projected changes in river flow

Changes in river flow due to climate change will primarily depend on changes in volume and timing of precipitation, evaporation and snowmelt. A large number of studies of the effect on river flow have been published and were summarized in AR4. Most of these studies use a catchment hydrological model driven by climate scenarios based on climate model simulations. Before data can be used in the catchment hydrological models, it is necessary to downscale data, a process where output from the GCM is converted to corresponding climatic data in the catchments. Such downscaling can be both temporal and spatial, and it is currently a high priority research area to find the best methods for downscaling.

A few global-scale studies have used runoff simulated directly by climate models (IPCC, 2007b).and hydrological models run off-line. [IPCC, 2007c] The results from these studies show increasing runoff in high latitudes and the wet tropics and decreasing runoff in mid-latitudes and some parts of the dry tropics. A summary of the results are shown in Figure 5.5.

Uncertainties in projected changes in the hydrological systems arise from internal variability in the climatic system, uncertainty in future greenhouse gas and aerosol emissions, the translations of these emissions into climate change by global climate models, and hydrological model uncertainty.

Projections become less consistent between models as the spatial scale decreases. The uncertainty of climate model projections for freshwater assessments is often taken into account by using multi-model ensembles (Bates *et al.*, 2008). Multi model ensembles approach is, however, not a guarantee of reducing uncertainty in mathematical models.

The global map of annual runoff illustrates a large scale and is not intended to refer to smaller temporal and spatial scales. In areas where rainfall and runoff is very low (e.g. desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet season runoff and decreased dry season runoff. Studies using results from few climate models can be considerably different from the results presented here (Bates *et al.*, 2008).

5.2.5 Projected effects on hydropower potential – Studies in AR4

Hydropower potential depends on topography and volume, variability and seasonal distribution of runoff. An increase in climate variability, even with no change in average runoff, can lead to reduced hydropower production unless more reservoir capacity is built. Generally, the regions with increasing precipitation and runoff will have increasing potential for hydropower production, while regions with decreasing precipitation and runoff will face a reduction in hydropower potential.

In order to make accurate quantitative predictions it is necessary to analyze both changes in average flow and changes in temporal distribution of flow, using hydrological models to convert time-series of climate scenarios into time-series of runoff scenarios. In catchments with ice, snow and glaciers it is of particular importance to study the effects of changes in seasonality, because a warming climate will often lead to increasing winter runoff and decreasing runoff in spring and summer. A shift in winter precipitation from snow to rain due to increased air temperature may lead to a temporal shift in stream peak flow and winter conditions (Stickler *et al.*, 2009) in many continental and mountain regions. The spring snowmelt peak is brought forward or eliminated entirely, and winter flow increases. As glaciers retreat due to warming, river flow increase in the short term but decline once the glaciers disappear (Kundzewicz *et al.*, 2008).

A number of studies of the effects on hydropower from climate change have been published, some reporting increased and some decreased hydropower potential. A summary of some of the findings related to hydropower can be found in (Bates *et al.*, 2008) largely based on work in IPCC (2007a). A summary from these findings are given below for each continent, with reference to IPCC (2007a) and relevant chapters:

5.2.5.1 Africa

The electricity supply in the majority of African States is derived from hydro-electric power. There are few available studies that examine the impacts of climate change on energy use in Africa (IPCC, 2007a).

5.2.5.2 Asia

Changes in runoff could have a significant effect on the power output of hydropower-generating countries such as China, India, Iran and Tajikistan etc.

5.2.5.3 Europe

Hydropower is a key renewable energy source in Europe (19.8% of the electricity generated). By the 2070s, hydropower potential for the whole of Europe is expected to decline by 6%, translated into a 20–50% decrease around the Mediterranean, a 15–30% increase in northern and Eastern Europe, and a stable hydropower pattern for western and central Europe (IPCC, 2007a).

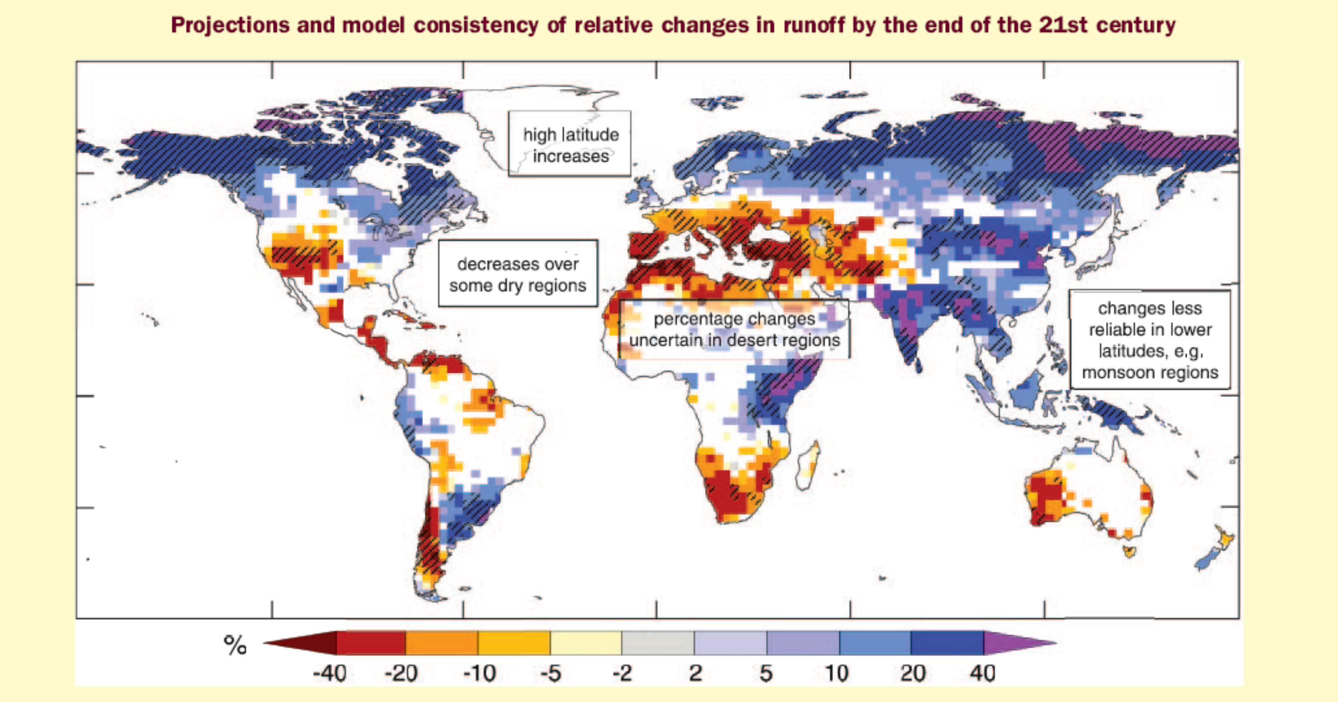


Figure 5.5: Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change (Bates et al., 2008).

5.2.5.4 Australia and New-Zealand

In Australia and New Zealand, climate change could affect energy production in regions where climate-induced reductions in water supplies lead to reductions in feed water for hydropower turbines and cooling water for thermal power plants. Hydropower is very important in New Zealand, supplying over 60% of electricity production. In New Zealand, increased westerly wind speed is very likely to enhance wind generation and spill over precipitation into major South Island hydro-catchments, and to increase winter rain in the Waikato catchment. Warming is virtually certain to increase melting of snow, the ratio of rainfall to snowfall, and to increase river flows in winter and early spring. This is very likely to increase hydro-electric during the winter peak demand period, and to reduce demand for storage (IPCC, 2007a).

5.2.5.5 South-America

Hydropower is the main electrical energy source for most countries in Latin America, and is vulnerable to large-scale and persistent rainfall anomalies due to El Niño and La Niña, as observed in Argentina, Colombia, Brazil, Chile, Peru, Uruguay and Venezuela. A combination of increased energy demand and droughts caused a virtual breakdown of hydro-electricity in most of Brazil in 2001 and contributed to a reduction in GDP. Glacier retreat is also affecting hydropower generation, as observed in the cities of La Paz and Lima (IPCC, 2007a)

5.2.5.6 North-America

Hydropower production is known to be sensitive to total runoff, to its timing, and to reservoir levels. During the 1990s, for example, Great Lakes levels fell as a result of a lengthy drought, and in 1999 hydropower production was down significantly both at Niagara and Sault St. Marie (IPCC, 2007a).For a 2–3°C warming in the Columbia River Basin and British Columbia Hydro service areas, the hydro-electric supply under worst-case water conditions for winter peak demand will be likely to increase (high confidence). Similarly, Colorado River hydropower yields will be likely to decrease significantly, as will Great Lakes hydropower. Lower Great Lake water levels could lead to large economic losses (Canadian $437–660 million/yr), with increased water levels leading to small gains (Canadian $28–42 million/yr). [TSU: convert to US $ 2005] Northern Québec hydropower production would be likely to benefit from greater precipitation and more open water conditions, but hydro plants in southern Québec would be likely to be affected by lower water levels. Consequences of changes in seasonal distribution of flows and in the timing of ice formation are uncertain. [IPCC, 2007c]

5.2.5.7 An assessment of global effect on hydropower resources

The studies reviewed in the literature predict both increasing and decreasing effect on the hydropower production, mainly following the expected changes in river runoff. So far no total figures have been presented for the global hydropower system.

In a recent study by Hamududu & Killingtveit (2010), the global effects on existing hydropower system were studied, based on previous global assessment of changes in river flow (Milly *et al.*, 2008) for the SRES A1B scenario using 12 different climate models. The estimated changes in river flow were converted to %-wise changes for each country in the world, compared to the present situation. For some of the largest and most important hydropower producing countries, a finer division into political regions was used (USA, Canada, Brazil, India, China and Australia). The changes in hydropower generation for the existing hydropower system (IJHD, 2005)were then computed for each country/region, based on changes in flow predicted from the climate models. Some of the results are summarized in Table 5.1. (Due to use of different sources the data in the table for 2005 will deviate slightly from those given in 5.2.1)

Table 5.1: Power generation capacity in GW and TWh/year (2005) and estimated changes (TWh/year) due to climate change by 2050. Results are based on analysis for SRES A1B scenario for 12 different climate models (Milly et al., 2008) and data for the hydropower system in 2005 (DOE, 2009). Results from Hamududu & Killingtveit (2010).

Region	Power Generation Capacity (2005)		Change by 2050 (TWh/yr)
	GW	TWh/yr	
Africa	22	90	0.0
Asia	246	996	2.7
Europe	177	517	-0.8
North America	161	655	0.3
South America	119	661	0.3
Oceania	13	40	0.0
TOTAL	737	2931	2.5

The somewhat surprising result from this study is that only small total changes seem to occur for the present hydropower system, even if individual countries and regions could have significant changes in positive or negative direction, as shown in the site-specific or regional studies (section 5.2.2.3). The future expansion of the hydropower system will probably mainly occur in the same areas as the existing system, since this is where most of the potential sites are located. Therefore, it can probably be stated that the total effects of climate change on the total hydropower potential will be small and slightly positive, when averaged over continents or globally. In practice, there might be problems to transmit surplus hydropower from regions with increasing to regions with decreasing hydropower production.

5.3 Technology and applications

5.3.1 Types

Hydro-Power Plant (HPP) is often classified in three main categories according to operation and type of flow. Run of River (RoR), reservoir based and pumped storage type projects are commonly used for different applications and situations. Hydropower projects with a reservoir also called storage hydropower deliver a broad range of energy services such as base load, peak, energy storage and acts as a regulator for other sources. Storage hydro also often delivers additional services which are going far beyond the energy sector such as flood control, water supply, navigation, tourism and irrigation. Pumped storage delivers its effect mainly when consumption is peaking. RoR HPP only has small intake basins with no storage capacity. Power production therefore follows the hydrological cycle in the watershed Nevertheless, some RoR HPPs also have small storage and are known as pondage-type plants.. For RoR HPP the generation varies as per water availability from rather short in the small tributaries to base-load in large rivers with continuous water flow.

5.3.1.1 Run of River (RoR)

A RoR HPP draws the energy for electricity production mainly from the available flow of the river. Such a hydropower plant generally includes some short-term storage (hourly, daily, or weekly), allowing for some adaptations to the demand profile. RoR HPPs are normally operated as base-load power plants. A portion of river water might be diverted to a channel, pipe line (penstock) to convey the water to hydraulic turbine which is connected to an electricity generator. Figure 5.6 shows such type of scheme. Their generation depends on the precipitation of the watershed area and may have substantial daily, monthly, or seasonal variations. Lack of storage may give the small RoR HPP situated in small rivers or streams the characteristics of a variable or intermittent source. Installation of small RoR HPPs is relatively cheap and has in general only minor environmental impacts. However, the relatively low investment does not allow putting aside a significant amount of financial resources for mitigation. RoR project may be constructed in the form of cascades along a river valley, often with a reservoir type HPP in the upper reaches of the valley that allows both to benefit from the cumulative capacity of the various power stations.

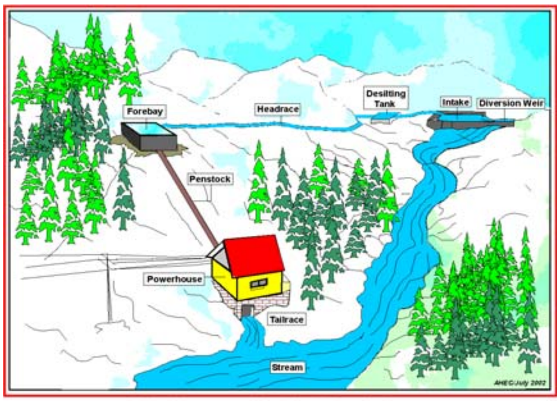
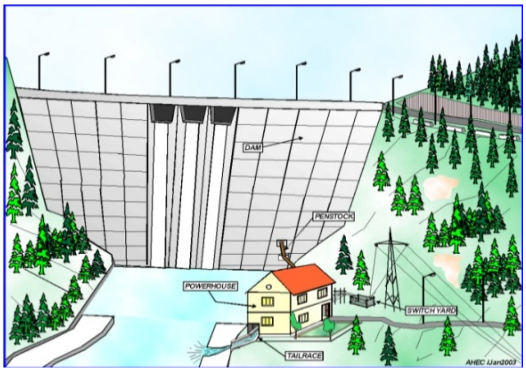


Figure 5.6: Run of river hydropower plant. (Shivasamudram, heritage, India)

(Source: Arun Kumar, AHEC IITR, India)

5.3.1.2 Reservoir

In order to reduce the dependence on the variability of inflow, many hydropower plants comprise reservoirs where the generating stations are located at the dam toe or further downstream through tunnel or pipelines as per the electricity or downstream water demand (Figure 5.7). Such reservoirs are often situated in river valleys. High altitude lakes make up another kind of natural reservoirs. In these types of settings the generating station is often connected to the lake serving as reservoir via tunnels coming up beneath the lake (lake tapping). For example, in Scandinavia natural high altitude lakes are the basis for high pressure systems where the heads may reach over 1000 m. The design of the HPP and type of reservoir that can be built is very much dependent on opportunities offered by the topography.



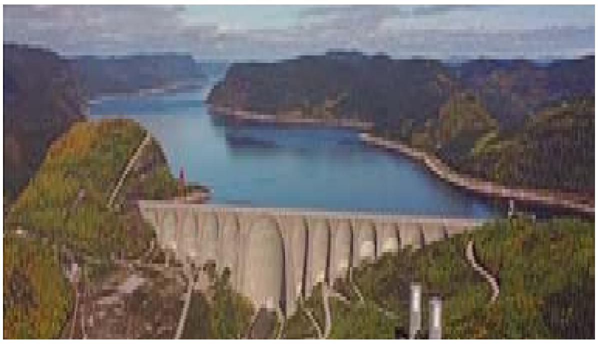


Figure 5.7: Hydropower plants with reservoir. (1,528 MW) Manic-5, Québec, Canada

(Source: Arun Kumar, AHEC IITR, India) (Vinogg *et al.*, 2003)

5.3.1.3 Pumped-storage

Pumped storage hydroelectricity is a type of hydroelectric power generation used by some power plants for load balancing. Pumped-storage plants pump water from a lower reservoir into an upper storage basin during off-peak hours using surplus electricity from base load power plants and reverse flow to generate electricity during the daily peak load period. Although the losses of the pumping process makes the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest. Pumped storage is the largest-capacity form of grid energy storage now available. It is considered to be one of the most efficient technologies available for energy storage. Figure 5.8 shows such type of development.

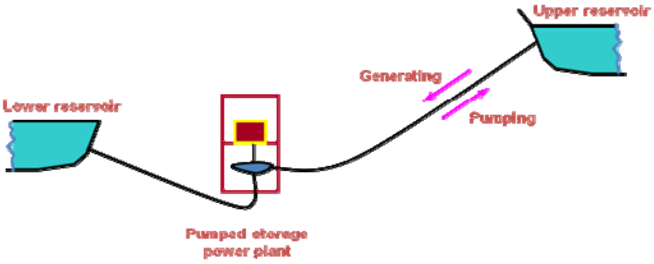


Figure 5.8: Pumped storage project (Source: IEA, 2000b). (Goldisthal, Thüringen Germany)

Source: (Taylor, 2008)

5.3.1.4 Instream technology using existing facilities

To optimise existing facilities like weirs, barrages, canals or falls, small turbines or hydrokinetic turbines can be installed for electricity generation. These are basically functioning like a run-of-river scheme shown in Figure 5.9. Hydrokinetic devices being developed to capture energy from tides and currents may also be deployed inland in both free-flowing rivers and in engineered waterways (se 5.7.4)

Figure 5.9: Typical arrangement of instream technology hydropower projects. (Narangawal,, India)

(Source: Arun Kumar, AEHC, IITR, India)

[TSU: rephrase figure captions in 5.3.1, figures 5.7 and 5.9 not readable]

5.3.2 Status and current trends in technology development

5.3.2.1 Efficiency

The potential for energy production in a hydropower plant is determined by these main parameters given by the hydrology, topography and design of the power plant:

- The amount of water available, Q_T (Million m^3 of water pr year = Mm^3/year)
- Water loss due to flood spill, bypass requirements or leakage, Q_L (Mm^3/year)
- The difference in head between upstream intake and downstream outlet, H_{gr} (m)
- Hydraulic losses in water transport due to friction and velocity change, H_L (m)
- The efficiency in energy conversion in electromechanical equipment, η

When these parameters are given, the total average annual energy, E_a (GWh/year) that can be produced in the power plant can be calculated by the formula (ρ is density of water in kg/m^3, η is the efficiency of the generating unit, g is the acceleration of gravity of 9.81 ms^{-2} and C is a unit conversion factor):

$$E_a = (Q_T - Q_L) \cdot (H_{gr} - H_L) \cdot \eta \cdot \rho \cdot g \cdot C \qquad \text{(GWh/year)}$$

The total amount of water available at the intake (Q_T) will usually not be possible to utilize in the turbines because some of the water (Q_L) will be lost or shall not be withdrawn. This loss occurs because of spill of water during high flows when inflow exceeds the turbine capacity, because of bypass releases for environmental flows and because of leakage.

In the hydropower plant the potential (gravitational) energy in water is transformed into kinetic energy and then mechanical energy in the turbine and further to electrical energy in the generator. The energy transformation process in modern hydropower plants is highly efficient, usually with well over 90% mechanical efficiency in turbines and over 99% in the generator. The inefficiency is due to hydraulic loss in the water circuit (intake, turbine, tail-race), mechanical loss in the turbo-generator group and electrical loss in the generator. Old turbines can have lower efficiency, and it can also be reduced due to wear and abrasion caused by sediments in the water. The rest of the potential energy (100% - η) is lost as heat in the water and in the generator.

In addition, there will be some energy losses in the head-race section where water flows from the intake to the turbines, and in the tail-race section taking water from the turbine back to the river downstream. These losses, called head loss (H_L), will reduce the head and hence the energy potential for the power plant. These losses can be classified either as friction losses or singular losses. Friction losses in tunnels, pipelines and penstocks will depend mainly on water velocity and the roughness.

The total efficiency of a hydropower plant will be determined by the sum of these three loss components. Loss of water can be reduced by increasing the turbine capacity or by increasing the reservoir capacity to get better regulation of the flow. Head losses can be reduced by increasing the area of head-race and tail-race, by decreasing the roughness in these and by avoiding too many changes in flow velocity and direction. The efficiency in electromechanical equipment, especially in turbines, can be improved by better design and also by selecting a turbine type with an efficiency profile that is best adapted to the duration curve of the inflow. Different turbines types have quite different efficiency profiles when the turbine discharge deviates from the optimal value, see Figure 5.10.

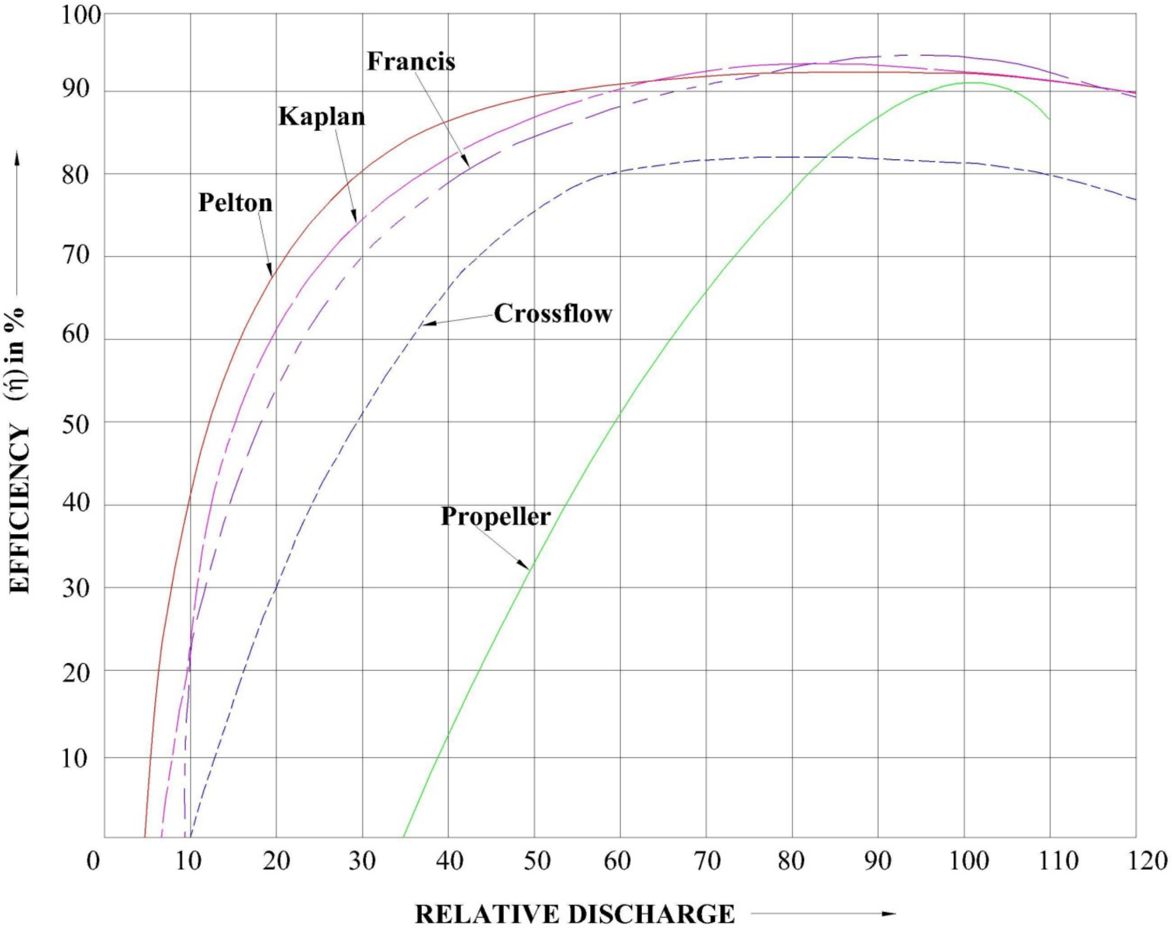


Figure 5.10: Typical efficiency curves for different types of hydropower turbines (Source: (Vinogg et al., 2003)

5.3.2.2 Tunneling capacity

5.3.2.2.1 Tunneling technology

In hydropower projects tunnels in hard rock are mainly used for transporting water from the intake to the turbines (head-race), and from the turbine back to the river, lake or fjord downstream (tail race). In addition, tunnels are used for a number of other purposes where the power station is placed underground, for example for access, power cables, surge shafts and ventilation.

Tunnelling technology has improved very much due to introduction of increasingly efficient equipment, as illustrated by Figure 5.11 (Zare et al., 2007). Today, the two most important technologies for hydropower tunnelling are:

- Drill and Blast method
- Tunnel boring machines

5.3.2.2.2 Drill and Blast method (D&B)

D&B is the conventional method for tunnel excavation in hard rock. In the D&B method, a drilling rig ("jumbo") sets a predetermined pattern of holes to a selected depth in the rock face. Explosives in the holes are then detonated and loosened debris or muck hauled away. After the broken rock is removed the tunnel must be secured, first by scaling (removing all loose rock from roof and walls) and then by stabilizing the rock faces permanently. Thanks to the development in tunnelling technology, the excavation costs have been drastically reduced in recent 30 years (see Fig. 5.11).

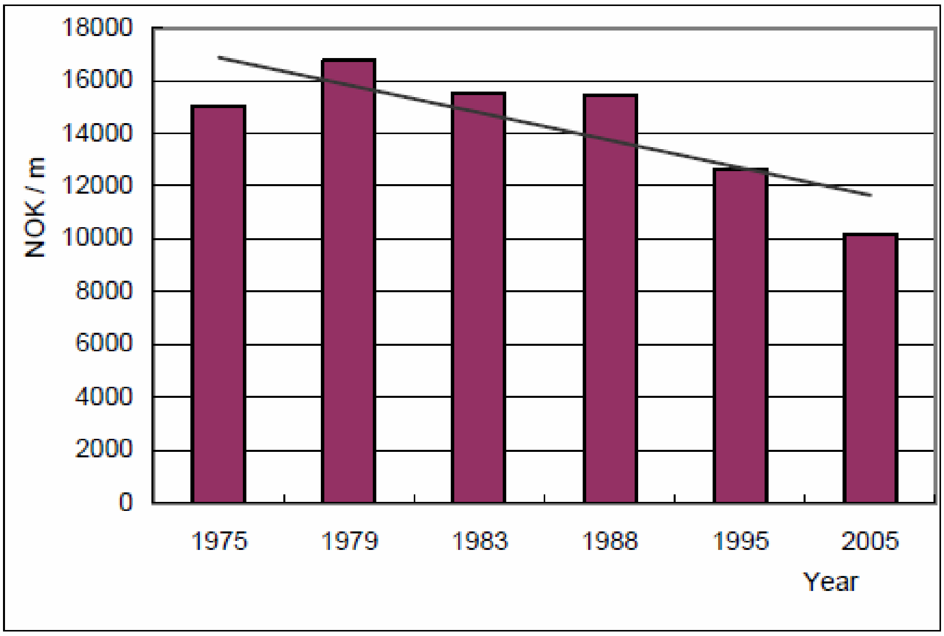


Figure 5.11: Development in tunneling technology - trend of excavation costs for a 60 m2 tunnel, price level 2005, Norwegian Kroner (NOK) pr m. (Zare et al., 2007). [TSU: convert to US $ 2005, specify technology]

5.3.2.2.3 Tunnel Boring Machines (TBM)

TBM excavates the entire cross section in one operation without the use of explosives. TBM's carry out several successive operations: drilling, support of the ground traversed and construction of the tunnel. During drilling, the cutting wheel turns on its axis under high pressure and the cutting wheels break up the rock. At the same time, the chutes receive the excavated material and drop them at the base of the shield in the operating chamber, from where they are removed. As drilling progresses, the TBM installs the segments constituting the walls of the tunnel. These are carried by the transporter system then taken towards the erectors, who install them under cover of the shield's metal skirt. The TBM can then be supported and move forward, using its drive jacks.

The TBMs are finalized and assembled on each site. The diameter of tunnels constructed can be up to 15 meters. The maximum excavation speed is typically from 30 up to 60 meters per day.

5.3.2.2.4 Support and lining

To support the long term stability and safety of the tunnel, it may be necessary to support the rock from falling into the tunnel. The most used technique is rock bolting, other techniques with increasing cost are spraying concrete ("shotcrete"), steel mesh, steel arches and full concrete lining. The methods and principles for rock support in TBM tunnels are basically the same as in D&B tunnels, but because of the more gentle excavation and the stable, circular profile, a TBM tunnel normally needs considerably less rock support than a D&B tunnel. In Norway, the support cost for a TBM tunnel has been found to be 1/3 to 2/3 of the cost for a D&B tunnel of the same cross section.

In good quality rock the self-supporting capacity of the rock mass can be used to keep the amount of extra rock support to a minimum. In poor quality rock the design of support should be based on a good understanding of the character and extent of the stability problem. The most important geological factors which influence the stability of the tunnel and the need for extra rock support are: 1) The strength and quality of the intact rock 2) The degree of jointing and the character of the discontinuities 3) Weakness zones and faults 4) Rock stresses and 5) Water inflow (Edvardsen *et al.*, 2002).

The use of full concrete lining is an established practice in many countries, and these add considerable to the cost and construction time for the tunnel. One meter of concrete lining normally costs from 3 to 5 times the excavation cost. Shotcrete is also quite expensive, from 1 to 1.2 times the excavation costs. Rock bolting is much cheaper, typically 0.6 times the excavation costs (Nilsen *et al.*, 1993).

In some countries, for example in Norway, the use of unlined tunnels and pressure shafts is very common. The first power plants with unlined pressure shafts were constructed in 1919 with heads up to 150 meters. Today, more than 80 high-pressure shafts and tunnels with water heads between 150 and up to almost 1000 meters are operating successfully in Norway (Edvardsen *et al.*, 2002).

5.3.3 Sedimentation Problem in Hydropower Projects

The problem of sedimentation is not caused by hydroelectric projects; nevertheless, it is one of the problems that need to be understood and managed. Fortunately there is a wealth of case studies and literature in this regard to be able to deal with the problem (Graf, 1971). Sedimentation or settling of solids occurs in all basins and rivers in the world and it must be recognized and controlled by way of land-use policies and the protection of the vegetation coverage.

For hydropower there are two kinds of projects: regulation projects with storage reservoir and run-of river, where flushing procedures using bottom gates during floods can be integrated into operation flood management to maintain stable and sustainable siltation rate in the reservoirs.

In every country, efforts are dedicated to determining and quantifying surface and subterranean hydrological resources, in order to assess the availability of water for human consumption and for agriculture. For hydropower projects this is also entry level data for the potential amount of water that can be transformed into electrical energy. It is important to get measurements at different basins throughout the territory and all hydrometric stations, during wet and dry season, to be organized and analyzed. Additionally, it is necessary to establish reservoir depth (bathymetric) monitoring programmes at all storage reservoirs for hydroelectric generation, which can be easily done by taking measurements at a time pace consistent with sedimentological process (siltation, erosion) time scale. To the previous results must be correlated with studies of basin or sub-basin erosion. Several models are available for these studies.

The Revised Universal Soil Loss Equation (*RUSLE*) is a method that is widely utilized to estimate soil erosion from a particular portion of land(Renard *et al.*, 1997). In general the GIS based model (Geographical Information System) includes calibration and the use of satellite images to determine the vegetation coverage for the entire basin, which determines the erosion potential of the sub-basins as well as the critical areas. The amount of sediment carried into a reservoir is at its highest during floods. Increases in average annual precipitation of only 10 percent can double the volume of sediment load of rivers ((McCully, 2001)). Reservoirs can be significantly affected by the changes in sediment transport processes.

Reservoir sedimentation problems, due to soil erosion and land degradation, are contributing to global water and energy scarcity. In many areas of the world average loss of surface water storage capacity due to sedimentation is higher than the increase in volume due to new dam construction (White, 2005). In a World Bank study (Mahmood, 1987) it was estimated that about 0.5% to 1% of the total freshwater storage capacity of existing reservoirs is lost each year due to sedimentation. Similar conditions were also reported by (WCD, 2000; ICOLD, 2004).

Sedimentation can also increase downstream degradation and give increased flood risk upstream of the reservoirs, perturbing morpho dynamics and ecological functionalities. Deposition of sediments can obstruct intakes blocking the flow of water through the system and also impact the turbines. The sediment-induced wear of the hydraulic machineries is more serious when there is no room for storage of sediments. Lysne *et al.* (2003) reported the effect of sediment induced wear of turbines in power plants can be among others:

- Generation loss due to reduction in turbine efficiency
- Increase in frequency of repair and maintenance
- Increase in generation losses due to downtime
- Reduction in life time of the turbine and
- Reduction in regularity of power generation

All these effects are associated with revenue losses and increased maintenance cost during the operation of power plant.

Several promising concepts for sediment control at intakes and mechanical removal of sediment from reservoirs and for settling basins have been developed and practiced. A number of authors (Mahmood, 1987; Morris *et al.*, 1997; ICOLD, 1999; Palmieri *et al.*, 2003; White, 2005) have reported measures to mitigate the sedimentation problems. These measures can be generalised as measures to reduce sediment load to the reservoirs, mechanical removal of sediment from reservoirs, design and operate hydraulic machineries aiming to resist effect of sediment passes through them.

However, measures are not easy to apply in all power plants. The application of most of the technical measures is limited to small reservoirs with a capacity inflow ratio of less than 3% and to reservoirs equipped with bottom outlet facilities. Each reservoir site has its own peculiarities and constraints. All alternatives will therefore not be suitable for all types of hydro projects. For efficient application of alternative strategies, choices have to be made based on assessment related to sediment characteristics, the shape and size of the reservoirs and its outlet facilities and operational conditions (Basson, 1997). Handling sediment in hydropower projects has therefore been a problem and remains a major challenge. In this context much research and development remains and need to be done to address sedimentation problems in hydropower projects.

It is important to note that erosion and sediment control efforts are not exclusive to hydroelectric projects, but are also an important part of national sustainability strategies for the preservation of water and land resources. Reforestation alone does not halt erosion; it must be complemented with land coverage and control of its human and animal usage.

5.3.4 Renovation and Modernization trends

Renovation, modernisation & upgrading (RM&U) of old power stations is often cost effective, environment friendly and requires less time for implementation. Capacity additions through RM&U of old power stations can be attractive. The economy in cost and time essentially results from the fact that apart from the availability of the existing infrastructure, only selective replacement of critical components such as turbine runner, generator winding with class F insulation, excitation system, governor etc., and intake gates trash cleaning mechanism can lead to increase in efficiency, peak power and energy availability apart from giving a new lease on life to the power plant/equipment. RM&U may allow for restoring or improving environmental conditions in already regulated areas.. The Norwegian Research Council has recently initiated a program for renewable energy where one of the projects is looking for so called win-win opportunities where the aim is to increase power production in existing power plants and at the same time improve environmental conditions (CEDREN, 2009).

Normally the life of hydro-electric power plant is 40 to 80 years. Electro-mechanical equipment may need to be upgraded or replaced after 30-40 years, while civil structures like dams, tunnels, etc usually function longer before it requires renovation. The lifespan of properly maintained hydropower plants can exceed 100 years. The reliability of a power plant can certainly be improved by using modern equipments like static excitation, microprocessor based controls, electronic governors, high speed static relays, data logger, vibration monitoring, etc. Upgrading/uprating of hydro plants calls for a systematic approach as there are a number of factors viz. hydraulic, mechanical, electrical and economic, which play a vital role in deciding the course of action. For techno-economic consideration, it is desirable to consider the uprating along with Renovation & Modernization/Life extension. Hydro generating equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Most of the 746,000 MW of hydro equipment in operation in 2005 will need to be modernised by 2030 (SER, 2007). Refurbished or up rated existing hydropower plants also result in incremental hydropower generation due to availability of higher efficient turbines and generators also uprated and renovation of capacity. Existing infrastructure (like existing barrages, weirs, dams, canal fall structures, water supply schemes) are also being reworked by adding new hydropower facilities.

There are 45,000 large dams in the world where the majority (75%) were not built for hydropower purposes (WCD, 2000) but for the purpose of irrigation, flood control, navigation and urban water supply schemes. Retrofitting these with turbines may represent a substantial potential. Only about 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multipurpose reservoirs In India during 1997-2008 about 500 MW has been developed out of 4000 MW potential on existing structures.

5.3.5 Storage of water and energy

Water is stored in reservoirs which enable its uneven availability spatially as well as temporally in a regulated manner to meet growing needs for water and energy in a more equitable manner. Hydropower reservoirs store rainwater and snow melt which after generating, can then be used for drinking or irrigation as water in neither is consumed or polluted in hydropower generation. By storing water, aquifers are recharged and reduce the vulnerability to floods and droughts. Studies have shown that the hydropower based reservoirs increase agriculture production and green vegetation covers downstream (Saraf *et al.*, 2001).

Reservoir based hydropower including pumped storage schemes may improve the performance of conventional thermal and nuclear power plants by harmonising the rapid changes in demand and facilitating thermal and nuclear plants to operate at their optimum steady state level. Such steady state operation reduces both fuel consumption and associated emissions.

5.4 Global and regional status of market and industry development

5.4.1 Existing generation, TWh/year (per region/total)

In 2006, the production of electricity from hydroelectric plants was 3,121 TWh compared to 1,295 TWh in 1973 (IEA, 2008), which represented an increase of 141% in this period, and was mainly a result of increased production in China and Latin America, which grew by 399.5 TWh and 562.2 TWh, respectively (Figure 5.12).

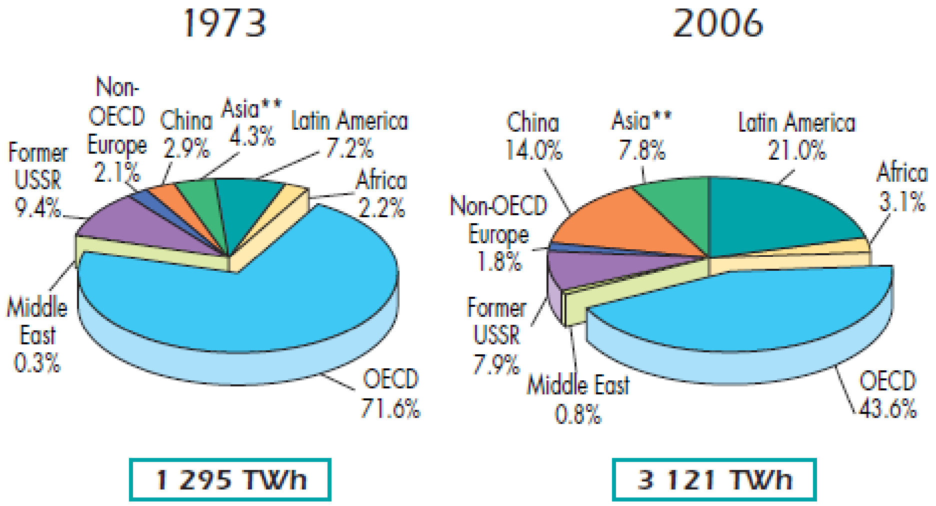


Figure 5.12: 1973 and 2006 regional shares of hydro production* (Source: IEA, 2008) [TSU: */** unspecified]

Hydro provides some level of power generation in 159 countries. Five countries make up more than half of the world's hydropower production: China, Canada, Brazil, the USA and Russia. The importance of hydroelectricity in the electricity matrix of these countries is, however, different (Table 5.2). On the one hand Brazil and Canada are heavily dependent on this source having a percentage share of the total of 83.2% and 58% respectively. On the other hand United States has a share of 7.4% only from hydropower. In Russia, the share is 17.6% and in China15.2%.

Table 5.2: Major Countries Producers / Installed Capacity. [TSU: caption not clear]

Country	**Installed Capacity** GW (2005 data)
China	118
United States	99
Brazil	71
Canada	72
Japan	47
Russia	46
India	32
Norway	28
France	25

Country Based on Top 10 Producers	**% of Hydro in Total Domestic Electricity Generation (2006 data)**
Norway	98.5
Brazil	83.2
Venezuela	72.0
Canada	58.0
Sweden	43.1
Russia	17.6
India	15.3
China	15.2
Japan	8.7

Italy	21
Rest of the world	308
World	**867**

United States	7.4
Rest of the world**	14.3
World	**16.4**

**Excludes countries with no hydro production

Sources: (IEA, 2006; 2008)

China, Canada, Brazil and the US together account for over 46% of the production (TWh) of electricity in the world and are also the four largest in terms of installed capacity (GW) (IEA, 2008). Fig 5.13 shows the country wise hydropower generation. It is noteworthy that five out of the ten major producers of hydroelectricity are among the world's most industrialized countries: Canada, the United States, Norway, Japan and Sweden. This is no coincidence, given that the possibility of drawing on hydroelectric potential was decisive for the introduction and consolidation of the main electro-intensive sectors on which the industrialization process in these countries was based during a considerable part of the twentieth century. There are four major developing countries on the list of major hydroelectricity producers: Brazil, China, Russia and India. [TSU: rephrase sentence, not including Russia in DCs] In these countries capitalism, although it developed later, seems to have followed in the footsteps of the industrialized countries drawing on previously untapped sources to provide clean and safe energy, in sufficient quantities to guarantee the expansion of a solid industrial base (Freitas, 2003). Russia is however an exception given it developed hydropower and industrialized much earlier than Brazil, China and India; albeit under a non-capitalistic economic system. It faces the twin challenges of developing new hydropower projects and the challenges of maintaining an ageing hydropower infrastructure.

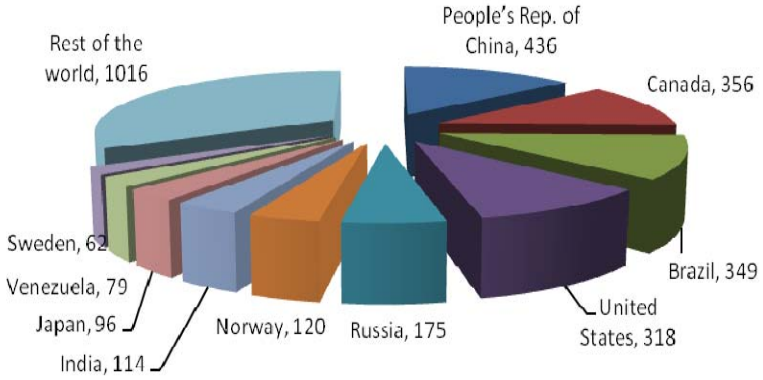
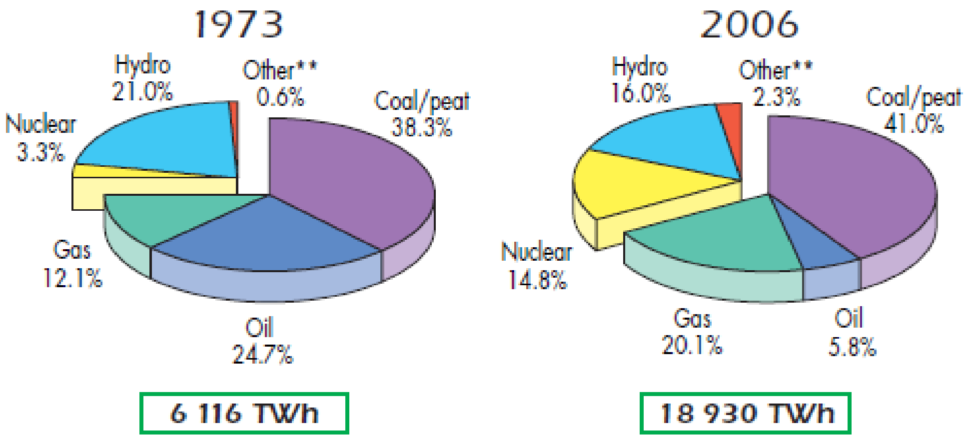


Figure 5.13: Hydro Generation by Country (TWh) (Source: IEA, 2008). [TSU: reference year missing in caption]

5.4.2 Deployment: Regional Aspects (organizations)

Figure 5.14 indicates that despite the significant growth of hydroelectric production, the percentage share of hydroelectricity fell in the last three decades (1973-2006). The major boom in electricity generation has been occurring due to the greater use of gas, and the greater participation of nuclear plants. Coal continues play a major role in the electricity matrix, with a small percentage growth in the 1973-2006 periods, growing from 38.3% to 41%.



*Excludes pumped storage.

**Other includes geothermal, solar, wind, combustible renewables & waste, and heat.

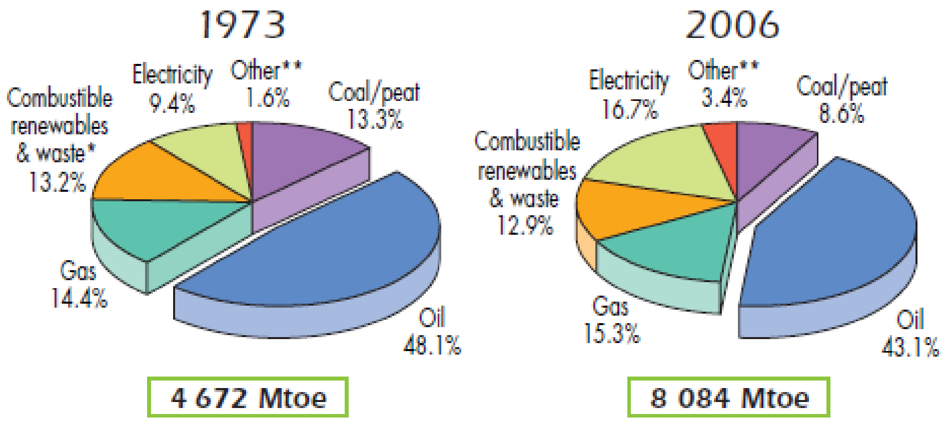
Figure 5.14: 1973 and 2006 fuel share of electricity generation* (Source: IEA, 2008).

Of the world’s five major hydroelectricity producers (China, Canada, Brazil, the United States and Russia), only the United States is listed as one of the ten major producers of electricity (consistently amongst the top 3) using the three fossil fuels, namely coal, combustible oil and gas. China heads the list of producers of electricity from coal, followed by the United States.

Electricity is considered to be one of the most efficient energy carriers given the relative ease with which it can be transported and converted for use. In 2006, of the 8,084 billion toe of final consumption, approximately 16.7% was served by electricity, derived principally from fossil fuels (IEA, 2008).

Although oil accounts for the major share of final consumption electricity is the second largest energy source in 2006 (figure 5.15), in part due to the increase of electricity generation and consumption in China, principally during the last decade (figure 5.16).

In 1973, China represented 2.8% of the worldwide generation of electricity, but by 2006, its share had grown over fivefold, accounting for 15.3% (IEA, 2008).



** Other includes geothermal, solar, wind, heat, etc.

Figure 5.15: 1973 and 2006 fuel share of total final consumption in terms of tons of oil equivalent toe (Source: IEA, 2008). [TSU: convert to EJ or TWh]

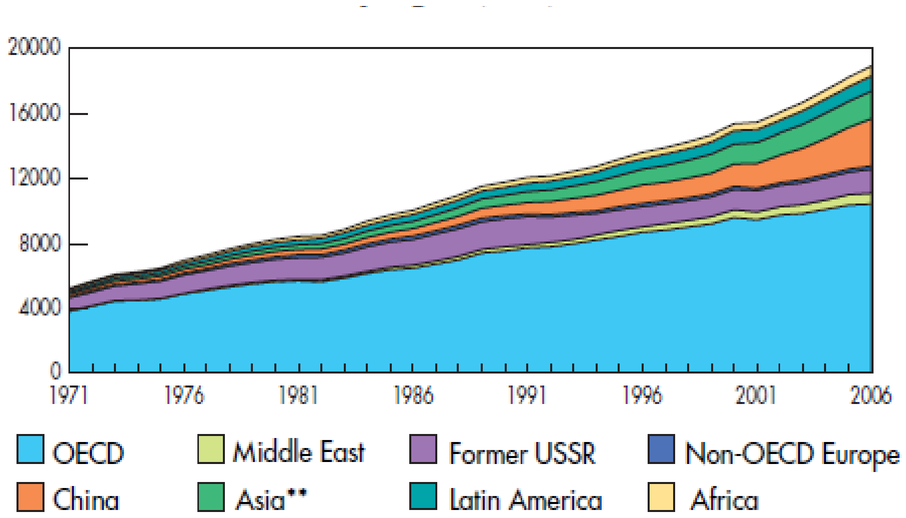


Figure 5.16: Evolution from 1971 to 2006 of world electricity generation by region (TWh). (Source: IEA, 2008).

5.4.3 Role of Hydropower in the Present Energy Markets (flexibility)

The primary role of hydropower is electricity generation. Hydro power plants can operate in isolation and supply independent systems, but most are connected to a transmission network. Hydroelectricity is also used for space heating and cooling in several regions. Most recently hydro electricity has also been used in the electrolysis process for hydrogen fuel production, provided there is abundance of hydro power in a region and a local goal to use H2 as fuel for transport. Hydropower can also provide the firming capacity for intermittent renewable. By storing potential energy in reservoirs, the inherent intermittent supply from intermittent renewable schemes can be supported. Peak power is expensive. The production of peak load energy from hydropower allows the optimization of base load power generation from other less flexible electricity sources such as nuclear and thermal power plants. By absorbing excess power, pumped-storage plants enable large thermal or nuclear power plants to operate at optimum output with high efficiency, even if demand is low. This contributes to reducing the GHG emissions from thermal power plants. Thus, in both a regulated or deregulated market hydropower plays a major role and provides an excellent opportunity for investment.

Hydro generation can also be managed to provide ancillary services such as voltage regulation and frequency control. With recent advances in 'variable-speed' technology (see 5.7.1), these services can even be provided in the pumping mode of reversible turbines. [TSU: references missing]

5.4.4 Carbon credit market

There are two main project-based instruments CDM (Clean Development Mechanism) and JI (Joint Implementation). Hydropower projects are one of the largest contributors to these mechanisms and therefore to existing carbon credit markets. The United Nations Framework convention for Climate Change (UNFCCC) Executive Board (EB) has decided that Storage Hydropower projects will have to follow the power density indicator, W/m2 (Installed effect on inundated area). However, this indicator treats all reservoirs as equal whether they are in cold climates or not and regardless of amount and sources of carbon in the reservoir. The power density rule seems presently to exclude storage hydropower based on arbitrary postulates and not scientific or professional documentation. The issue of methane production from reservoirs are discussed later in this chapter.

Out of the 2 062 projects registered by the CDM EB by March 1st 2010, 562 are hydropower projects (see figure 5.17). With 27% of the total number, hydro is the larger contributor. When considering the predicted volumes of carbon credits, known as Certified Emission Reduction (CERs), to be delivered, registered hydro projects are expected to avoid more than 50 million tonnes of CO2 per year by 2012, equivalent to 15% of the total. China, India, Brazil and Mexico represent roughly 75% of the hosted projects.

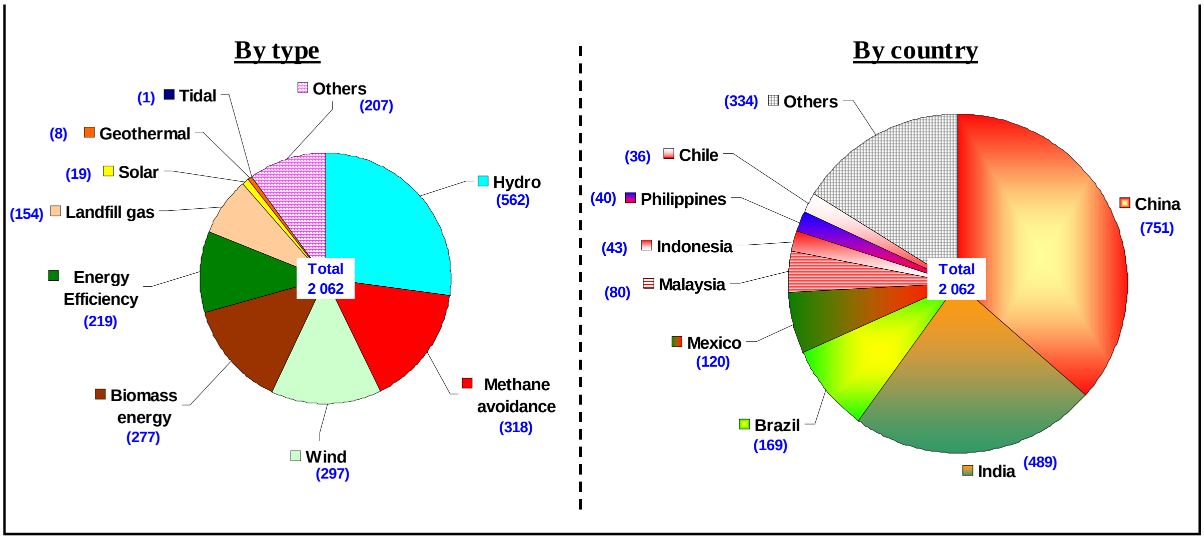


Figure 5.17: A type and country analysis of all projects registered in the CDM pipeline as on March, 1st 2010. Source: UNEP (2010) and UNFCCC (2010)

JI process is less developed today, but it is also growing. There are 114 JI registered projects on March 1st 2010, out of which 5 are hydropower (see Figure 5.18). When considering the predicted volumes of carbon credits (Emission Reduction Units-ERUs) to be delivered, registered hydro projects are expected to avoid more than 140 thousand tonnes of CO2 per year by 2012. Czech Republic and Ukraine represent more than half of those projects.

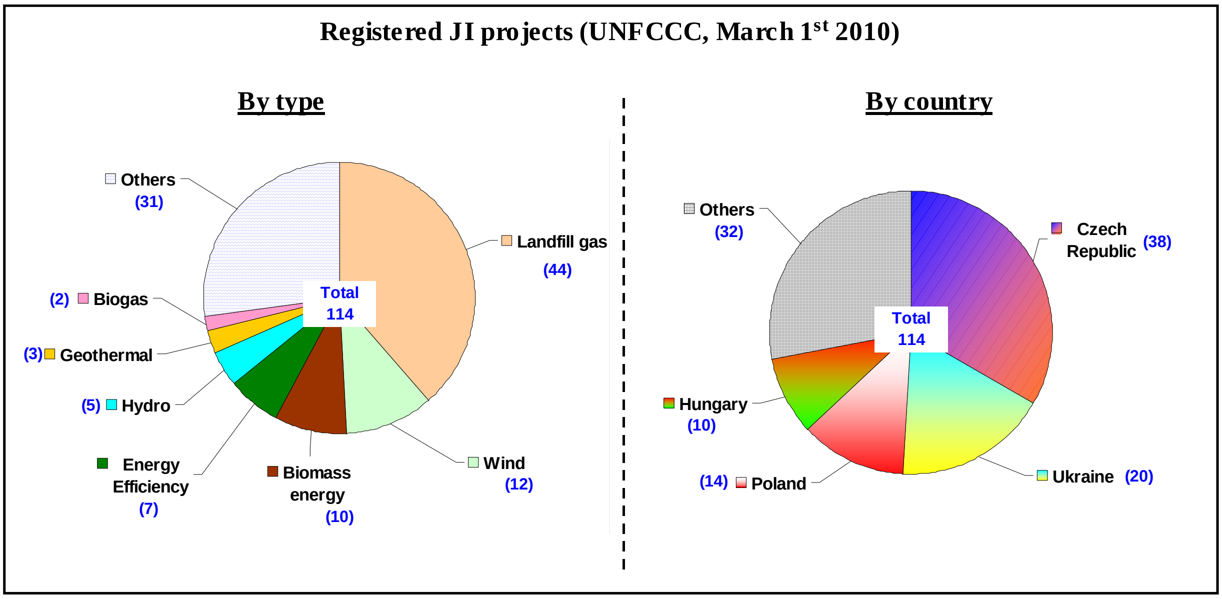


Figure 5.18: A type and country analysis of all projects registered in the JI pipeline as on March, 1st 2010 (source: UNFCCC (UNFCCC, 2010)and UNEP Risoe(UNEP, 2010).

In Europe the Linking Directive allows a fixed amount of CERs to be brought into the EU Emission Trading Scheme (ETS, the biggest CO_2 market in the World) and this Directive sets conditions on the use of such credits. For hydropower projects of 20 MW capacity and above Member States must "ensure that relevant international criteria and guidelines, including those contained in the World Commission on Dams Report (see section 5.62) will be respected during the development of such project activity". However Member States have interpreted this Directive in different ways because this Report is not specific for implementation (see section 5.6.3 on Existing Guidelines and Regulation of this chapter). This has led to European carbon exchanges (European Climate Exchange, Nord Pool etc) refusing to offer such credits for trade on their platforms, as it is not clear whether they are fully fungible. The European Union has therefore initiated a process to harmonize this procedure so as to give the market and the Member States confidence when using and accepting carbon credits under the EU ETS. As a result the European carbon exchanges are likely to admit CERs from hydro with a capacity over 20 MW in the near future.

Carbon credits benefit hydro projects helping to secure financing and to reduce risks. Financing is a most decisive step in the entire project development. Therefore additional funding from carbon credit markets could be a significant financial contribution to project development (increase in return on equity and improve internal rate of return) which can be observed in several ways: 1) additional revenues from the credits and 2) higher project status as a result of CDM designation (enhanced project's attractiveness for both equity investors and lenders). [TSU: references missing]

5.4.5 Removing barriers to hydropower development

As with any energy source, the choice of hydroelectricity represents physical action and impacts, with inevitable modification of the environmental conditions and the ecological system. The recurring challenge of this option is to minimize the environmental and social aspects relating to its considerable scale gains, whilst at the same time broadening the multiplying effects of investment in infra-structure, stimulating the economy and engendering local research and technological development.

This option requires a large volume of initial resources for the project, contrary to thermal and gas/oil/coal options which require fewer resources initially, but which have higher operational costs and a greater level of pollution emissions. Allied to greater initial costs and longer time necessary to reach the operational stage, hydroelectric projects tend to be more exposed to regulatory risks, particularly in developing countries where there are regulatory lacunae. Such lacunae include, for example: lack of definition in relation to the use of the land of indigenous peoples or conservation units.

At the same time, environmental issues have been assuming greater significance in the analysis of hydroelectric plants, both from the standpoint of multilateral investment agencies or from civil society which is more organized, aware and demanding in relation to the impacts and inherent benefits of multiple use of water resources.

The challenges, which, naturally, are not limited to those referred to above, must be addressed and met by public policies bearing in mind the need for an appropriate environment for investment, a stable regulatory framework, incentive for research and technological development and the provision of credit for the hydroelectricity option. [TSU: references missing]

5.4.5.1 Financing

Many economically feasible hydropower projects are financially challenged. High front end costs are too often a deterrent for investment. Also, hydro tends to have lengthy lead times for planning, permitting, and construction. The operating life of a reservoir is normally expected to be in excess of 100 years. Equipment modernization would be expected every 30 to 40 years. In the evaluation of life-cycle costs, hydro often has the best performance, with annual operating costs being a fraction of the capital investment and the energy pay-back ratio being extremely favorable because of the longevity of the power plant components (Taylor, 2008).

The energy payback is the ratio of total energy produced during that system's normal lifespan to the energy required to build, maintain and fuel the system (Fig 5.19). A high ratio indicates good performance. If a system has a payback ratio of between 1 and 1.5, it consumes nearly as much energy as it generates (Gagnon, 2008).

The main challenges for hydro relate to creating private-sector confidence and reducing risk, especially prior to project permitting. Green markets and trading in emissions reductions will undoubtedly give incentives. Also, in developing regions, such as Africa, interconnection between countries and the formation of power pools is building investor confidence in these emerging markets. Feasibility and impact assessments carried out by the public sector, prior to developer tendering, will ensure greater private-sector interest in future projects (Taylor, 2008).

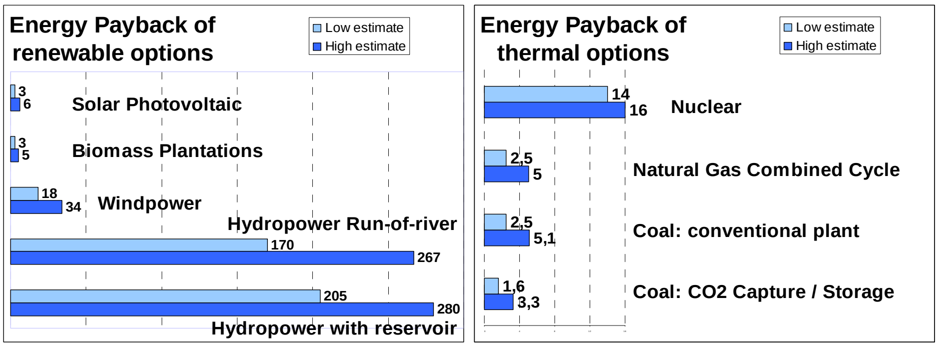


Figure 5.19: Energy Pay back Ratio (Source: Gagnon, 2008).

The development of more appropriate financing models is a major challenge for the hydro sector, as is finding the optimum roles for the public and private sectors.

5.4.5.2 Administrative and Licensing process

The European Union differentiates between small and large hydropower. There are different incentives used for small scale hydro[2] (feed-in tariffs, green certificates and bonus) depending on the country, but no incentives are used for large scale hydro. For instance, France currently applies a legislation which provides a financial support scheme for renewable energy based on feed-in tariffs (FIT) for power generation. For renewable energy installations up to 12 MW, tariffs depend on source type and may include a bonus for some sources (rates are corrected for inflation). For hydro the tariff duration is 20 years, and the FIT is 60.7 €/MWh, plus 5 to 25 €/MWh for small installations, plus up to 16.8 €/MWh bonus in winter for regular production.

In France, under the law of 16 October 1919 on the use of hydropower potential, any entity wishing to produce electricity from water over and above 4.5 MW must be granted a specific concession by the French State. Power plants producing less than this capacity threshold are subject to a more flexible authorisation regime. Under this specific applicable regime, a concession can be granted for a maximum period of 75 years. The ownership of any installations constructed by the concession holder on the site is transferred to the State when the concession terminates. Also, these installations must be in a good order and free of any duties or rights, and this in effect imposes upon the concession holder a "custody obligation" to maintain the facilities in good working order throughout the term of the concession. The existing hydroelectric concessions in France will be opened to competition when they come up for renewal (the first call for bids is scheduled to take place in 2009). Similar arrangements may be seen in many countries. For Instance, the recent evolution of the relicensing process in the US in the years 2000', coming from a Traditional (TLP)

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[2] In European Union, the limit for small hydro is 1.5 MW, 10 MW, 12 MW, 15 MW or 20 MW, depending on the country.

to a fully Integrated Licensing Process (ILP), where settlement agreement between stakeholders are shared early in the process to ensure that main environmental and social issues (represented by a variety of stakeholders : state env. conservation Agencies, Associations for river protection, river uses,...) have been integrated and made compatible together, before filing documents into the Administrative process (FERC, Feb. 2006) [TSU: reference missing in reference list] The environmental licence also is an important issue.

5.5 Integration into broader energy systems

Electricity markets and transmission systems have developed over the years to link large, 'centralised' power stations, producing firm power from fossil fuels, nuclear power and hydropower. The integration of electricity from other non-hydro renewable energy sources such as wind energy, solar and tidal wave energy therefore represents a degree of departure from the traditional pattern. The variability of electricity output from certain renewable energy technologies will, at a significant production share, necessitate changes in market and power system design, planning and communications, to ensure balance of supply and demand. Although large wind farms may be connected to medium, high or very high voltage networks, some new RES generation is connected to lower voltage distribution networks. The integration of hydropower into transmission systems should be seen in the perspective of the potential it represents for increasing the output of power systems and also smoothing the output from variable output technologies. Through integrated strategies, hydropower can buffer fluctuations in power system output, increasing the economic value of the power delivered (DOE, 2004). Likewise, other renewable energy technologies can provide hydropower operators with additional flexibility in managing their water resources.

5.5.1 Contribute to less GHG from thermal by allowing steady state operation

Hydro power plants have extremely quick response to intermittent loads as they can be brought on stream within a few minutes and their outputs can be varied almost instantaneously to respond to varying loads. Thermal power plants (coal, gas or liquid fuel) on the other hand require considerable lead times (4 hours for gas turbines and over 8 hours for steam turbines) before they attain the optimum thermal efficiency state when the emission per unit output is minimum. In an integrated system, the hydro power plant is used as the peaking plant; the thermal units are used as base loads thus ensuring maximum thermal efficiency and lower emissions per output.

5.5.2 Grid/independent applications (isolated grids, captive power plants)

Hydropower can be served through national and regional electric grid, mini grid and also in isolated mode. There are several hydro projects which are for captive use and have been since very beginning of hydropower development. Water mills in England and many other parts of the world, for grinding the cereals, for water lifting and for textile industry are the early instances where hydropower has been used as captive power in mechanical as well as electrical form (See Figure 5.20). The tea and coffee plantation industry have used and still are using hydropower for their captive needs in isolated areas. In the era of electricity deregulation which allows open access to the grid, people are encouraged to install hydropower plants and use the electricity for captive purpose by industry such as aluminium smelters and mines or individual or group of individuals.

Figure 5.20: 200 kW captive hydropower plant in Dewata Tea Estate, Indonesia. [TSU: source missing]

On the other hand rural areas may not have grids due to economic reasons and mini grid or isolated systems based hydropower , such the 200 kW captive power plant shown in figure 5.20 may be economically justified. Depending upon power availability and demand there are mini or local grids where hydropower (especially small hydro power) is used. These mini grids often work as isolated grids.

Hydropower plants are good investment opportunity as captive power house for industry and municipal bodies. The captive power plants may work in isolation through local, regional and national grids.

Isolated grids often faces the problem of poor plant load factor resulting in difficult financial return for the plant. But this provides opportunities for the area to have industry expansion, cottage or small industry, irrigation pumping, drinking water, agriculture and other application, education and entertainment activity for the overall development of the area. [TSU: references missing]

5.5.3 Rural electrification

Nearly two billion people in rural areas of developing countries do not have electricity (Table 5.3). They use kerosene or wood to light their homes. Their health is damaged by the smoke given off by these fuels. The problems of rural energy have long been recognized. Without electricity, moreover, poor households are denied a host of modern services such as electric lighting, fans, entertainment, education, health care and power for income generating activities.

The access to affordable and reliable energy services will contribute and will help in alleviation of illiteracy, hunger and thirst, disease, uncontrolled demographic proliferation, migration etc as well as improvement of the economic growth prospects of developing countries.

Extending an electricity grid to a remote village can be quite expensive and a challenge for a power utility. Renewable energy such as solar, wind, and small hydropower are often ideal to provide decentralized electrification of rural areas. There has been a growing realisation in developing countries that small hydro schemes have an important role to play in the economic development of remote rural areas, especially hilly areas. Small hydro plants can provide power for industrial, agricultural and domestic uses both through direct mechanical power or producing electricity. Small scale hydropower based rural electrification in China has been one of the most successful examples, building over 45,000 small hydro plants of 50,000 MW and producing 150 Billion kWh annually, and accounting for one third of country’s total hydropower capacity, covering its half territory and one third of counties and benefitting over 300 Million people (up to 2007 (SHP-News, 2008).

Table 5.3: Electricity Access in 2005; Regional Aggregates.

Region	**Population**				**Electrification rate** %	**Urban electrification rate** %	**Rural electrification rate** %
	Total Million	**Urban** Million	**without electricity** Million	**with electricity** Million			
Africa	891	343	554	337	37.8	67.9	19.0
North Africa	153	82	7	146	95.5	98.7	91.8
Sub-Saharan Africa	738	261	547	194	25.9	58.3	8.0
Developing Asia	3418	1063	930	2488	72.8	86.4	65.1
China and East Asia	1951	772	224	1728	88.5	94.9	84.0
South Asia	1467	291	706	760	51.8	69.7	44.7
Latin America	449	338	45	404	90.0	98.0	65.6
Middle East	186	121	41	145	78.1	86.7	61.8
Developing Countries	**4943**	**1866**	**1569**	**3374**	**68.3**	**85.2**	**56.4**
Transition economies and OECD	**1510**	**1090**	**8**	**1501**	**99.5**	**100.0**	**98.1**
World	**6452**	**2956**	**1577**	**4875**	**75.6**	**90.4**	**61.7**

Source: (IEA, 2006)

Small scale hydro is one of the best options for rural electrification which can offer considerable financial benefits to the individual as well as communities served. Even though the scale of small hydro capital cost may not be comparable with large hydropower, several cost aspects associated with large hydropower schemes justify the small scale hydropower development due to their dispersed location and opportunity advantage.

- They are normally RoR schemes
- Locally manufactured equipment may be used
- Electronic load controller – allows the power plant to be left unattended, thereby reducing manpower costs
- Using existing infrastructure such as dams or canal fall on irrigation schemes
- Locating close to villages avoid expensive high voltage distribution equipment
- Using pumps as turbines and motors as generators as a turbine/generator set
- Use of local materials for the civil works
- Use of community labour

The development of small scale hydropower for rural areas involves social, technical and economic considerations. Local management, ownership and community participation, technology transfer and capacity building are the basic issues for success of small scale hydro plants in rural areas. [TSU: references missing]

5.5.4 Hydropower peaking

Demands for power vary greatly during the day and night, during the week and seasonally. For example, the highest peaks in advanced/developed countries are usually found during summer daylight hours when air conditioners are running in hot weather. In northern regions the highest peak hours are usually found in the morning and in the afternoon during the coldest periods in the winter. In developing countries, where lighting is the commonest electrical device, the peak hours are usually in the evenings.

Given their operational requirements and their long startup time nuclear and fossil fuel plants are not efficient for producing power for the short periods of increased demand during peak periods.. Since hydroelectric generators can be started or stopped almost instantaneously, hydropower is more responsive than most other energy sources for meeting peak demands. Water can be stored overnight in a reservoir until needed during the day, and then released through turbines to generate power to help supply the peak load demand. This technique of mixing power sources offers utility companies the flexibility to operate steam plants most efficiently as base plants while meeting peak needs with the help of hydropower and can help ensure reliable supplies and eliminate brownouts and blackouts caused by partial or total power failures.

Increasing use of other types of energy-producing power plants in the future will not make hydroelectric power plants obsolete or unnecessary. On the contrary, while nuclear or fossil-fuel power plants can provide base loads, hydroelectric power plants can deal more economically with varying peak load demands in addition to delivering base load.

From an operational standpoint hydropower is important as it needs no "ramp-up" time, as many combustion technologies do. With this important load-following capability, peaking capacity and voltage stability attributes, hydropower plays a significant part in ensuring reliable electricity service and in meeting customer needs in a market driven industry (US-Department-of-Interior, 2005).

5.5.5 Energy storage (in reservoirs)

Hydroelectric generation differs from other types of generation in that the quantity of “fuel” (i.e. water) that is available at any given time is fixed. This unique property coupled with its short response time allows hydropower plants to be used as storage reservoirs, is well suited for peaking or load-following operation and is generally used for this service if storage or pondage is available and if river conditions permit. Techniques such as seasonal/multi seasonal storage or daily/weekly pondage can be used in many cases to make the distribution of stream flow better suitable to the power demand pattern.

Storing of water is considered storage of energy and can be loosely termed as batteries for the power system. It should be emphasized however that while hydropower reservoirs store energy as a source for electricity before it is produced, pumped storage plants store electricity after it is produced. Pumped storage is normally not a source for energy. However if the upstream pumping reservoir also is used as a traditional reservoir the inflow from the watershed may balance out the energy loss caused by pumping.

Electricity already produced cannot be stored directly except by means of small capacitors and therefore has to be stored in other forms, such as chemical (batteries or on a large scale in Flow Batteries), potential energy (pumped storage) or mechanical energy as compressed air in compressed air energy storage schemes (CAES) or flywheels. Various technologies for storing electricity in the grid are compared in figure 5.21.

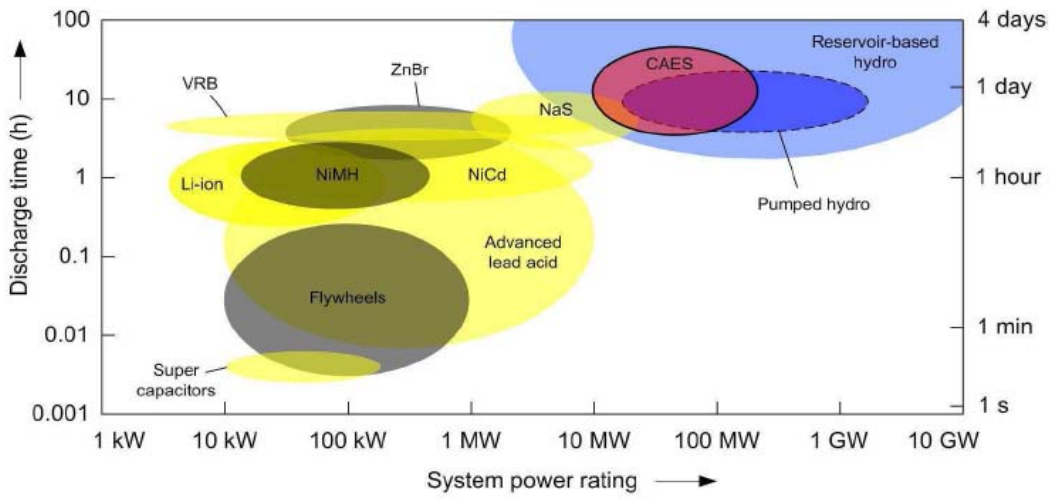

Figure 5.21: Discharge time vs. power rating of electricity storage technologies (Source: Thwaites, 2007).

Pumped storage refers to the technique where water is pumped to a storage pool above the power plant at a time when customer demand for energy is low, such as during the middle of the night. The main components of a pumped storage project are the upper and lower reservoirs, water conductor, a power house with reversible pump/turbine motor/generators and a high voltage transmission connection. Some recent projects such as Kops II in Austria also rely on ternary units (Pelton + pump on the same shaft) or separate turbines and pumps. Pumped storage is very versatile as it can be adapted in various situations to the geography of the sites and to the needs of the power systems. It is noteworthy that recent technologies allow those facilities to closely follow up the load curve MW by MW.

The hydraulic, mechanical and electrical efficiencies determine the overall cycle efficiency. The overall cycle efficiency of pumped storage plants ranges from 65 to 80 per cent. Refer to fig.5.8.

Like peaking, pumped storage keeps water in reserve for peak period power demands. The water is then allowed to flow back through the turbine-generators at times when demand is high and a heavy load is placed on the system. The reservoir acts much like a battery, storing power in the form of water when demands are low and producing maximum power when needed at peak. Conventional pumped storage projects are often constructed in conjunction with large base-load generating stations such as nuclear and coal fired stations (- or may be an integral part of a large storage HPP). The pumped storage plant complements the large base load plant by providing guaranteed load during early morning hours when system demand is low. Pumped storage is also desired, in the case of nuclear plants, providing frequency control and reserve generation required maintaining operation of critical cooling pumps. Pumped storage schemes have the same common benefits as conventional hydropower plants: flexibility and reliability. Their capacity is usually high as compared to conventional schemes, they can be used to consume excess energy during off-peak hours, for instance from intermittent sources like Wind Power. Their use and benefit in the power system depend on the mix of generating plants and the architecture of the transmission system. Pumped storage today represents 5% of the world's installed capacity. [TSU: referenced parameter not clear] Figures vary from 2.4% in the USA to nearly 9% in Japan. It is very difficult to state what should be the optimum value in a power system. It is dependent on the mix of the system, the amount of existing hydro storage facilities and on the architecture of the grid with respect to consumption load centres.

Variable energy sources such as solar power and wind power may be tied to pumped storage hydro power systems to be economical and feasible as the hydropower can serve as an instant backup and to meet peak demands. Wind power on the other hand can be used when the wind is blowing, to reduce demands on hydropower, allowing dams to save their water for later release to generate power in peak periods.

Pumped storage hydroelectricity is used by some power plants for *load balancing*. The method stores energy by pumping water from a low to a higher elevation. Low-cost off-peak electric power is used to run the pumps. Although the losses of the pumping process makes the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of *peak demand*, when electricity prices are highest.

Along with energy management, pumped storage systems help control electrical network frequency and provide reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydropower plants, can also respond to load changes within seconds. [TSU: references missing]

5.5.6 Supply characteristics

Electricity markets and transmission systems have developed over the years to link large, ‘centralized’ power stations, producing firm power from fossil fuels, nuclear power and hydropower. The hydropower is a traditional power source and operates in all integrated grid systems.

The large-scale, worldwide, development of hydroelectric energy, aside from its low cost, is due to the excellent characteristics of energy supply for the power system. It is common to have machine availability percentages that are over 95% at a hydroelectric plant. The most important characteristic is the storage capacity that hydroelectric energy can offer the electric system and the speed the hydraulic machines offer in following the electric demand. The hydroelectric plants usually offer an auxiliary service called Automatic Generation Control or AGC. Power plants that use combustion processes in the transformation of energy (thermal cycle), are not as fast in their time response when faced with sudden and important variations in demand, as there exists a risk of damage to their components by thermal stress.

The optimizing exercise for a hydroelectric power plant is based on the size of the units and the available power, at a specific site. The project's final costs per unit of energy produced are reduced when the size of the units to be installed is large. This also represents an advantage for the electrical power system, because the large power units provide stability to the electric grid. A hydroelectric plant with large machines (> 50 MW) is desirable in order to provide black start service, which is indispensable in any electrical power system.

5.5.6.1 Electrical services and use factors

The net capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its output if it had operated at full rated capacity the entire time. A hydroelectric plant's production may also be affected by requirements to keep the water level from getting too high or low and to provide water for fish downstream or for navigation upstream. When hydroelectric plants have water available, they are also useful for load following, because of their high *dispatchability*. Typically a hydropower plant can operate from a stopped condition to full power I just a few minutes

Example of representative international statistics can be found in table 5.4. The hydropower plants exhibit the less Equivalent Forced Outage Factor **(**EFOR).

Table 5.4: Availability Indexes.

Technology	Number Of Units (Sample)	Service Time (Years)	PLF	AF	FOF	FOR	EFOR
Hydro	1179	53	40.8	89.4	2.50	3.70	3.75
Thermal Oil (1-99 MW)	35	14	25.0	90.8	1.92	5.47	12.38
Thermal Coal (100-199 MW)	226	46	65.6	88.6	3.58	4.11	6.03
Gas Turbines (20-49 MW)	54	26	6.4	89.6	1.52	34.59	38.21
Gas Turbines (> 50 MW)	501	14	4.3	92.4	2.16	25.34	25.91
Diesel Engines	87	33	6.7	94.5	2.20	26.90	27.82

(Source: North-American-Electric-Reliability-Council).[TSU:reference year missing]

PLF	Plant Load Factor show the percent of time in a year that the station can operate at full capacity
AF	Availability Factor (Available hours/hours of period).
FOF	Forced Outage Factor (Hours of forced outage/hours of period).
FOR	Forced Outage Rate (hours of forced outage/hours of forced outage + hours of service).
EFOR	Equivalent Forced Outage Factor (hours of equivalent forced outage/hours of equivalent forced outage + hours of service).

5.5.6.2 Security

The subject of Energy Security in its broadest sense encompasses a wide range of issues, technologies and government policies. Energy Security (also known as System Security) involves the design of the system to provide service to the end user despite fuel availability problems, forced outages of generators and outages of transmission system components. Grids with hydro power plants into it can fulfil the Security requirement due to hydro storage on reservoirs, give sufficient system-wide transmission capacity.

5.5.6.3 Reliability/quality

Hydroelectric power is usually extremely dispatchable and more reliable than other energy sources. Many dams can provide hundreds of megawatts within seconds to meet demand, the exact nature of the power generation availability depending on the type of plant. However the availability of power from run of river plants are dependent on the flow of the river.

5.5.6.4 Ancillary services

Ancillary Service refers to a service, necessary to support the transmission of energy from resources to loads while maintaining reliable operation of the transmission system in accordance with Good Utility Practice. Such services include mainly: voltage control, operating reserves, black-start capability and frequency control.

Hydroelectric generators have technical advantages over other types of generation with respect to the supply of ancillary services (Altinbilek, 2007). The advantages include:

- Fast response.
- Better part-load efficiency.
- Better controllability.
- Lower maintenance costs.
- Minimum to no start up (unit commitments) costs.

The incentivsiation of ancillary services in order to facilitate the scaling-up of electricity generation by other renewable sources of energy and smart grids is being investigated at the international policy level.

We can conclude that the energy supply characteristics of hydroelectric plants make it indispensable in the development energy matrix of any electric system, aside from the collateral advantages such as providing water reserves for human, agricultural and industrial development. [TSU:references missing for whole section]

5.5.7 Regional cooperation

Availability and movement of water may cross political or administrative boundaries. There are 263 transboundary river basins and 33 nations have over 95 percent of their territory within international river basins. While most transboundary river basins are shared between two countries, this number is much higher in some river basins. Worldwide, thirteen river basins are shared between five to eight countries. Five river basins, namely the Congo, Niger, Nile, Rhine and Zambezi, are shared between nine to eleven countries. The Danube River flows through the territory of 18 countries which is the highest for any basin. Management of transboundary waters poses one of the most difficult and delicate problems. Vital nature of freshwater provides a powerful natural incentive for cooperation. Fears have been expressed that conflicts over water might be inevitable as water scarcity increases. International cooperation is required to ensure that the mutual benefits of a shared watercourse are maximized and optimal utilization of the water resources may play a key role in economic development.

One hundred twenty-four of the 145 treaties (86%) are bilateral. Twenty-one (14%) are multilateral; two of the multilateral treaties are unsigned agreements or drafts. Most treaties focus on hydropower and water supplies: fifty-seven (39%) treaties discuss hydroelectric generation and fifty-three (37%) distribute water for consumption. Nine (6%) mention industrial uses, six (4%) navigation, and six (4%) primarily discuss pollution. Thirteen of the 145 (9%) focus on flood control. Not surprisingly, mountainous nations at the headwaters of the world's rivers are signatories to the bulk of the hydropower agreements. Dispute on treaties are resolved through technical commissions, basin commissions, or via government officials.

There are opportunities for cooperation in transboundary water management which can help in building mutual respect, understanding and trust among countries and may promote peace, security and sustainable economic growth. The 1997 UN Convention on the Non-Navigational Uses of International Watercourses (1997 IWC Convention) is the only universal treaty dealing with the use of freshwater resources. Nepal alone has four treaties with India (the Kosi River agreements, 1954, 1966, 1978, and the Gandak Power Project, 1959) to exploit the huge power potential in the region. Itaipu Hydropower on river Parana in Brazil and Paraguay and Victoria Lake hydropower in Uganda, Tanzania and Kenya are some notable instances of regional cooperation. [TSU:references missing]

5.5.8 Support to other renewables

Hydropower provides high degree of flexibility and reliability of its services and is a great opportunity to ensure the backup for a stable grid with intermittent renewable electricity sources, such as wind and sun. Hydropower plants and their reservoirs serve as a universal energy, power regulator. Hydropower plants with reservoirs work as energy storage and regulator to the other renewable and may be described as below**:**

- Hydro plants with reservoirs can lower or shut down their output when the wind turbines, or the solar panel, or the run-of-river hydro plants are able to provide their energy services;
- Hydropower plants can operate when intermittent power from other renewable or run of river is not available. Such service may be provided on an hourly, weekly, monthly, annual or inter-annual basis;
- It provides to the other renewable all the ancillary services;
- Hydropower plants with reservoirs are not affected on hourly, daily or weekly basis and thus are a good backbone to other renewable;
- Pumped storage and reservoir based hydro plants provided natural support to other renewable sources of energy;
- Reservoir based hydropower can complement continuous, base-load generation from geothermal schemes;
- "Peaking" biomass schemes can provide backup to run of river hydro schemes. [TSU:point not consistent with subheading]

[TSU:references missing]

5.6 Environmental and social impacts

Like all other energy and water management options, hydropower projects do have positive and negative impacts. On the environmental side, hydropower offers advantages on the macro-ecological level, but shows a significant environmental foot print on the local and regional level. With respect to social impacts, a hydropower scheme will often be a driving force for socio-economic development (see sub-section 5.6.4), yet a critical question remains on how these benefits are shared.

Moreover, each hydropower plant (HPP) is a unique product tailored to the specific characteristics of a given geographical site and the surrounding society and environment. Consequently, the magnitude of environmental and social impacts as well as the extent of their positive and negative effects is rather site dependent. For this reason the mere size of a HPP is not a relevant criterion to anticipate impacts. Nevertheless, sub-section 5.6.1 hereafter attempts to summarize the main environmental and social impacts which can be created by the development of the various types of hydropower projects, as well as a number of practicable mitigation measures which can be implemented to minimize negative effects and maximize positive outcomes. More information about existing guidance for sustainable hydropower development is provided in sub-section 5.6.2.

One of hydropower's main environmental advantages is that it creates no atmospheric pollutants or waste. Over its life cycle, a HPP generally emits much less CO_2 than most other sources of electricity, as described in sub-section 5.6.3 hereafter. In some cases, reservoirs absorb more GHG than they emit. However, under certain conditions[3] some reservoirs may emit methane (CH_4). Thus, there is a need to properly assess the net change in GHG emissions induced by the creation of such reservoirs. Sub-section 5.6.3 also aims at recapitulating current scientific knowledge about these particular circumstances.

Furthermore, throughout the past decades project planning has evolved acknowledging a paradigm shift from a technocratic approach to a participative one (Healey, 1992). Nowadays, stakeholder

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[3] Climate, temperature, inundated biomass, topography, water residence time, oxygen level, etc.

consultation has become an essential tool to improve project outcomes. It is therefore important to identify key stakeholders[4] early in the development process in order to ensure positive and constructive consultations. Emphasizing transparency and an open, participatory decision-making process, this new approach is driving both present day and future hydropower projects toward increasingly more environment-friendly and sustainable solutions. At the same time, the concept and scope of environmental and social management associated with hydropower development and operation have changed moving from a mere impact assessment process to a global management plan encompassing all sustainability aspects. This evolution is described in more details in Figure 5.22.

5.6.1 Typical impacts and possible mitigation measures

Although the type and magnitude of the impacts will vary from project to project, it is possible to describe some typical effects, along with the experience which has been gained throughout the past decades in managing and solving problems. Though some impacts are unavoidable, they can be minimized or compensated as experience in successful mitigation demonstrates. There are now a number of "good practice" projects where environmental and social challenges were handled successfully (IEA, 2000a; UNEP, 2007). By far the most effective measure is impact avoidance, weeding out less sustainable alternatives early in the design stage.

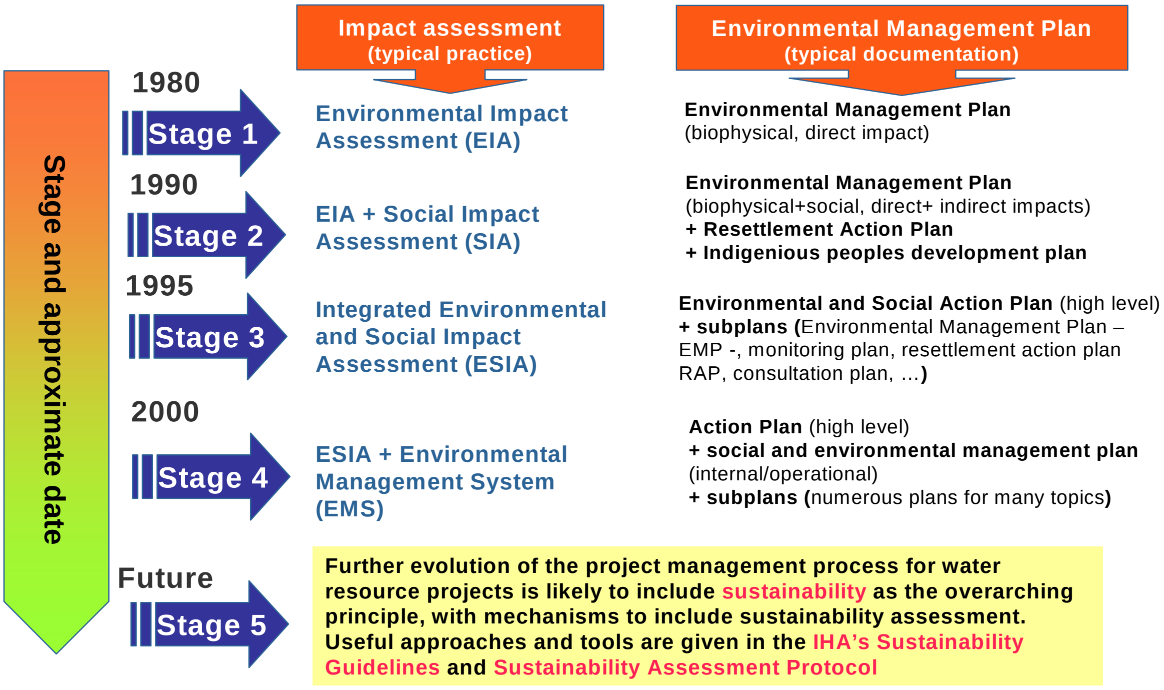

Figure 5.22: Evolution of the E&S process, adapted from UNEP (2007). [TSU: caption not clear (E&S not defined)]

HPP can be an opportunity for better protecting existing ecosystems. Some hydropower reservoirs have even been recognized as new, high-value ecosystems by being registered as "Ramsar" reservoirs (Ramsar List of Wetlands of International Importance, 2009). At the same time, HPPs modify aquatic and riparian ecosystems (shifting from riverine and terrestrial to lentic ecosystem), which can have significant adverse effects according to the project's specific site conditions. Altered flow regimes, erosion and heavily impacted littoral zones in reservoirs are well known types of negative impacts (Helland-Hansen *et al.*, 2005). In addition, dams represent a barrier for fish migration (long-distance as well as local), both upwards and downwards (see below). Hydro

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[4] Local/national/regional authorities, affected population, NGOs, etc.

peaking operation may also affect the downstream fish populations. Yet, in some cases the effect on the river system may also be positive. Recent investigations from Norway in the regulated river Orkla have shown an increase in the salmon production caused by the flow regulating effect of hydropower schemes which increases winter flows and protects the roe and young fish from freezing (net increase in smolt production after the hydropower development of 10-30% (Hvidsten, 2004). This was also supported by LAbée-Lund et al. (L'Abée-Lund *et al.*, 2006) who compared 22 Norwegian rivers, both regulated and not-regulated, based on 128 years of catch statistics. For the regulated rivers they observed no significant effect of hydropower development on the annual catch of anadromous salmonids. For two of the regulated rivers the effect was positive. In addition enhancement measures such as stocking and building fish ladders significantly increased annual catches. A review (Bain, 2007) looking at several hydropower peaking cases in North-America and Europe indicates clearly that the impacts from HPPs in the operational phase is variable, but in may have a positive effect on downstream areas. Dams can namely be a tool to improve the following ecological services: management of water quantity and quality, ground water stabilization in adjacent areas, preservation of wetlands, control of invasive species, sediment management.

With respect to social impacts, HPPs are generating revenues from a natural and domestic resource, a river. One of the main social impacts of HPP projects is the relocation of communities possibly living in the reservoir area, as well as impacts on the livelihoods of the downstream populations. Restoration and improvement of living standards of affected communities is a long term and challenging task, which has been managed with variable success in the past. Large emphasis given to the physical relocation to the detriment of livelihood development is one of the main reason for these unsuccessful programs (WCD, 2000). However, as documented by Scudder (Scudder, 2005), HPPs may have positive impacts on the living conditions of local communities and the regional economy. Thus on the positive side, a hydropower often fosters socio-economic development, not only by generating electricity but also by facilitating through the creating of freshwater storage schemes multiple other water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries while protecting against floods and droughts. Yet, inevitably questions arise about the sharing of these revenues among the local affected communities, government, investors and the operator. Key challenges in this domain are the fair treatment of affected communities and especially vulnerable groups like indigenous people, resettlement if necessary and public health issues, as well as appropriate management of cultural heritage values (see section 5.6.1.7).

Massive influx of workers and creation of transportation corridors also have a potential impact on environment and surrounding communities if not properly controlled and managed. In addition, workers should be in a position once demobilized at least to return to their previous activities, or to have access to other construction sites thanks to their increased capacities and experience.

According to hydropower-specific studies carried over during last ten year period by the IEA (2000b; 2006), eleven sensitive issues have been identified that need to be carefully assessed and managed to achieve sustainable hydropower projects. These have been summed up at paragraphs 5.6.1.1 to 5.6.1.11 [TSU: several of the following subsections lack references]

5.6.1.1 Hydrological Regimes

Depending on the type of hydropower project, the river flow regime is more or less modified (WCD, 2000). Run-of-river projects can use all the river flow or only a fraction of it, but leave the river's flow pattern essentially unchanged, reducing downstream impacts of the project. HPPs with reservoirs alter significantly the hydrological cycle downstream, both in terms of frequency and magnitude of flow discharge. Some projects involve river diversions that may modify the hydrological cycle along the diversion routes. Physical and biological changes are related to variations in water level. The out-levelling of the annual flow pattern may affect dramatically the natural habitats changes that may have been naturally exiting in the downstream areas, prior to the project (succession of inundation and drawdown, with vegetation regrowth for instance). This may affect vegetation species and community structure, which in turn affect the mammalian and birds fauna. On the other hand, frequent (daily or weekly) fluctuations of the water level downstream a hydropower reservoir and a tailrace area might create problems both for mammals and birds. Sudden water release could drown animals and wash nests of waterfowls away. The magnitude of these changes can sometimes be mitigated by proper power plant operation and discharge management, regulating ponds, information and warning systems as well as access limitations. There is also a trend to incorporate ecological minimum flow considerations (Scudder, 2005) into the operation of water control structures as well as increasing needs for flood and drought control. Major changes in the flow regime may entail modifications in the estuary, where the extent of salt water intrusion depends on the freshwater discharge. Another impact associated with dam construction is decreased sediment loading to river deltas. A thorough flow management program can ensure to prevent loss of habitats and resources. Further possible mitigation measures might be to release controlled floods in critical periods and to build weirs in order to maintain water levels in rivers with reduced flow or to prevent salt intrusion from the estuary.

5.6.1.2 Reservoir Creation

Although not all HPPs do have a reservoir, it is the impoundment of land which has the most important adverse impacts, while the thus created new freshwater and renewable energy storage capacity is also providing the most benefits to society, as it helps to manage water quantity and balance fluctuations in the electricity supply system. Creating a reservoir entails not only the transformation of a terrestrial ecosystem into an aquatic one, it also brings along important modifications to river flow regimes by transforming a relatively fast flowing water course into a still standing water body. For this reason, the most suitable site for a reservoir needs to be thoroughly studied, as the most effective impact avoidance action is to limit the extent of flooding on the basis of technical, economic, social and environmental considerations.

Generally, reservoirs may be good habitat for fish. However, the impacts of reservoirs on fish species will only be perceived positive, if species are of commercial value or appreciated for sport and subsistence fishing. If water quality proves to be inadequate, measures to enhance the quality of other water bodies for valued species should be considered in co-operation with affected communities. Other options to foster the development of fish communities and fisheries in and beyond the reservoir zone are for example to create spawning and rearing habitat, to install fish incubators, to introduce fish farming technologies, to stock fish species of commercial interest which are well adapted to reservoirs as long as this is compatible with the conservation of biodiversity within the reservoir and does not conflict with native species, to develop facilities for fish harvesting, processing and marketing, to build access roads ramps and landing areas or to cut trees prior to impoundment along navigation corridors and fishing sites, to provide navigation maps and charts and to recover floating debris.

As reservoirs take the place of terrestrial habitats, it is also important to protect and/or recreate the types of habitats lost through inundation (WCD, 2000). In general, long-term compensation and enhancement measures have turned out to be much more beneficial than the conservation of terrestrial habitats. Further possible mitigation measures might be to protect areas and wetlands that have an equivalent or better ecological value than the land lost, to preserve valuable land bordering the reservoir for ecological purposes and erosion prevention, to conserve flooded emerging forest in some areas for brood rearing waterfowl, to enhance habitat of reservoir islands for conservation purpose, to develop or enhance nesting areas for birds and nesting platforms for raptors or to practice selective wood cutting for herbivorous mammals as well as to implement wildlife rescue and management plans.

5.6.1.3 Water Quality

In some densely populated areas with rather poor water quality (e.g. Weser, Germany) run-of-river power plants are regularly used to improve oxygen levels and filter tons of floating waste (more than 1400 t/year) out of the river, or to reduce too high water temperature levels from thermal power generating outlets. However maintaining the water quality of reservoir is often a challenge, as reservoirs constitute a focal point for the river basin catchment. In cases where municipal, industrial and agricultural waste waters entering the reservoir are exacerbating water quality problems, it might be relevant that proponents and stakeholder cooperate in the context of an appropriate land and water use plan encompassing the whole catchment area, preventing for example excessive usage of fertilizers and pesticides. Most water quality problems, however, can be avoided or minimized through proper site selection and design, based on reservoir morphology and hydraulic characteristics. In this respect the two main objectives are to reduce the area flooded and to minimize water residence time in the reservoir. Selective or multi-level water intakes may limit the release of poor quality water in the downstream areas due to thermal stratification, turbidity and temperature changes both within and downstream of the reservoir. They may also reduce oxygen depletion and the volume of anoxic waters. The absence of oxygen can especially in warm climates contribute to the formation of methane in the first years after impoundment. Hence appropriate mitigation measures to prevent the formation of reservoir zones without oxygen also help to maintain the climate-friendly carbon footprint of hydropower (see 5.6.3 for more details).

Some hydropower schemes have been successfully equipped with structures for re-oxygenation both in the reservoir (e.g. bubbling tubes, stirring devices) or downstream of the reservoir. Downstream gas super saturation may be mitigated by designing spillways, installing stilling basins or adding structures to favour degassing like aeration weirs. While some specialists recommend pre-impoundment clearing of the reservoir area, this must be carried out carefully because, in some cases, significant re-growth may occur prior to impoundment, and the massive and sudden release of nutrients may lead to algal blooms and water quality problems. In some situations “Fill and Flush”, prior to commercial operation, might contribute to water quality improvement, whereas planning periodic peak flows can increase aquatic weed drift and decrease suitable substrate for weed growth reducing problems with undesired invasive species. Increased water turbidity can be mitigated by protecting shorelines that are highly sensitive to erosion, or by managing flow regimes in a manner that reduces downstream erosion.

5.6.1.4 Sedimentation

In 2000, the WCD reported an annual loss of 0.5 to 1% of the world reservoir volume due to sedimentation. However, this phenomenon is very site specific, and tends to affect more (i) reservoirs in the lower reaches of rivers, and (ii) smaller reservoirs (WCD, 2000, p 65). In some mountainous regions like Himalayas the sediment load may however significantly reduce the life span of both the reservoir (sediment deposition) and runners (abrasion), whereas in some countries like Norway or Canada, sedimentation is not an issue due to mainly hard, rocky underground. Yet, in areas with sandy or highly volcanic geology, or steep slopes, there is a natural predisposition for sedimentation which can be exacerbated by unsustainable land use in the river basin. Distinction of project behaviour with respect to sedimentation problems must be made between run-of-river projects on one hand and storage reservoirs on the other hand. The formers are characterized by some possibility of using flow in the upstream pond to erode and transport sediments downstream (particularly during floods), while the latter do not have the same possibility, and specific solutions must be considered.

Sedimentation has a direct influence on the maintenance costs and even on the feasibility of a HPP, and the type and volume of sediments is usually thoroughly studied during the assessment phase of any HPP project.. The effect of sedimentation is not only reservoir storage capacity depletion over time due to sediment deposition, but also an increase in downstream degradation and increased flood risk upstream of the reservoirs. If significant reservoir sedimentation is unavoidable, appropriate attention must be paid during project planning to establish a storage volume that is compatible with the required life time of the project. Further possible actions to prevent reservoir sedimentation include careful site selection, determining precisely long-term sediment inflow characteristics to the reservoir, extracting coarse material from the riverbed, dredging sediment deposits, using special devices for sediment management like the installation of gated structures to flush sediment under flow conditions comparable to natural conditions, conveyance systems equipped with an adequate sediment excluder, sediment trapping devices or bypass facilities to divert floodwaters. Measures may also include agricultural soil (cover plants) or natural land (reforestation) protection in the catchment.

5.6.1.5 Biological Diversity

Although existing literature related to ecological effects of river regulations on wildlife is extensive (Nilsson *et al.*, 1993; WCD, 2000), the knowledge is mainly restricted to and based on EIA studies. A restricted number of long-term studies have been carried out enabling predictions of species-specific effects of hydropower development on mammals and birds. In general four types of environmental disturbances are singled out:

- habitat changes,
- geological and climatic changes,
- direct mortality and
- increased human use of the area.

Most predictions are, however, very general and only able to focus on type of change, without quantifying the short- and long-term effects. Thus, it is generally realized that the current knowledge cannot provide a basis for precise predictions. The impacts are however highly species-, site-, seasonal -and construction-specific.

The most serious ecological effects of hydropower development to wildlife is in general

- permanent loss of habitat and special biotopes through inundation
- loss of flooding
- fluctuating water levels (and habitat change)
- aspects of landscape ecology and secondary effects

A submerged area looses all terrestrial animals, and many animals will be drowned and dispelled when a new reservoir is filled up. This can be partly mitigated through implementation of a wildlife rescue program, although it is generally recognized that these programs may have limited effect on the wild populations on the long term (WCD, 2000; Ledec *et al.*, 2003). Endangered species attached to specific biotopes require particular attention and dedicated management programs prior to impoundment. Increased aquatic production caused by nutrient leakage from the inundated soil immediately after damming, have been observed to affect both invertebrates and vertebrates positively for some time, i.e. until the soil nutrients have been washed out. An increase in aquatic birds associated with this damming effect in the reservoir has been observed.

Whereas many natural habitats are successfully transformed for human purposes, the natural value of certain other areas is such that they must be used with great care or left untouched. The choice can be made to preserve natural environments that are deemed sensitive or exceptional. To maintain biological diversity, the following measures have proven to be successful: establishing protected areas; choosing a reservoir site that minimizes loss of ecosystems; managing invasive species through proper identification, education and eradication, conducting specific inventories to learn more about the fauna, flora and specific habitats within the studied area.

5.6.1.6 Barriers for Fish Migration and Navigation

Dams are creating obstacles for the movement of migratory fish species and for river navigation. They may reduce access to spawning grounds and rearing zones, leading to a decrease in migratory fish populations and fragmentation of non-migratory fish populations. However, natural waterfalls also constitute obstacles to upstream fish migration and river navigation. Those dams which are built on such waterfalls do therefore not constitute an additional barrier to passage. Solutions for upstream fish migrations are now pretty well managed: a variety of solutions have been tested for the last 30 years and have shown acceptable to high efficiency. Fish ladders can partly restore the upstream migration, but they must be carefully designed, and well suited to the site and species considered (Larinier *et al*., 2004)). In particular they may not be adapted to high head schemes. Conversely, downstream fish migration remains more difficult to address. Most fish injuries or mortalities during downstream movement are due to their passage through turbines and spillways. In low-head HPPs, improvement in turbine design (“Fish Friendly Turbines”), spillway design or overflow design has proven to successfully reduce fish injury or mortality rates, especially for eels, and to a lesser extent salmonids (Amaral et al., 2009). [TSU: reference missing in reference list] More improvements may be obtained by adequate management of the power plant flow regime or through spillway openings during downstream movement of migratory species. Once the design of the main components (plant, spillway, overflow) has been optimized for fish passage, some avoidance systems may be installed (screens, strobe lights, acoustic cannons, electric fields, etc.), efficiency of which is highly site and species dependant, especially in large rivers. In some cases, it may be more useful to capture the fish in the headrace or upstream and release the individuals downstream. Other common devices include by-pass channels, fish elevators with attraction flow or leaders to guide fish to fish ladders and the installation of avoidance systems upstream of the power plant.

To ensure navigation at a dam site, ship locks are the most effective technique available. For small craft, lifts and elevators can be used with success. Navigation locks can also be used as fish ways with some adjustments to the equipment. Sometimes, it is necessary to increase the upstream attraction flow. In some projects, by-pass or diversion channels have been dug around the dam.

5.6.1.7 Involuntary Population Displacement

Although not all hydropower projects require resettlement, involuntary displacement is part of the most sensitive socio-economic issues surrounding hydropower development (WCD, 2000; Scudder, 2005). It consists of two closely related, yet distinct processes: displacing and resettling people as well as restoring their livelihoods through the rebuilding or “rehabilitation” of their communities.

When involuntary displacement cannot be avoided, the following measures might contribute to optimise resettlement outcomes:

- involving affected people in defining resettlement objectives, in identifying reestablishment solutions and in implementing them; rebuilding communities and moving people in groups, while taking special care of indigenous peoples and other vulnerable social groups;
- publicizing and disseminating project objectives and related information through community outreach programs, to ensure widespread acceptance and success of the resettlement process;

- improving livelihoods by fostering the adoption of appropriate regulatory frameworks, by building required institutional capacities, by providing necessary income restoration and compensation programs and by ensuring the development and implementation of long-term integrated community development programs;
- allocating resources and sharing benefits, based upon accurate cost assessments and commensurate financing, with resettlement timetables tied to civil works construction and effective executing organizations that respond to local development needs, opportunities and constraints.

5.6.1.8 Affected People and Vulnerable Groups

Like in all other large-scale interventions it is important during the planning of hydropower projects to identify through a proper social impact study who will benefit from the project and especially who will be exposed to negative impacts. Project affected people are individuals living in the region that is impacted by a hydropower project's preparation, implementation and/or operation. These may be within the catchment, reservoir area, downstream, or in the periphery where project-associated activities occur, and also can include those living outside of the project affected area who are economically affected by the project. Particular attention needs to be paid to groups that might be considered vulnerable with respect to the degree to which they are marginalized or impoverished and their capacity and means to cope with change. Although it is very difficult to mitigate or fully compensate the social impacts of reservoir hydropower projects on indigenous or other culturally vulnerable communities for whom major transformations to their physical environment run contrary to their fundamental beliefs, special attention has to be paid to those groups in order to ensure that their needs are integrated into project design and adequate measures are taken. Negative impacts can be minimised for such communities, if they are willing partners in the development of a hydropower project, rather than perceiving it as a development imposed on them by an outside agency with conflicting values. Such communities require to be given sufficient lead time, appropriate resources and communication tools to assimilate or think through the project's consequences and to define on a consensual basis the conditions in which they would be prepared to proceed with the proposed development. Granting a long-term financial support for activities which define local cultural specificities may also be a way to minimize impacts as well as ensuring early involvement of concerned communities in project planning; to reach agreements on proposed developments and economic spin-offs between concerned communities and proponents. Furthermore, granting legal protections so that affected communities retain exclusive rights to the remainder of their traditional lands and to new lands obtained as compensation might be an appropriate mitigation measure as well as to restrict access of non-residents to the territory during the construction period while securing compensation funds for the development of community infrastructure and services such as access to domestic water supply or to restore river crossings and access roads. Also, it is possible to train community members for project-related job opportunities.

5.6.1.9 Public Health

In warmer climate zones the creation of still standing water body such as reservoirs can lead to increases in waterborne diseases like malaria, river blindness, dengue or yellow fever, although the need to retain rainwater for supply security is most pressing in these regions. In other zones, a temporary increase of mercury may have to be managed in the reservoir, due to the liberation of often airborne mercury from the soil through bacteria, which can then be entering in the food chain in form of methyl mercury. Ratio of anthropogenic vs natural emissions of mercury is difficult to assess, although it is now considered that two thirds of mercury in global fluxes is from anthropogenic sources (Hoffman *et al.*, 2003). In some areas human activities like coal burning (North America) and mining represent a significant contributor. Moreover, higher incidences of behavioural diseases linked to increased population densities are frequent consequences of large construction sites. Therefore public health impacts should be considered and addressed from the outset of the project. Reservoirs that are likely to become the host of waterborne disease vectors require provisions for covering the cost of health care services to improve health conditions in affected communities. In order to manage health effects related to a substantial population growth around hydropower reservoirs, it may be considered to control the influx of migrant workers or migrant settlers as well as to plan the announcement of the project in order to avoid early population migration to an area not prepared to receive them. Moreover, mechanical and/or chemical treatment of shallow reservoir areas could be considered to reduce proliferation of insects carrying diseases, while planning and implementing disease prevention programs. Also, it may be considered to increase access to good quality medical services in project-affected communities and in areas where population densities are likely to increase as well as to put in place detection and epidemiological monitoring programs, to establish public health education programs directed at the populations affected by the project as well as to implement a health plan for work force and along the transportation corridor to reduce risk for transmittable diseases (e.g. STD).

5.6.1.10 Cultural heritage

Cultural heritage is the present manifestation of the human past and refers to sites, structures and remains of archeological, historical, religious, cultural and aesthetic value (Bank, 1994). Exceptional natural landscapes or physical features of our environment are also an important part of human heritage as landscapes are endowed with a variety of meanings. The creation of a reservoir might lead to disappearance of valued exceptional landscapes such as spectacular waterfalls and canyons. Long-term landscape modifications can also be incurred by soil erosion, sedimentation, low water levels in reservoirs as well as through associated infrastructure impacts (e.g. new roads, transmission lines). It is therefore important that appropriate measures are taken to preserve natural beauty in the project area and to protect cultural properties with high historic value.

Possible measures to minimise negative impacts are for example to ensure on site protection, conservation and restoration or relocation and/or re-creation of important physical and cultural resources, to create a museum in partnership with local communities to make archaeological findings, documentation and record keeping accessible, to include landscape architecture competences into the project design to optimise harmonious integration of the infrastructure into the landscape, to use borrow pits and quarries for construction material which will later disappear through impoundment, to re-vegetate dumping sites for soil and excavation material with indigenous species, to put transmission lines and power stations underground in areas of exceptional natural beauty, incorporate residual flows to preserve important waterfalls at least during the touristic high season, to keep as much as possible the natural appearance of river landscapes by constructing weirs using local rocks to adjust the water level instead of concrete weirs, and by constructing small islands in impounded areas.

5.6.1.11 Sharing of Development Benefits

There is no doubt that well sited and designed hydropower projects have a substantial potential to generate significant national and regional economic benefits. It is difficult to overstate the economic importance of hydropower and irrigation dams for densely populated countries that are affected by scarce water resources for agriculture and industry, limited access to indigenous sources of oil, gas or coal, and frequent shortages of electricity. In many cases, however, hydropower projects have resulted both in winners and losers: affected local communities have often born the brunt of project-related economic and social losses, while the regions to which they are connected have benefited from better access to affordable power and to regulated downstream water flows and water levels. Although economic benefits are often substantial, effective enhancement measures should ensure that local and regional communities fully benefit from the hydropower project. This may take many forms including business partnerships, royalties, development funds, equity sharing, job creation and training, jointly managed environmental mitigation and enhancement funds, improvements of roads and other infrastructures, recreational and commercial facilities (e.g. tourism, fisheries), sharing of revenues, payment of local taxes, or granting preferential electricity rates and fees for other water-related services to local companies and project-affected populations.

5.6.2 Guidelines and regulations

The assessment and management of the above impacts represent a key challenge for hydropower development. The issues at stake are very complex and have often been subject of intense controversy (Goldsmith *et al.*, 1984). Moreover, unsolved socio-political issues, which are often not project related, tend to come up to the forefront of the decision-making process in a large-scale infrastructure development (Beauchamp, 1997).

All in all, the planning of larger hydropower developments can be rather complex due to the wide range of stakeholders[5] involved in the preparation, funding, construction and operation of a hydropower project, as those stakeholder need to acquire a common and clear understanding of the associated environmental and social impacts, risks and opportunities. Therefore guidelines and regulations are needed to ensure that those impacts are assessed as objectively as possible and managed in an appropriate manner. In many countries a strong national legal and regulatory framework has been put in place to determine how hydropower projects shall be developed and operated through a licensing process and follow-up obligations enshrined into the operating permit often also known as concession agreement. Yet, discrepancies between various national regulations as well as controversies have lead to the need to establish international guidelines on how to avoid, minimise, compensate negative impacts while maximising the positive ones.

Besides the international financing agencies' safeguard policies, one of the first initiatives was launched in 1996 by countries like Canada, USA, Norway, Sweden and Spain for which hydropower is an important energy resource. Their governments set up in collaboration with their mainly state-owned hydropower utilities and research institutions a five-year research program under the auspices of the International Energy Agency (IEA, 2000b) called "Hydropower and the Environment". This IEA research program relied on the assessment of more than 130 hydropower projects, involving more than 110 experts from 16 countries, the World Bank and the World Commission on Dams (WCD). The WCD was established in 1998 to review the development effectiveness of large dams, to assess alternatives for water and power development, and to develop acceptable criteria, guidelines and standards, where appropriate, for the planning, design, appraisal, construction, operation, monitoring and decommissioning of dams. It has set on five core values[6], seven strategic priorities[7] and twenty-six guidelines (WCD, 2000). While governments, financiers and the industry have widely endorsed the WCD core values and strategic priorities, they consider the guidelines to be only partly applicable. As a consequence, international financial institutions such as World Bank (WB), Asian Development Bank (ADB), African Development Bank (AfDB) or the European Bank for Reconstruction and Development (EBRD) have not endorsed the WCD report as a whole, in particular not its guidelines, but they have kept or developed their own guidelines and criteria (Bank, 2001). All major export credit agencies (ECAs) have done the same (Ecologic, 2008). Whereas the WCD's work focused on analysing the reasons for shortcomings with respect to poorly performing dams, its follow-up initiative the "Dams and Development

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[5] E.g. local population, governments, developers, financing institutions, NGOs and others

[6] Equity, efficiency, participatory decision-making, sustainability, and accountability

[7] Gaining public acceptance, comprehensive options assessment, addressing existing dams, sustaining rivers and livelihoods, recognising entitlements and sharing benefits, ensuring compliance, sharing rivers for peace, development and security

Project" (DDP) hosted by UNEP, put an emphasis on gathering good practice into a compendium (UNEP, 2007). In a similar perspective, the IEA launched in 2000 a second hydropower specific 5-year research program called "Hydropower Good Practice" (IEA, 2006).

Even though the International Finance Corporation's Performance Standards and the Equator Principles have become the most widely-accepted general framework among international project financiers for managing environmental and social risks and opportunities of projects in the developing world, the need remains for a specific practical reference tool to properly assess the economic, social and environmental performance of hydropower projects. In order to meet this need, the International Hydropower Association (IHA) has produced Sustainability Guidelines (IHA, 2004) and a Hydropower Sustainability Assessment Protocol (IHA, 2006) which are based on the broadly shared five core values and seven strategic priorities of the WCD report, while it has taken the hydropower-specific previous IEA study as starting point (IEA, 2000b). In 2007, a detailed analysis of the tools available for the environmental criteria for hydropower development was conducted on behalf of the ADB, Mekong River Commission, and the Worldwide Fund for Nature. The report concludes that "*the IHA Sustainability Guidelines appears to be the most comprehensive and a possible best starting point for the Greater Mekong Sub region*" (ADB-MRC-WWF, 2007). This industry initiated process remains open to continued improvement and has recently (IHA, 2008)) be broadened to a systematic integration of other parties concerns through the Hydropower Sustainability Assessment Forum. This multi-stakeholder working group is financed by the governments of Germany, Iceland and Norway as well as by the World Bank and is carrying out further expert review of the IHA Hydropower Sustainability Assessment Protocol and the process of its application.

Guidelines are key tools to manage E&S impacts, but they will need to be adapted to the specific context of each particular project (IHA, 2006). National regulations issued from such international guidelines should be writing in a way to promote sustainable hydropower development "The report is not intended as a blueprint" (WCD, 2000).

5.6.3 Life-cycle assessment and GHG emissions of hydropower

Life cycle assessment (LCA) allows taking into account a macro-perspective by comparing impacts of all available technology options in a comprehensive cradle to grave approach. This paragraph only focuses on the climate change indicator (IPCC – 100 years), e.g. greenhouse gas emissions (GHG). LCA of electricity generation in terms of GHG emissions was elaborated by the International Energy Agency (IEA, 2000b). In contrast with thermal generating units, in the case of hydro, there is no GHG emissions associated with the fuel production and fuel transportation, but only with the electricity generation itself. LCA of a hydroelectric kWh consists of 3 main stages:

- **Construction:** in this phase, GHG are from the production and transportation of construction materials (e.g. concrete, steel, etc) and the use of civil work equipments (diesel engines). Those data can differ significantly from one project to another and are rarely available. These emissions are not considered to be important for the whole life cycle of the reservoir. Furthermore, emissions associated with land use change (including deforestation, agricultural practices, and urbanisation) have to be approached with care, as they are not always a direct consequence of the dam construction.

- **Operation and maintenance**: when a hydro reservoir is created the carbon cycle can be modified and in some cases net GHG emissions may occur (see below). Additional GHG emissions can be generated by operation and maintenance activities (building heating/cooling system, auxiliary diesel generating units, staff transportation, etc).

- **Dismantling:** dams can be decommissioned for economic, safety or environmental reasons. Up to now, only few small-size dams have been removed, mainly in the USA. During this phase GHG emissions are emitted due to transportation/storage/recycling of materials, diesel engines, etc.

LCAs carried out on hydropower projects up to now have clearly demonstrated the difficulty to establish generalities regarding this particular technology, among others because most of the studied projects are multipurpose projects. Yet, a study carried out by IEA (2000b) based on LCA and later published in Energy Policy (EIA, 2002), mentioned that the amount of CO_2 – equivalent emitted by hydropower is around 15g CO2eq/kWh or less (VGB-Power-Tech, 2009). Similarly, a study carried out in 2002 by IEA and CRIEPI on the Japanese system has shown LCA GHG emissions to be around 11g CO2eq/kWh. These emissions from mainly temperate and Nordic reservoirs rank very low compared to those of thermal power plants, which would typically be in the range of 500-1000 g CO_2eq /kWh. However, significantly different results can be obtained in some cases under particular circumstances, which are covered in more details hereafter.

Research and field surveys on freshwater systems involving 14 universities and 24 countries (Tremblay *et al.*, 2005) have lead to the following conclusions:

- All freshwater systems, whether they are natural or manmade, emit greenhouse gases (GHG) due to decomposing organic material. This means that lakes, rivers, estuaries, wetlands, seasonal flooded zones and reservoirs emit GHG. They also bury some carbon in the sediments (Cole *et al.*, 2007).
- Within a given region that shares similar ecological conditions, reservoirs and natural water systems produce similar levels of CO_2 emissions per unit area. In some cases, natural water bodies and freshwater reservoirs even absorb more CO_2 than they emit.

Reservoirs are collection points of material coming from the whole drainage basin area upstream. As part of the natural cycle, organic matter is flushed into these collection points from the surrounding terrestrial ecosystems. In addition, domestic sewage, industrial waste and agricultural pollution will also enter these systems and produce GHG emissions, the cause of which should not be attributed to the collection point. Therefore it is a challenge to estimate man-made GHG emissions from flooded lands, as they must consider only the net emissions by subtracting the natural emissions from the terrestrial ecosystem, wetlands, rivers and lakes that were located in the area before impoundment and abstract the effect of carbon inflow from the terrestrial ecosystem, both natural and related to human activities, on the net GHG emission before and after impoundment..

The main GHG produced in freshwater systems are carbon dioxide (CO_2,) and methane (CH_4). The nitrous oxide (N2O) could be also an issue in some cases and more particularly in reservoirs with large drawdown zones or in tropical areas. Yet with respect to N_2O emissions, no global estimation exists presently. Studied reservoirs in boreal environment would emit a low quantity of N_2O, while a recent study does not allow determining clearly whether tropical reservoirs are neutral or sources of N_2O for the atmosphere (Guerin *et al.*, 2008).

For most of the studied reservoirs, two GHG pathways from the reservoir to the atmosphere have been studied (Figure 5.23): ebullition and diffusive fluxes from the surface of the reservoir. In addition, studies at Petit-Saut, Samuel and Balbina have investigated GHG emissions downstream of the dam (degassing just downstream of the dam and diffusive fluxes along the river course downstream of the dam). CH_4 transferred through diffusive fluxes from the bottom to the water surface of the reservoir may undergo oxidation, that is to say transformed in CO_2, in the water column nearby the oxicline when methanotrophic bacteria are present. Regarding N_2O, Guérin et al. (2008b) have identified several possible pathways for N_2O emissions: emissions could occur via diffusive flux, degassing and possibly through macrophytes but this last pathway has never been quantified neither in boreal or tropical environment.

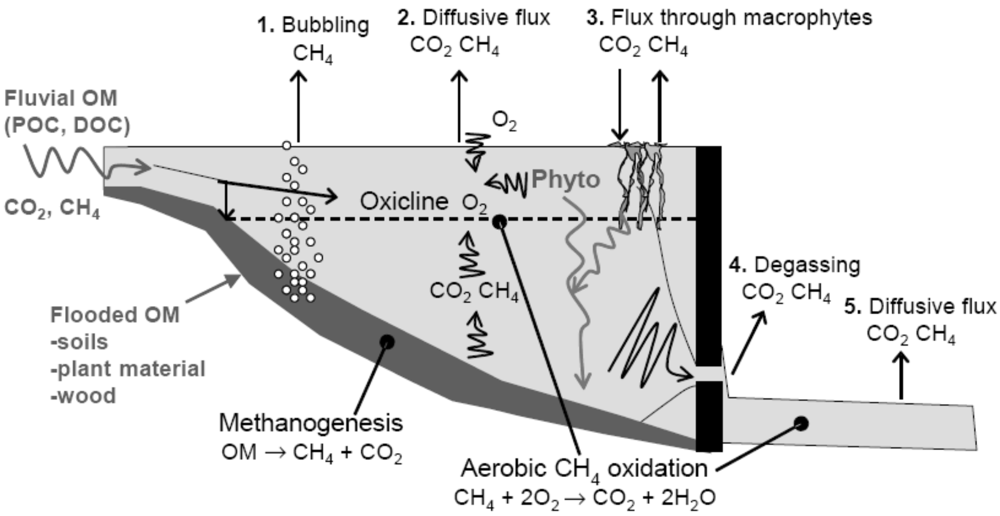

Figure 5.23: Carbon dioxide and methane pathways in freshwater reservoir with an anoxic hypolimnion (e.g. Guerin et al., 2008).

Still, for the time being, only a limited amount of studies appraising the net emissions from freshwater reservoirs (i.e. excluding unrelated anthropogenic sources and pre-existing natural emissions) is available, whereas gross fluxes have been investigated in boreal (e.g. Rudd *et al.*, 1993; Tremblay *et al.*, 2005), temperate (Casper *et al.*, 2000; Soumis *et al.*, 2004; Therrien *et al.*, 2005) and tropical/subtropical (e.g. Guerin *et al.*, 2008) regions. Gross emissions measurements in are summarized in Table 5.5. below.

Table 5.5: Range Of Gross CO_2 And CH_4 Emissions From Hydroelectric Freshwater Reservoirs. [TSU: source missing]

GHG pathway	**Boreal & temperate**		**Tropical**	
	CO_2 **mmol $m^{-2}d^{-1}$**	**CH_4** **mmol $m^{-2}d^{-1}$**	**CO_2** **mmol $m^{-2}d^{-1}$**	**CH_4** **mmol $m^{-2}d^{-1}$**
Diffusive fluxes	-23 – 145 (107)	-0.3 – 8 (56)	-19 – 432 (15)	0.3 – 51 (14)
Bubbling	0	0 – 18 (4)	0	0 – 88 (12)
Degassing[$]	~0.1 (2)	n.a.	4 – 23 (1)	4 – 30 (2)
River below the dam	n.a.	n.a.	500 – 2500 (3)	2- 350 (3)

[$] The degassing (generally in Mg d^{-1}) is attributed to the surface of the reservoir and is expressed in the same unit as the other fluxes (mmol $m^{-2}d^{-1}$)

Numbers in parentheses are the number of studied reservoirs (UNESCO-RED, 2008). [TSU: include sentence in table caption]

Gross emissions measurements in boreal and temperate regions from Canada, Finland, Iceland, Norway, Sweden and USA imply that highly variable results can be obtained for CO_2 emissions, so that reservoirs can act as sinks, but also can present significant CO_2 emissions. Significant CH_4 emissions were not observed in these studies (under boreal/temperate conditions, significant CH_4

emissions are expected only for reservoirs with large drawdown zones and high organic and nutrient inflows).

In tropical regions, high temperatures coupled with important demand in oxygen due to the degradation of substantial Organic Matter (OM) amounts favour the production of CO_2, the establishment of anoxic conditions and thus the production of CH_4. OM is mainly coming from submerged biomass and soil organic carbon with different absolute and relative values (Galy-Lacaux *et al.*, 1999; Blais *et al.*, 2005; Descloux *et al.*, 2010).

According to UNESCO/IHA (2008) measurements of gross emissions have been taken in the tropics at four Amazonian locations[8] and additional sites in central and southern Brazil[9]. They have shown, in some cases, high gross GHG emissions. Measurements are not available from reservoirs in other regions of the tropics or subtropics except for Gatum in Panama, Petit-Saut in French Guyana and Nam Theun 2, Nam Ngum and Nam Leuk in Lao PDR. Preliminary studies on Nam Ngum and Nam Leuk indicate that an old reservoir might act as a carbon sink under certain conditions[10]. This underlines the necessity to also monitor old reservoirs. The age of the reservoir has proved to be an important issue as well as the organic carbon standing stock, water residence time, type of vegetation, season, temperature, oxygen and local primary production, themselves dependent on the geographic area (Fearnside, 2002). According to IPCC (2006) evidence suggests that CO_2 emissions for approximately the first ten years after flooding are the results of decay of some of the organic matter on the land prior to flooding, but, beyond this time period, these emissions are sustained by the input of inorganic and organic carbon material transferred into the flooded area from the watershed or by internal processes in the reservoir. In boreal and temperate conditions, GHG emissions have been observed to return to the levels found in neighbouring natural lakes after the 2-4 years following impoundment (Tremblay *et al.*, 2005). Further measurements could resolve this question for tropical conditions. Comparisons of these results are not easy to achieve, and require intense data interpretation, as different methodologies (equipment, procedures, intensity, units of measurement, etc.) were applied for each study. Few measurements of material transported into or out of the reservoir have been reported, and few studies have measured carbon accumulation in reservoir sediments (UNESCO-RED, 2008)[11].

More coordinated research is needed to establish a robust methodology to accurately estimate the change in GHG emissions caused by the creation of a reservoir: the net GHG emissions. Since 2008, UNESCO and IHA have been hosting an international research project, which aims to improve through a consensus-based, scientific approach, the understanding of reservoir induced impacts, excluding unrelated anthropogenic sources as well as natural GHG emissions from the watershed. The goals are to gain a better understanding on the processes involved and to overcome knowledge gaps.

The project will present a measurement specification guidance in July 2010 to enable standardised measurements and calculations worldwide, and aims at delivering a database of results and characteristics of the measurement specification guidance being applied to a representative set of reservoirs worldwide. The final outcome will be building predictive modelling tools to assess the GHG status of unmonitored reservoirs and new reservoir sites, and guidance on mitigation for vulnerable sites.

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[8] Balbina, Curuá-Una, Samuel, Tucuruí

[9] Barra Bonita, Sarvalho, Corumbá, Funil, Furnas, Itaipu, Itumbiara, L.C.B., Manso, Mascarenhas de Moraes, Miranda, Ribeirão das Lajes, Serra da Mesa, Segredo, Três Marias, Xing (Duchemin et al. 1995)

[10] data scheduled to be published during the first semester of 2010

[11] More information can be found at http://www.hydropower.org/climate_initiatives.html. [TSU: URL in text]

5.6.4 Multiplier effects of hydropower projects

Dam projects generate numerous impacts both on the region where they are located, as well as at an inter-regional, national and even global level (socio-economic, health, institutional, environmental, ecological, and cultural impacts). The WCD and numerous other studies have discussed the importance and difficulties of evaluating a number of these impacts. One of the issues raised by these studies is the need to extend consideration to indirect benefits and costs of dam projects (Bhatia *et al*., 2003). According to the WCD's Final Report (WCD, 2000) "a simple accounting for the direct benefits provided by large dams - the provision of irrigation water, electricity, municipal and industrial water supply, and flood control - often fails to capture the full set of social benefits associated with these services. It also misses a set of ancillary benefits and indirect economic (or multiplier) benefits of dam projects". Indirect impacts are called multiplier impacts, and are resulting from both inter-industry linkage impacts (increase in the demand for an increase in outputs of other sectors) and consumption-induced impacts (increase in incomes and wages generated by the direct outputs). Multipliers are summary measures expressed as a ratio of the total effects (direct and indirect) of a project to its direct effects. A multi-country study on multiplier effects of large hydropower projects was performed by the World Bank (WB, 2005), [TSU: reference missing in reference list] which estimates that the multiplier values for large hydro projects are varying from 1.4 to 2.0, what means that for every dollar of value generated by the sectors directly involved in dam related activities, another 40 to 100 cents could be generated indirectly in the region.

5.7 Prospects for technology improvement and innovation,

Hydropower is a mature technology where most components have been tested and optimized during long term operation. Large hydropower turbines are now close to the theoretical limit for efficiency, with up to 96% efficiency. Older turbines can have lower efficiency by design or reduced efficiency due to corrosion and cavitation. It is therefore a potential to increase energy output by retrofitting new equipment with improved efficiency and usually also with increased capacity. Most of the existing hydropower equipment in operation today will need to be modernized during the next three decades, opening up for improved efficiency and higher power and energy output (UNWWAP, 2006).

The structural elements of a hydropower project, which tend to take up about 70 percent of the initial investment cost, have a projected life of about 100 years. On the equipment side, some refurbishment can be an attractive option after thirty years. Advances in hydro technology can justify the replacement of key components or even complete generating sets. Typically, generating equipment can be upgraded or replaced with more technologically advanced electro-mechanical equipment two or three times during the life of the project, making more effective use of the same flow of water (UNWWAP, 2006).

DOE reported that a 6.3 percent generation increase could be achieved in the USA from efficiency improvements if plant units fabricated in 1970 or prior years, having a total capacity of 30,965 MW, are replaced. Based on work done for the Tennessee Valley Authority (TVA) and other hydroelectric plant operators, a generation improvement of 2 to 5.2 percent has also been estimated for conventional hydropower in the USA (75,000 MW) from installing new equipment and technology, and optimizing water use (Hall *et al*., 2003). In Norway it has been estimated that increase in energy output from existing hydropower from 5-10% is possible with a combination of improved efficiency in new equipment, increased capacity, reduced head loss and reduced water losses and improved operation.

There is much ongoing research aiming to extend the operational range in terms of head and discharge, and also to improve environmental performance, reliability and reduce costs. Some of the promising technologies under development are described briefly in the following section. Most of the new technologies under development aim at utilizing low (< 15m) or very low (< 5m) head, opening up many sites for hydropower that have not been possible to use by conventional technology. Use of Computational Fluid Dynamics (CFD) is an important tool, making it possible to design turbines with high efficiency over a broad range. Other techniques like artificial intelligence, neural networks, fuzzy logic and genetic algorithms are increasingly used to improve operation and reducing cost of maintenance of hydropower equipment.

Most of the data available on hydropower potential is based on field work produced several decades ago, when low head hydro was not a high priority. Thus, existing data on low head hydro potential may not be complete. As an example, in Canada a potential of 5000 MW has recently been identified for low head hydro alone (Natural Resources Canada, 2009).

Another example, in Norway the economical and environmentally feasible small scale hydropower potential (<10 MW) was previously assumed to be 7 TWh. A new study initiated in 2002-2004, revealed this potential to be nearly 25 TWh at a cost below 0.06 US$/kWh and 32 TWh at a cost below 0.09 US$/kWh (Jensen, 2009) [TSU:convert to US $ 2005].

5.7.1 Variable speed technology

Usually, hydro turbines are optimized for an operating point defined by speed, head and discharge. At fixed speed operation, any head or discharge deviation involves an important decrease in efficiency. The application of variable speed generation in hydroelectric power plants offers a series of advantages, based essentially on the greater flexibility of the turbine operation in situations where the flow or the head deviate substantially from their nominal values. In addition to improved efficiency, the abrasion from silt in the water will also be reduced. Substantial increases in production in comparison to a fixed-speed plant have been found in simulation studies (Terens *et al.*, 1993) (Fraile *et al.*, 2006).

5.7.2 Matrix technology

A number of small identical units comprising turbine-generator can be inserted in a frame the shape of a matrix where the number of (small) units is adapted to the available flow. During operation, it is possible to start and stop any number of units so those in operation can always run under optimal flow conditions. This technology, already well accepted, is well suited to install at existing structures for example irrigation dams, low head weirs, ship locks etc where water is released at low heads (Schneeberger *et al.*, 2004).

5.7.3 Fish-friendly turbines

Fish-friendly turbine technology is an emerging technology that provides a safe approach for fish passing though low-head hydraulic turbines minimizing the risk of injury or death. While conventional hydro turbine technologies focus solely on electrical power generation, a fish-friendly turbine brings about benefits for both power generation and protection of fish species (Natural Resources Canada, 2009).

5.7.4 Hydrokinetic turbines

Generally, projects with a head under 1.5 or 2 m are not viable with traditional technology. New technologies are being developed to take advantage of these small water elevation changes, but they generally rely on the kinetic energy in the stream flow as opposed to the potential energy due to hydraulic head. These technologies are often referred to as kinetic hydro or hydrokinetic (see Chapter 6.3 for more details on this technology). Hydrokinetic devices being developed to capture energy from tides and currents may also be deployed inland in both free-flowing rivers and in engineered waterways such as canals, conduits, cooling water discharge pipes, or tailraces of existing dams. One type of these systems relies on underwater turbines, either horizontal or vertical. Large turbine blades would be driven by the moving water, just as windmill blades are moved by the wind; these blades would turn the generators and capture the energy of the water flow (Wellinghoff *et al.*, 2007).

"Free Flow" or "hydrokinetic" generation captures energy from moving water without requiring a dam or diversion. While hydrokinetics includes generation from ocean tides, currents and waves, it is believed that it's most practical application in the near term is likely to be in rivers and streams. Hydrokinetic turbines have low energy density.

A study from 2007 concluded that the current generating capacity of hydropower of 75 000 MW in the USA (excluding pumped storage) could be nearly doubled, including a contribution from hydrokinetic in rivers and constructed waterways of 12 800 MW (EPRI, 2007).

In a "Policy Statement" issued on November 30, 2007 by the Federal Energy Regulatory Commission in the USA (Federal Energy Regulatory Commission, 2007) it is stated that:

"Estimates suggest that new hydrokinetic technologies, if fully developed, could double the amount of hydropower production in the United States, bringing it from just under 10 percent to close to 20 percent of the national electric energy supply. Given the potential benefits of this new, clean power source, the Commission has taken steps to lower the regulatory barriers to its development."

The potential contribution from very low head projects and hydrokinetic projects are usually not included in existing resource assessments for hydropower (See 5.2). The assessments are also usually based on rather old data and lower energy prices than today and future values. It is therefore highly probable that the hydropower potential will increase significantly as these new sources are more closely investigated and technology is improved.

5.7.5 New materials

Major wearing effects on hydropower equipment are corrosion, cavitation damages and abrasion. An intensified use of suitable proven materials such as stainless steel and the invention of new developments as coatings limit the wear on equipment and extend lifespan. Improvements in material development have been performed for almost any plant component. Examples are: a) penstocks made of fiberglass; b) better corrosion protection systems for hydro-mechanical equipment; c) better understanding of electrochemical corrosion leading to a suitable material combination; d) trash rack systems with plastic slide rails.

Water in rivers will often contain large amounts of sediments, especially during flood events when soil erosion creates high sediment loads. In reservoirs the sediments may have time to settle, but in run-of-the-river projects most of the sediments may follow the water flow up to the turbines. If the sediments contain hard minerals like quarts, the abrasive erosion on guide vanes, runner and other steel parts may become very high, and quickly reduce efficiency or destroy turbines completely within a very short time (Lysne *et al.*, 2003; Gummer, 2009). Erosive wear of hydro turbine runners is a complex phenomenon, depending on different parameters such as particle size, density and hardness, concentration, velocity of water, and base material properties. The efficiency of the turbine decreases with the increase in the erosive wear. The traditional solution to the problem has been to build de-silting chambers to trap the silt and flush it out in bypass outlets, but it is very difficult to trap all particles, especially the fines. New solutions are being developed by coating steel surfaces with a very hard ceramic coating, protecting against erosive wear or delaying the process.

The problem of abrasive particles in hydropower plants is not new, but is becoming more acute with increasing hydropower development in developing countries with sediment rich rivers. For example, many new projects in India, China and South America are planned in rivers with high sediment concentrations (Gummer, 2009). The problem may also become more important in case of increased peaking.

Modern turbine design using 3D-flow-simulation provides not only better efficiencies in energy conversion by improved shape of turbine runner and guide/stay vanes. It also leads to a decrease of cavitation damages at high head power plants and to reduced abrasion effects when dealing with heavy sediment loaded propulsion water. Other inventions concern e.g. improved self lubricating bearings with lower damage potential and the invention of electrical servo motors instead of hydraulic ones.

5.7.6 Tunnelling technology

Tunneling technology is used widely in hydropower to transport water from intake up to the turbines, and back to the river or reservoir downstream. Technology in use today includes both drilling and blasting (D&B) and tunneling boring machines (TBM). Recently, new equipment for very small tunnels (0.7 – 1.3 m diameter) based on oil-drilling technology, has been developed and tested in hard rock in Norway, opening up for directional drilling of "penstocks" for small hydropower directly from power station up to intakes, up to one kilometer or more from the power station (Jensen, 2009). This could lower cost and reduce the environmental and visual impacts from above-ground penstocks for small hydropower, and open up for even more sites for small hydro.

5.7.7 Dam technology

The International Commission on Large Dams (ICOLD) has recently decided to focus on better planning of existing and new (planned) hydropower dams. It is believed that over 30 billion US [TSU: state currency as US $ 2005, depending on origin consider converting the figure] will be invested in new dams during the next decade, and the cost can be reduced by 10-20% by more cost-effective solutions. ICOLD also wants to promote multipurpose dams and better planning tools for multipurpose water projects (Berga, 2008). Another main issue ICOLD is focusing on is that of small dams, less than 15 meters high.

The RCC (Roller Compacted Concrete) dam is relatively new dam type, originating in Canada in the 1970s. This dam type is built using much drier concrete than in other gravity dams, and it allows a quicker and more economical dam construction (as compared to conventional concrete placing methods). It is assumed that this type of dams will be much more used in the future, lowering the construction cost and thereby also the cost of energy for hydropower projects.

5.7.8 Optimization of operation

Hydropower generation can be increased at a given plant by optimizing a number of different aspects of plant operations, including the settings of individual units, the coordination of multiple unit operations, and release patterns from multiple reservoirs. Based on the experience of federal agencies such as the Tennessee Valley Authority and on strategic planning workshops with the hydropower industry, it is clear that substantial operational improvements can be made in hydropower systems (DOE Hydropower Program Biennial Report, 2006). In the future, improved hydrological forecasts combined with optimization models is likely to improve operation and water use, increasing the energy output from existing power plants significantly.

5.8 Cost trends

5.8.1 Cost of project implementation

The hydropower generation potential has been described in section 5.2.1, where the global technical potential was given as 14368 TWh/year, and the developed hydropower system 2794 TWh/year per

2005. The cost of project implementation for remaining hydropower will vary a lot from project to project, so a general estimate is difficult to give. A number of studies have been published, however, and a summary of findings and conclusions from the most relevant studies are given below. The most important data are summarized in Table 5.6.

Table 5.6: Cost projection for Hydropower investment in different studies [TSU: give reference year for Greenpeace/EREC]

Source	Investment cost in US $/KW	O&M cost in %	Full load hours	Energy cost in cent/KWh	Comments
WEA 2004	1000 - 3500 $/KW			2 - 8	No trend - future cost same as those in 2004
					Energy cost calculated here based on
IEA-WEO 2008	2184 $/KW in 2005	2.5		*7.1*	*10% interest rate*
	2194 $/KW in 2030	2.5		*7.1*	*Load factor 0.45*
	2202 $/KW in 2050	2.5		*7.1*	*40 year depreciation period*
IEA-ETP 2008	1000-5500 $/KW in 2005	2.2 - 3			
	1000-5400 $/KW in 2030	2.2 - 3			
	1000-5100 $/KW in 2050	2.2 - 3			
IEA-2010	750-19000 $/KW in 2010			*2.3 - 45.9*	13 projects from 0.3 to 18000 MW
	1278 $/KW in 2010		4470	4.8	Weighted average all projects
VLEEM-2003	500-4500 $/KW				240 Projects commisioned from 2002-2020
Lako et al 2003	1000 $/KW				Weighted average all projects
	90% below 1600 $/KW				
					Energy cost calculated here based on
Greenpeace/EREC	2880 $/KW in 2010	4		*10.4*	*10% interest rate*
	3200 $/KW in 2030	4		*11.5*	*Load factor 0.45*
	3420 $/KW in 2050	4		*12.3*	*40 year depreciation period*
BMU Lead Study 2008	2440 $/KW in 2005			7.3	6 % Interest rate used in the study
	3125 $/KWin 2030			8.5	
	3125 $/KW in 2050			8.0	
Krewitt et al 2009	1000-5500 $/KW in 2005				30 year depreciation period is used in this study
	2000	4	2900	9.8	Indicative estimate (average)
	1000-5400 $/KW in 2030				
	2200	4	2900	10.8	Indicative estimate (average)
	1000-5100 $/KW in 2050				
	2500	4	2900	11.9	Indicative estimate (average)

World Energy Assessment (WEA) was first published in 2000 by UNDP and World Energy Council. This study has later been widely used and is being referred to by many later studies. The original report was updated in 2004 (UNDP/UNDESA/WEC, 2004)) and it is this version of the report that is used here. The 2004 report gives an estimate of both theoretical potential for hydropower (40 500 TWh/year or 147 EJ/year), technical exploitable potential (14 320 TWh/year or 50 EJ/year) and economic potential (8100 TWh/year). Unfortunately, the definition of what is considered economic accessible is not defined precisely. The report gives cost estimates both for current and future hydropower development. The cost estimates are given both as turnkey investment cost in US$ pr kW and as energy cost in US cents per kWh. Both cost estimates and capacity factors are given as a range with separate values for small and large hydropower. After a discussion of factors contributing to increasing future cost (mostly environmental and social factors) and factors contributing to decreasing cost (various technological innovations), the conclusion is that these factors probably balance each other, and it is difficult to see any clear trend up or down. Future cost for large hydropower (96.5% of all) is expected to be in the range of 2 to 8 cent per kWh, for small hydro (3.5% of all) [TSU: referenced parameter not clear] it is expected to be in the range 3 to 10 cent per kWh in the future. Since large hydro is dominating both in the present and future system, it will be most correct to focus on the large hydro cost values.

Very Long Term Energy-Environment Model (VLEEM) was an EU-funded project executed by a number of research institutions in France, Germany, Austria and Netherland. Of the many interesting reports from this project, we will focus on "Hydropower Development with a Focus on Asia and Western Europe" (Lako et al., 2003).

This report contains very detailed information, including cost estimates, for 240 hydropower projects worldwide, with most in-depth focus on Asia and Western Europe. The projects were planned for commissioning between 2002 and 2020. A key result from this report is the distribution of investment cost vis-à-vis cumulative capacity for different regions and countries. A summary of cost estimates for the projects were compiled and is presented in Figure 5.24.

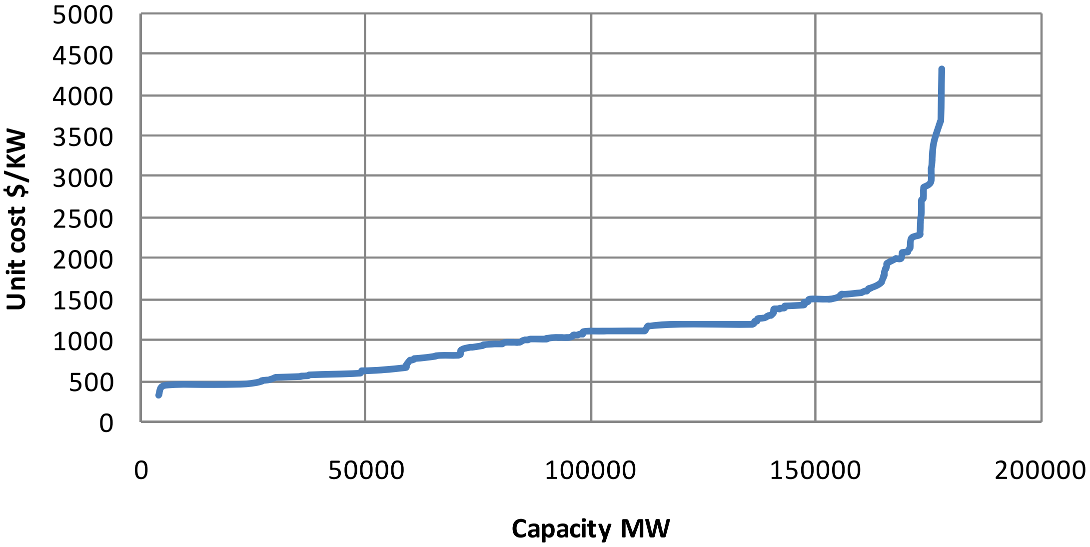

Figure 5.24: Distribution of unit cost ($/kW) for 190 hydropower project sites studied in the VLEEM project. (Source: Hall et al., 2003). [TSU: convert to US $ 2005]

REN21 - "Renewable Energy Potentials - Opportunities for the rapid deployment of renewable energy in large energy economies" was published in 2008 (REN21, 2008). Hydropower is studied in a special report "Global potential of renewable energy sources: A literature assessment". In this report data can be found both for assumed hydropower potential and cost of development for remaining potential. Data seem to come mostly from UNDP/UNDESA/WEC, 2000.

European Renewable Energy Council (EREC) and Greenpeace presented a study in 2008 called "Energy [R]evolution: A Sustainable World Energy Outlook" The report presents a global energy scenario with increasing use of renewable energy, in particular wind and solar energy. The report contains a detailed analysis up to 2050 and perspectives beyond, up to 2100. Also hydropower is included and future scenarios for cost are given from 2008 up to 2050.(EREC,2008)

BMU Lead Study 2008 - "Further development of the strategy to increase the use of renewable energies within the context of the current climate protection goals of Germany and Europe" was commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and published in October 2008. It contains estimated cost for hydropower development up to 2050.

IEA (International Energy Agency) have published several very important reports recently, "World Energy Outlook 2008", "Energy Technology Perspective 2008" and "Projected cost of generating electricity 2010 Edition" where cost data can be found both for existing and future hydropower projects.

Krewitt et al (2009) reviewed and summarized findings from a number of studies from 2000 till 2008. The main source of data for future cost estimates were (UNDP/UNDESA/WEC, 2000; Lako *et al.*, 2003; UNDP/UNDESA/WEC, 2004; IEA, 2008) (EREC, 2008).

Hall *et al.* (2003) published a study for USA where 2155 sites with a total potential capacity of 43 000 MW were examined and classified according to unit cost. The distribution curve shows unit costs that varies from less than 500 $/kW up to over 6000 $/kW [TSU: convert to US $ 2005] (Figure 5.25). Except from a few projects with very high cost, the distribution curve is nearly linear, for up to 95% of the projects. Development cost of hydropower include cost on Licensing, Plant construction, Fish and wildlife mitigation, Recreation mitigation, Historical and archaeological mitigation and Water quality monitoring cost.

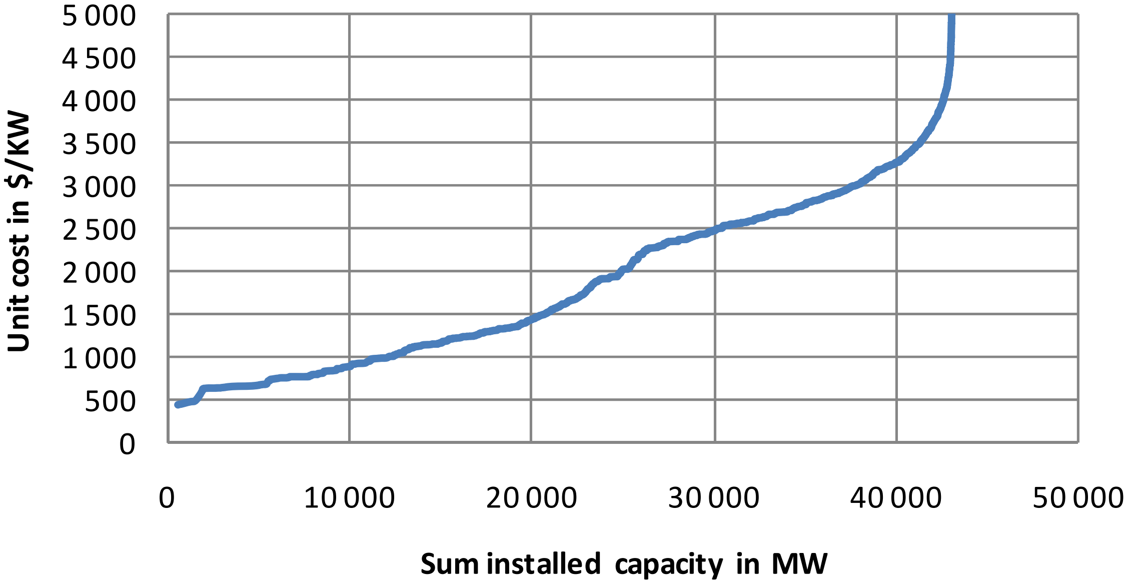

Figure 5.25: Distribution of unit cost ($/kW) for 2155 hydropower project sites studied in USA. (Source: Hall et al., 2003). [TSU: convert to US $ 2005]

Results from all these different studies are summarized in Table 5.6. Most important cost parameters are Investment cost ($/kW) and levelized cost of energy (LCOE) in cent/kWh.

The calculation of LCOE includes a number of parameters, beside investment costs, and a careful selection of these are needed to get a correct result. Most important are Load factor, Operation and Maintenance costs (O&M costs), Depreciation period and Interest rate.

For intermittent energy sources like wind, water and waves, the statistical distribution of the resource will determine the load factor. A low load factor gives low production and higher levelized cost for the energy. Krewitt *et al.* (2009) used a very low value, 2900 hours or 33% while for example IEA 2010 (IEA, 2010) found an average of 4470 hours or 51%. By analyzing energy statistics from IEA we find that typical load factors for existing hydropower systems are in the range from 37% to 56% (USA 37%, China 42%, India 41%, Russia 43%, Norway 49%, Brazil 56%, Canada 56%). We suggest that an average load factor of 45% will be most correct for future hydropower developments.

Operation and Maintenance cost (O&M-cost). Once built and put in operation, hydropower usually requires very little maintenance and operation costs can be kept low. O&M costs are usually given as % of investment cost per kW. Greenpeace/EREC Krewitt *et al.* (2009) used 4% . This may be appropriate for small hydro but is probably too high for large hydropower plants. IEA-WEO 2008 used 2.5%. IEA-ETP 2009 used 2.2% for large hydro increasing to 3% for smaller and more expensive projects. We suggest to use 2.5% as a typical value for O&M cost for future hydropower development.

Depreciation period is the number of years (“Lifetime”) the station is expected to be fully operational and contributing to production and income. For hydropower, and in particular large hydropower, the largest cost components are civil structures with very long lifetime, like dams, tunnels, canals etc. Electrical and mechanical equipment, with much shorter lifetime, usually contributes less to the cost. It is therefore common to use a much longer depreciation period for hydropower that for example wind or wave power where most of the cost is connected to E&M equipment. Krewitt *et al.* (2009) used 30 years for hydropower and 20 years for wind and wave technology. The IEA-2010 study use 80 years for hydropower, 20 years for wave and tidal plants and 25 years for wind and solar plant. We suggest 40 years as a reasonable value, this may be too low for large hydro but ok for small hydro.

Interest rate on investment is a critical parameter, in particular for renewable technologies where the initial investment costs dominates in the calculation of energy cost. A high interest rate will be beneficial for technologies with low initial investment and high running costs, like coal and gas fired power plants. A low interest rate will favor renewable technologies, and in particular technologies with long lifetime like hydropower. In some of the studies it is not stated clearly what interest rate that has been used. BMU Lead Study 2008 used 6%. In IEA-2010 energy costs were computed both for 5% and 10% interest rate. For hydropower an increase from 5% to 10% gives an increase in energy cost of nearly 100%. We have calculated energy cost for two alternatives, a low (6%) and a high (10%).

5.8.2 Future cost of hydropower

There is still a large untapped potential for new hydropower development up to the assumed economic potential of between 8000 and 9000 TWh/year. Since all hydropower projects are site-specific, the untapped potential includes projects with varying cost, ranging from below 500 $/kW up to 10000 $/kW and even higher [TSU: state US$2005 instead of US$; depending on origin consider converting this figure]. The exact cost for all possible projects is not well known, but an estimate of the variability can be seen from the range of cost given for example in UNDP/UNDESA/WEC (2000; 2004) and IEA (2010) (Table 5.6) and in more detail from the two studies summarized in Figure 5.24 and 5.25 It is reasonable to assume that in general projects with low cost will be developed first, and as the best projects have been developed, increasingly costly projects will be used. Very expensive project will usually have to wait and possibly be used at a later stage. But there are many barriers and the selection of the “cheapest projects first” may not always be possible. In Europe, for example, small hydro with rather high cost is now being developed (IEA, 2010) at very high cost, but still favorable compared to other alternatives.

Estimates of potential deployment of new hydropower up to 2030 (Ch. 5.9) is in the order of 2000-3000 TWh/year, still far below the economic potential. Considering the cost structure distribution for mostly large projects (Figure 5.6) and mixture of small and medium size projects (Figure 5.YY) [TSU: reference inexistent], it seem reasonable to assume a gradually increasing cost from today and up to 2050. A typical investment cost can be 1500 $/kWh in 2010, increasing to 2000 $/kWh in 2030 and 2500 $/kWh in 2050 [TSU: convert to US $ 2005], as the more favorable projects have been developed. Using these figures and assumptions regarding Load factor, O&M cost, Depreciation time and Interest rate as discussed before, cost trends for hydropower can be computed from now up to 2050. The results are given in Table 5.7

Table 5.7: Cost projection for hydropower investment – suggested values by SRREN

Interest rate/Depreciation	Investment cost in US$/kW	O&M cost in %	Full load hours	LCOE cent/kWh	Comments
3% interest rate	1500 $/kW in	2.5%	3950	2.6	Projects with lowest cost

40 year depreciation period	2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5%	3950 3950	3.5 4.3	implemented first Increasing cost for remaining projects
7% interest rate 40 year depreciation period	1500 $/kW in 2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5% 2.5%	3950 3950 3950	3.8 5.1 6.3	Projects with lowest cost implemented first Increasing cost for remaining projects
10% interest rate 40 year depreciation period	1500 $/kW in 2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5% 2.5%	3950 3950 3950	4.8 6.4 8.1	Projects with lowest cost implemented first Increasing cost for remaining projects

The results clearly show the importance of the interest rate. With a low interest rate of 6% [TSU: reconcile with table 5.7 reporting 3,7 and 10% interest rate] the energy cost from hydropower will increase from 3.5 c/kWh in 2010 up to 5.8 c/kWh in 2050. With a higher interest rate of 10%, the typical hydropower energy cost will increase from 4.8 c/kWh today up to 8.1 c/kWh in 2050.

These values are well within the range of cost estimates given by UNDP/UNDESA/WEC (2000; 2004) and the various analyses published by IEA, but much lower than the values found by EREC (2008) and (Krewitt, 2009). The energy cost for hydropower in these two analyses are very high due to an unfavorable combination of assumptions regarding initial investment cost, O&M cost, depreciation time and interest rate.

Development cost of hydropower and also cost per unit of energy produced, depend on licensing, plant construction, fish and wildlife mitigation, recreation mitigation, historical and archaeological mitigation and water quality monitoring cost. Hall *et al*. (2003) in their study also presents typical plant construction cost for new sites according to Fig 5.26.

Basically, there are two major cost groups: the civil construction costs, which normally are greater costs of the hydropower project, and those that have to do with electromechanical equipment for energy transformation. The civil construction costs follow the price trend of the country where the project is going to be developed. In the case of countries with economies in transition, the costs are relatively low due to the use of local labor, and local construction materials for civil works

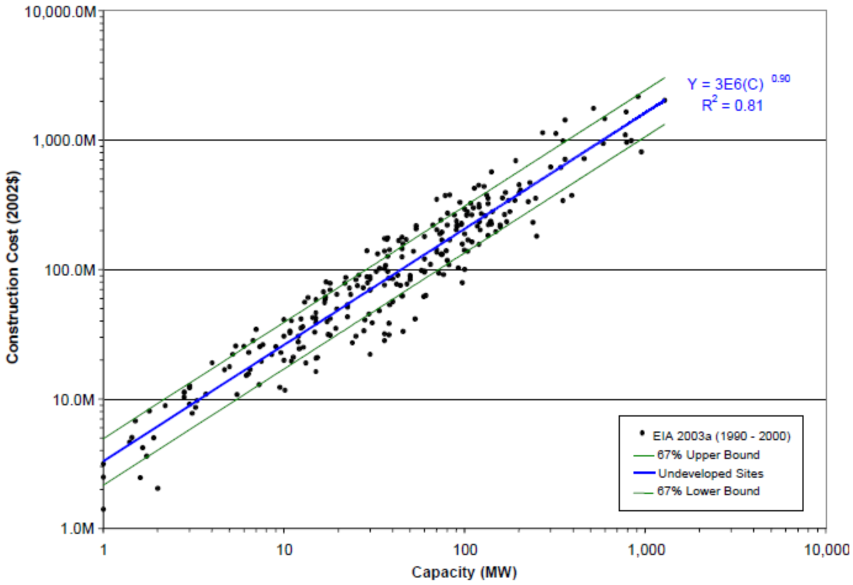

Figure 5.26: Hydropower cost as a function of plant capacity for new sites. [TSU: source missing, convert to US $ 2005]

The costs of electromechanical equipment follow the global prices for these components, except in the countries, where most of the machinery used in the hydropower projects is produced, and where prices are more stable. Although cost estimates are specific for each site, due to the inherent characteristics of the geological conditions and the construction design of the project, for a sound estimate of electromechanical equipment costs, it is possible to have cost estimates that follow a tendency. Avarado-Anchieta (2009,) presents the cost of electromechanical equipment from various hydroelectric projects as given in Figure 5.27.

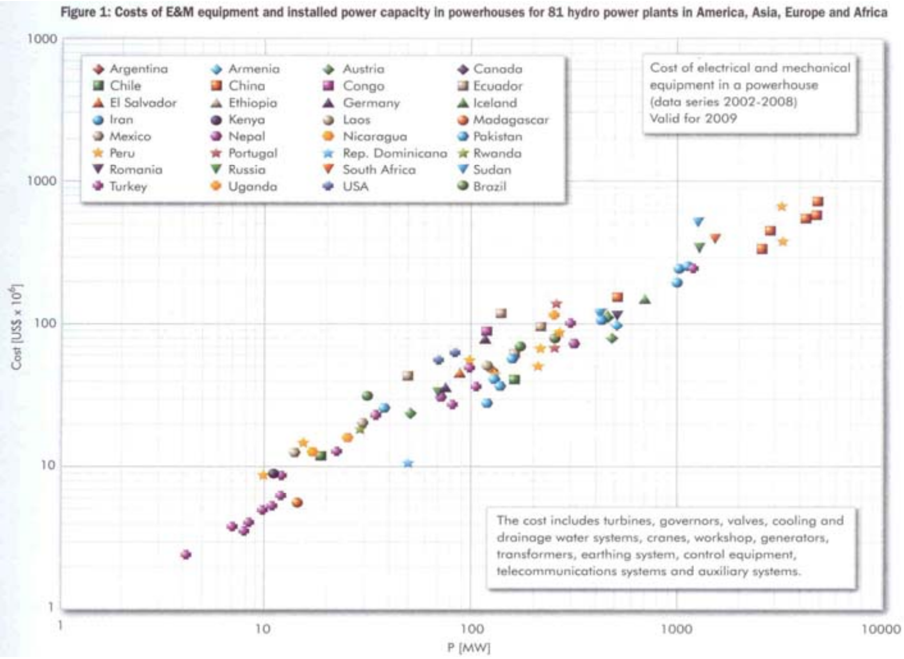

Figure 5.27: Costs of electrical and mechanical (E&M) equipment and installed power capacity in powerhouses for 81 hydro power plants in America, Asia, Europe and Africa. (Source: Avarado-Anchieta (2009,) [TSU: readability, convert to US $ 2005]

Specific installation costs (per installed MW) tend to be reduced for a higher head and installed capacity of the project. This is important in countries or regions where differences of level can be used to advantage. The hydropower project can be set up to use less volume flow, and therefore smaller hydraulic conduits or passages, also the size of the equipment is smaller and costs are lower.

Isolated systems are generally more expensive than systems that can be built near centers of consumption. There is a tendency towards lower costs if projects are in a cascade, all along a basin, given that the water resource is used several times

Use of local labor and materials also reduces cost, which is an advantage for small scale hydroelectric projects. Costs associated with the number of generator units in a hydropower project increase when the number of unit's increases, but this is compensated by a greater availability of the hydroelectric plant into the electric grid. In hydropower projects where the installed power is lower than 5 MW, the electromechanical equipment costs are dominating. As the power to be installed increases, the costs are more influenced by the civil construction. The components of the construction project that impact the total cost, the most are the dam and the hydraulic pressure conduits; therefore these elements have to be optimized during the engineering design stage.

5.8.3 Cost allocation for other purposes

There is a greater need of sharing the cost of hydropower stations serving multipurpose like irrigation, flood control, navigation, roads, drinking water supply, fish, and recreation. Many of the purposes cannot be served alone due to consumptive nature and different priority of use. Cost allocation often has no absolute correct answer. The basic rules are that the allocated cost to any purpose does not exceed that benefit of that purpose and each purpose will carry out at its separable cost. Separable cost for any purpose is obtained by subtracting the cost of a multipurpose project without that purpose from the total cost of the project with the purpose included (Dzurik, 2003). Three commonly used cost allocation methods are: the separable cost-remaining benefits method, the alternative justifiable expenditure method and the use-of-facilities method (Hutchens, 1999).

Until the last decade the reservoirs were mostly funded and owned by the public sector, thus project profitability was not the highest considerations or priority in the decision. Nowadays, the liberalisation of the electricity market has set new economic standards in the funding and management of dam based projects. The investment decision is based on an evaluation of viability and profitability over the full life cycle of the project. The merging of economic elements (energy and water selling prices) with social benefits (supplying water to farmers in case of lack of water) and the value of the environment (to preserve a minimum environmental flow) are becoming tools for consideration for cost sharing of multipurpose reservoirs (Skoulikaris, 2008).

Votruba *et al.* (1988) reported the practice in Czechoslovakia for cost allocation in proportion to benefits and side effects expressed in monetary units. In the case of the Hirakund project in India, the principle of alternative justifiable expenditure method was followed with the allocation of the costs of storage capacities between flood control, irrigation and power was in the ratio of 38:20:42 (Jain, 2007). The Government of India later adopted the use-of-facilities method for allocation of joint costs of multipurpose river valley projects (Jain, 2007).

The issue of estimating costs and projections is not an obstacle for the development of hydroelectricity as a renewable resource.

5.9 Potential deployment

Hydropower offers significant potential for near- and long-term carbon emissions reduction. The hydro capacity installed by the end of 2008 delivers roughly 16% of worldwide electricity supply: hydropower is by far the largest RES in the electricity sector (hydro represents 86% of RE electricity). On a global basis, the hydro resource is unlikely to constrain further development (section 5.2). Hydropower technology is already being deployed at a rapid pace (Sections 5.3 and 5.4), therefore offering an immediate option for reducing carbon emission in the electricity sector. With good conditions, the cost of hydro energy can be less than USD 0.02/kWh (see section 5.8). Hydropower is a mature technology and is at the cross-roads of 2 major issues for a country development: water and energy. This provides hydro a key role for both energy and water security.

This section begins by highlighting near-term forecasts for hydro deployment (5.9.1). It then discusses the prospects for and potential barriers to hydro deployment in the longer-term and the potential role of that deployment in meeting various GHG mitigation targets (5.9.2). Both subsections are largely based on energy-market forecasts and carbon and energy scenarios literature published in the 2007-2009 time period.

5.9.1 Near-term forecasts

The continuing rapid increase in hydro capacity from the last 10 years is expected by many studies to continue in the near- to medium-term (see Table 5.8). Much of the world increase in renewable electricity supply is fuelled by hydropower and wind power. Hydro is economically competitive with fossil fuels over the projection period. From the 923 GW of hydro capacity installed at the end of 2007, the International Energy Agency (IEA, 2009) and U.S. Energy Information Administration (IEA, 2009) reference-case forecasts predict growth to 1,099 GW and 1,047 GW by 2015 respectively (e.g. additional 22 GW/annum and 30 GW/annum by 2015 respectively).

Table 5.8: Near-Term Hydro Energy Forecasts

Study	**Hydro situation**				**Hydro forecast in 2015**		
	Reference year	**Installed capacity (GW)**	**Electricity generation (TWh)**	**% of global electricity supply**	**Installed capacity (GW)**	**Electricity generation (TWh)**	**% of global electricity supply**
IEA (2009a)	2007	923	3 078	16%	1 099	3 692	15%
U.S. EIA (2009)	2006	776	2 997	17%	1 047	3 887	17%

Non-OECD countries, and in particular Asia (China and India) and Latin America, are projected to lead in hydro additions over this period. In 2008, it should be noted that 40 GW of new hydropower has been put in operation.

5.9.2 Long-term deployment in the context of carbon mitigation

The IPCC's Fourth Assessment Report (AR4) assumed that hydro could contribute 15% of global electricity supply by 2030, or 4,300 TWh/year (~ 15.5 EJ) (IPCC, 2007b). This figure is lower than some commonly cited business-as-usual case. The IEA's World Energy Outlook 2009 reference case, for example predicts 4,680 TWh/year of hydro by 2030, or 14% of global electricity supply (IEA, 2009). The US EIA forecasts 4,780 TWh/year of hydro in its 2030 reference case projection, or 15% of net electricity production (IEA, 2009).

It should be noted that the IEA's World Energy Outlook 2008 presents, in addition to the reference case, 2 scenarios regarding the context of carbon mitigation (IEA, 2008). The table 5.9 summarizes these results. In the most stringent 450 ppm stabilization scenarios in 2030, installed capacity of new hydro increases by 545 GW compared to the reference case (e.g. approximately +40%). This study highlights that there is an increase in hydro supply with increasingly aggressive GHG targets.

Hydro can increase annually by roughly 5% in the lowest carbon concentration scenario (e.g. 450 ppm) by 2030.

Table 5.9: Long-term hydro deployment scenarios in the context of carbon mitigation according to IEA forecasts

Hydro installed capacity in GW, in regards to CO2 concentration (IEA, 2008)	2006	2020	2030	Average annual increase (GW/year)	Average annual increase (%/year)
Reference case scenario	**919**	**1 239**	**1 436**	**22**	**2.3%**
550 ppm scenario		**1 409**	**1 659**	**31**	**3.4%**
450 ppm scenario		**1 409**	**1 981**	**44**	**4.8%**

The figure 5.28 summarizes the different scenarios for hydropower generation in 2020 and 2030. For instance in 2030, the hydropower can generate annually between 4680 TWh (IEA, 2009)and 6454 TWh (IEA, 2008) depending on carbon mitigation scenarios.

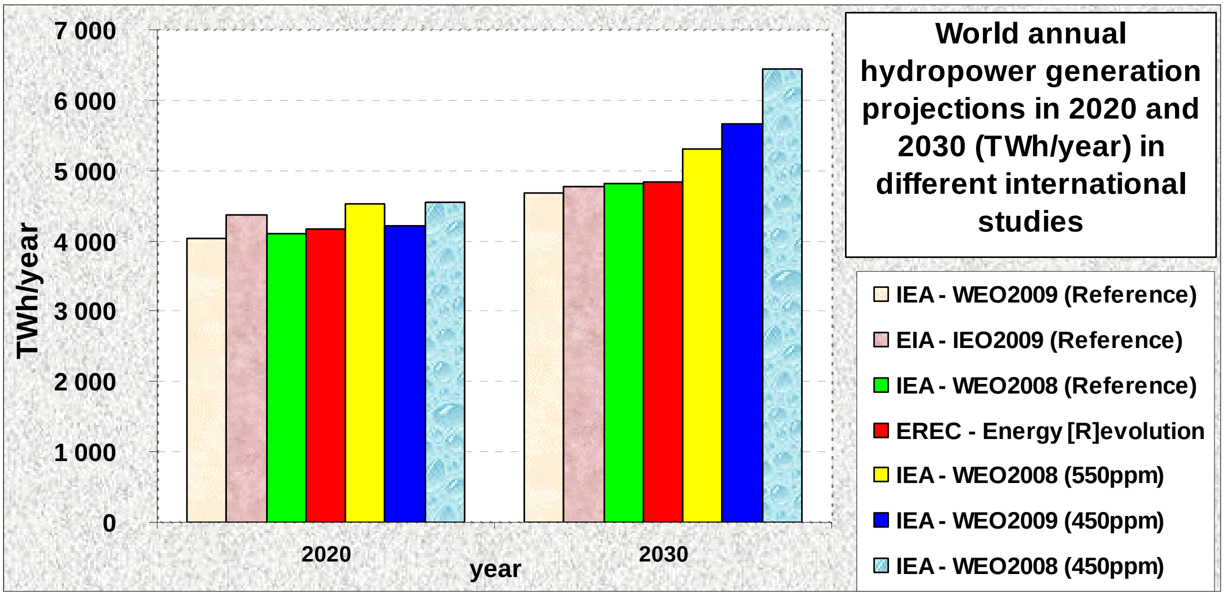

Figure 5.28: Hydro deployment scenarios for the year 2020 and 2030 from different studies

A summary of the literature on the possible contribution of RE supplies meeting global energy needs under a range of CO2 stabilization scenarios is provided in Chapter 10. Focusing specially on hydro, Figures 5.29 present modelling results on the global supply of hydro (in EJ and as a percent of global electricity demand, respectively) ; refer to Chapter 10 for a full description of this literature.

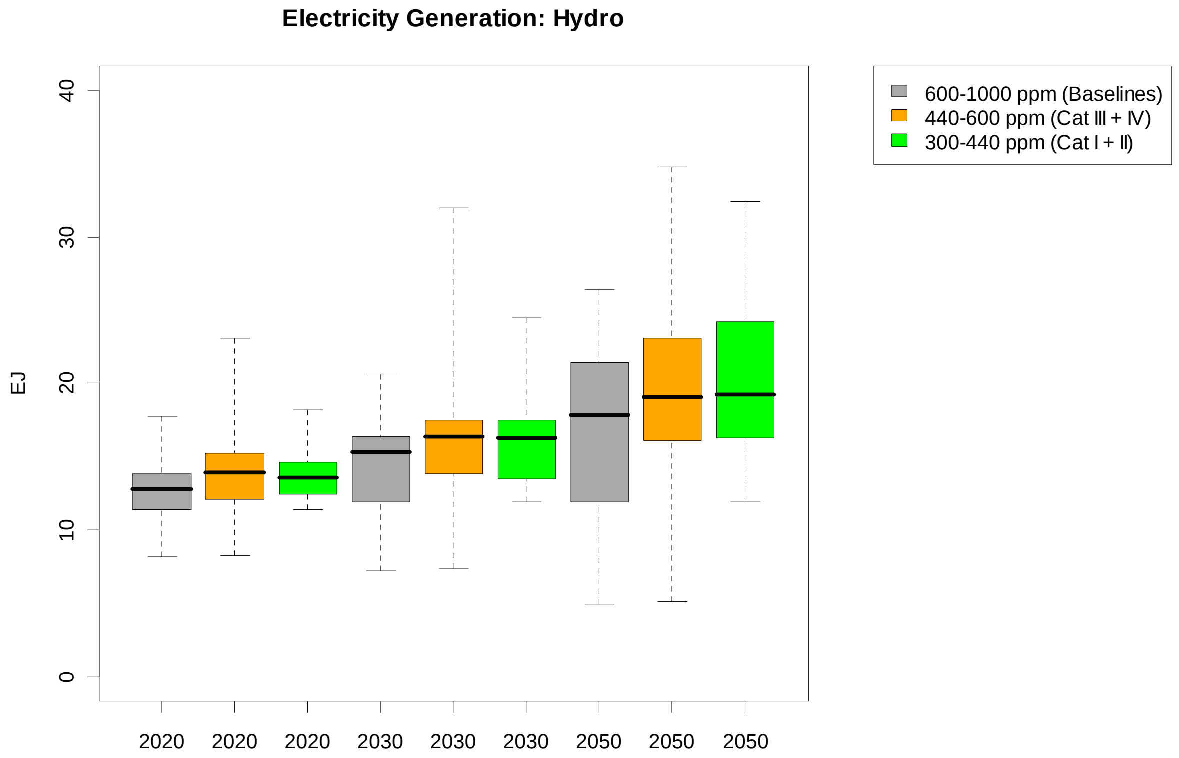

Figure 5.29: Global supply of hydro in carbon stabilization scenarios (median, 25th to 75th percentile range, and absolute range) [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

The reference-case projections of hydro's role in global energy supply span a broad range, but with a median of roughly 13 EJ in 2020, 16 EJ in 2030 and 19 EJ in 2050 (Figure 5.29). Substantial growth of hydro is therefore projected to occur even in the absence of GHG mitigation policies, with hydro median contribution to global electricity supply maintaining its share at around 15%. Therefore hydro remains the main RES technology. The contribution of hydro grows as GHG mitigation policies are assumed to become more stringent: by 2030, hydro's median contribution equals roughly 16.5 EJ (e.g. x% of global electricity supply) in the 440-600 and 300-400 ppm-CO2 stabilization ranges, increasing to 19-20 EJ by 2050 (~% of global electricity supply).

The diversity of approaches and assumptions used to generate these scenarios is great, however, resulting in a wide range of findings. Reference case results for hydro supply in 2050 range from 5-26 EJ (median 18 EJ), or x-y% (median of z%) of global electricity supply. In the most stringent 200-440 ppm stabilization scenarios, hydro supply in 2050 ranges from 12-32 EJ (median 20 EJ), equivalent to x-y% (median of z%) [TSU:values missing] of global electricity supply.

Despite this wide range, hydro has the lowest range compared to all other renewable energy sources. IPCC-2007a estimate for potential hydro supply of around 16 EJ (+/- 0.5 EJ) by 2030 appears conservative compared to the more-recent scenarios literature presented above, can reach 24 EJ in 2030 for the 450 ppm scenario (IEA, 2008).

Though the literature summarized in Figures 5.29 shows an increase in hydro supply with increasingly aggressive GHG targets, that impact is not great as it is for biomass, geothermal, and solar energy, where increasingly stringent carbon stabilization ranges lead to more-dramatic increases in technology deployment (Chapter 10). One explanation for this result is that hydro is already mature and economically competitive; as a result, deployment is predicted to proceed rapidly even in the absence of aggressive efforts to reduce carbon emissions.

The scenarios literature also shows that hydro could play a significant long-term role in reducing global carbon emissions: by 2050, the median contribution of hydro in the 2 carbon stabilization scenarios is around 19 EJ, increasing to 24 EJ at the 75th percentile, and to 35 EJ in the highest scenario. To achieve this contribution requires hydro to deliver around 11% of global electricity supply in the medium case, or 14% at the 75th percentile.

The figure 5.30 represents the potential deployment scenarios of hydropower up to 2050 (high and low development scenarios). The graph is adapted from several studies {IEA, 2008; IEA, 2009 128; EREC, 2008}. Assuming low cost trend scenarios (see section 5.8) the realistic sustainable potential (approximately 9000 TWh/year) is reached in 2050. With econometrical changing assumptions, hydro deployment could even be higher and exceed 10000TWh a year.

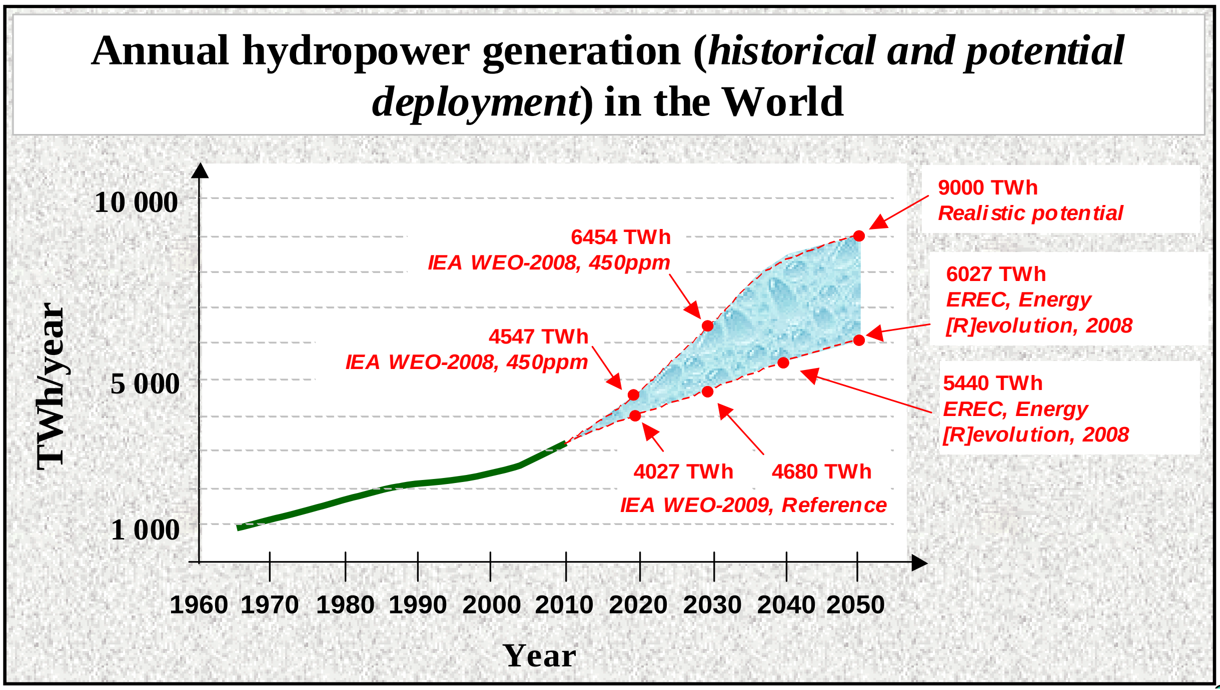

Figure 5.30: Hydropower development scenarios from 1960 to 2050 [TSU: source missing, caption not correct]

To achieve these levels there are no real technical and markets challenges, compared to other non mature RES technologies. Furthermore, a variety of possible challenges or opportunities to an aggressive growth of hydro may be added:

Resource Potential: First, even the highest estimates for long-term hydro production in Table 5.9 are within the global resource estimates presented in section 5.2, suggesting that technical resource potential is unlikely to be a barrier to hydro deployment. On a regional basis, however, higher deployment levels may begin to constrain the most economical resource supply (see section 10.3) in some regions.

Regional Deployment: Second, hydro would need to expand beyond its current status where most of the resource potential has been developed so far in Europe and North-America. The EIA reference-case forecast projects the majority of hydro deployment by 2030 to come majority (58%) from non-OECD Asia countries (e.g. 38% in China, and 8% in India), 22% from non-OECD Latin America (e.g., 17% Brazil), and 7% in both OECD Europe and OECD North-America (see Table 5.10). Regional collaboration can be enhanced in order to harmoniously combine power systems development with sound integrated water resources management, as it was assumed for example in Nile Basin Initiative or Great-Mekong Sub-Region development.

Table 5.10: Regional distribution of global hydro generation in 2006 and projection in 2030 (percentage of total worldwide hydro generation, average annual percent change from 2006 to 2030) (IEA, 2009).

U.S. EIA reference case for hydro generation deployment (EIA, 2009)		**2006 (History)**		**2030 (Projections)**		
		TWh	**% world hydro**	**TWh**	**% world hydro**	**2006-2030 average annual increase (%)**
OECD	OECD North America	671	22%	789	17%	0,7%
	United States	289	10%	301	6%	0,2%
	Canada	352	12%	447	9%	1,0%
	Mexico	30	1%	41	1%	1,3%
	OECD Europe	476	16%	604	13%	1,0%
	OECD Asia	127	4%	137	3%	0,3%
	Japan	85	3%	91	2%	0,3%
	South Korea	3	0%	4	0%	1,2%
	Australia / New Zealand	39	1%	42	1%	0,3%
	Total-OECD	**1 274**	**43%**	**1 530**	**32%**	**0,8%**
Non-OECD	Non-OECD Europe and Eurasia	300	10%	354	7%	0,7%
	Russia	174	6%	228	5%	1,1%
	Other	126	4%	127	3%	0,0%
	Non-OECD Asia	670	22%	1 693	35%	3,9%
	China	431	14%	1 098	23%	4,0%
	India	113	4%	262	5%	3,6%
	Other Non-OECD Asia	126	4%	333	7%	4,1%
	Middle-East	23	1%	44	1%	2,7%
	Africa	91	3%	126	3%	1,4%
	Central-and-South-America	640	21%	1 026	21%	2,0%
	Brazil	345	12%	647	14%	2,7%
	Other Central and South America	294	10%	379	8%	1,1%
	Total-Non-OECD	**1 723**	**57%**	**3 242**	**68%**	**2,7%**
Total-World		**2 997**	**100%**	**4 773**	**100%**	**2,0%**

Supply chain issues: Third, while efforts may be required to ensure an adequate supply of labour and materials during a long period (for instance more than 40 GW were installed in 2008, which is equivalent to the highest annual long-term IEA forecast scenario in its 450 ppm scenario WEO-2008), no fundamental long-term constraints to materials supply, labour availability, or manufacturing capacity are envisioned if policy frameworks for hydro are sufficiently attractive.

Technology and Economics: Fourth, hydro is a mature technology with very good economics compared to other RES, and cost competitive with other thermal units. Hydropower are in a broad range of types and size, and can meet both large centralised needs and small decentralised consumption.

Integration and Transmission: Fifth, hydro development occurs in synergy with other RES deployment. Indeed hydro with reservoirs and/or pumped storage power plants (PSPP) provide a storage capacity that can help transmission system operators (TSO) to operate their networks in a safe and flexible way, by providing back-up for intermittent variable RES (for instance wind, and solar PV). Hydro is useful for ancillary services and for balancing unstable transmission network, as hydro is the most responsive energy source for meeting peak demand (see Chapter 8). PSPP and storage hydropower can therefore ensure transmission, and also distribution, security and quality of services.

Social and Environmental Concerns: Finally, given concerns about social and environmental impacts of hydro projects, summarised in section 5.6, efforts to better understand the nature and magnitude of these impacts, together with efforts to mitigate any remaining concerns, will need to be pursued in concert with increasing hydro deployment. This work has been initiated by the World Commission on Dams (WCD, 2000) which has been endorsed and improved by International Hydropower Association (IHA, 2006) {IHA, 2003 #143;IHA, 2009 #144}which address these E&S issues. Concerns on fish migration, GHG emissions and water quality degradation in some tropical reservoirs, loss of biological diversity, and population displacement are perhaps the most prominent E&S impacts. However these impacts could be mitigated in most cases and even turned to positive impacts.

Overall, the evidence suggests that hydro high deployment levels in the next 20 years, remaining hydro as the leader of RES, are feasible. Even if hydro share in regards to the global electricity supply may decrease (from 16% to 10%-14% according to the scenarios) by 2050, hydro remains one of the most attractive RES within the context of global carbon mitigation scenarios. Furthermore this trend should continue given the world growing problem related to water resources (see section 5.10). Hydro can be vital for the economic and infrastructure development of poorer nations in terms of providing a steady supply of water and electricity. Besides providing a source of clean energy, hydropower dams are often essential for flood control, irrigation, drinking water supply, recreation, etc.

5.10 Integration into water management systems

Water, energy and climate change are inextricably linked. These issues must be addressed in a holistic way as pieces of the same puzzle and therefore it is not practical to look at them in isolation (WBCSD, 2009). Agriculture, and then food, is also a key component which cannot be considered independently of each other for sustainable development (UNESCO-RED, 2008). Providing energy and water for sustainable development requires global water governance. As it is often associated with the creation of water storage facilities, hydropower is at the crossroads of these stakes and has a key role to play in providing both energy and water security.

Therefore hydropower development is part of water management systems as much as energy management systems, both of which are increasingly climate driven.

5.10.1 The need for climate-driven water management

As described in section 5.2.2, climate change will probably lead to changes in the hydrological regime in many countries, with increased variability and more frequent hydrological extremes (floods and droughts). This will introduce additional uncertainty into water resources management. For poor countries that have always faced hydrologic variability and have not yet achieved water security, climate change will make water security even more difficult and costly to achieve. Climate change may also reintroduce water security challenges in countries that for a hundred years have enjoyed water security. Today, about 700 million people live in countries experiencing water stress or scarcity. By 2035, it is projected that 3 billion people will be living in conditions of severe water stress. Many countries with limited water availability depend on shared water resources, increasing the risk of conflict over these scarce resources. Therefore, adaptation in water management will become very important (Saghir, 2009). Major IFIs are aware of the growing need for water storage (see Box 5.1, World Bank).

Box 5.1: A need to increase investment in infrastructure for water storage and control

In order to increase security of supply for water and energy, both within the current climate and in a future with increasing hydrological variability, it will be necessary to increase investment in infrastructure for water storage and control. This is stated in one of the main messages in the World Bank Water Resources Sector Strategy (World-Bank, 2003).

”*Message 4: Providing security against climatic variability is one of the main reasons industrial countries have invested in major hydraulic infrastructure such as dams, canals, dykes and inter basin transfer schemes. Many developing countries have as little as 1/100th as much hydraulic infrastructure as do developed countries with comparable climatic variability. While industrialized countries use most available hydroelectric potential as a source of renewable energy, most developing countries harness only a small fraction. Because most developing countries have inadequate stocks of hydraulic infrastructure, the World Bank needs to assist countries in developing and maintaining appropriate stocks of well-performing hydraulic infrastructure and in mobilizing public and private financing, while meeting environmental and social standards*”.

The issue of mitigation is addressed in the IPCC – 2007d report (Mitigation), where the following seven sectors were discussed: energy supply, transportation and its infrastructure, residential and commercial buildings, industry, agriculture, forestry, and waste management. Since water issues were not the focus of that volume, only general interrelations with climate change mitigation were mentioned, most of them being qualitative. However, other IPCC reports, such as the TAR, also contain information on this issue.

Climate change affects the function and operation of existing water infrastructure as well as water management practices. Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change, and urbanization. Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, large changes in irrigation water demand as a result of climate change are likely. Current water management practices are very likely to be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems. Improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier.

The need for climate driven water management is often repositioning hydro development as a component of multipurpose water infrastructure projects.

5.10.2 Multipurpose use of reservoirs

Creating reservoirs is often the only way to adjust the uneven distribution of water in space and time that occurs in the unmanaged environment.

“In a world of growing demand for clean, reliable, and affordable energy, the role of hydropower and multipurpose water infrastructure, which also offers important opportunities for poverty alleviation and sustainable development, is expanding.” (World-Bank, 2009).

Reservoirs add great benefit to hydropower projects, because of the possibility to store water (and energy) during periods of water surplus, and release the water during periods of deficit, making it possible to produce energy according to the demand profile. This is necessary because of large seasonal and year-to-year variability in the inflow. Such hydrological variability is found in most regions in the world, and it is caused by climatic variability in rainfall and/or air temperature. Most reservoirs are built for supplying seasonal storage, but some also have capacity for multi-year regulation, where water from two or more wet years can be stored and released during a later sequence of dry years. The need for water storage also exists for many other types of water-use, like irrigation, water supply, navigation and for flood control. Reservoirs, therefore, have the potential to be used for more than one purpose. Such reservoirs are known as multipurpose reservoirs.

About 75% of the existing 45,000 large dams in the world were built for the purpose of irrigation, flood control, navigation and urban water supply schemes (WCD, 2000). About 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multipurpose reservoirs (WCD, 2000).

In addition to these primary objectives, reservoirs can serve a number of other uses like recreation and aquaculture. Harmonious and economically optimal operation of such multipurpose schemes may require trade-off between the various uses, including hydropower generation.

Since the majority of dams do not have a hydropower component, there is a significant market for increased hydropower generation in many of them. A recent study in the USA indicated some 20 GW could be installed by adding hydropower capacity to the 2500 dams that currently have none (UNWWAP, 2006). New technology for utilizing low heads (sec 5.7.1) also opens up for hydropower implementation in many smaller irrigation dams.

For instance China is constructing more than 90 000 MW of new hydro, and much of this development is designed for multipurpose utilization of water resources ((Zhu *et al.*, 2008). For the Three Gorges Project (22 400MW of installed capacity) the primary purpose of the project is flood control.

In Brazil, recommendations are provided to expand and sustain the generation of hydro, given the uncertainties of the current climatologic models when predicting future rainfall patterns in the Brazilian and in its trans-boundary drainage basins (Freitas, 2009; Freitas *et al.*, 2009).

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 6

Ocean Energy

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	LAs:	John Huckerby, Walter Musial, Teresa Pontes, Julio Torrez-Martinez, Kwang-soo Lee
	CAs:	Frederic Louis, Sandvik Øystein Scråmestø
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Turquoise highlighted – inserted comment text from Authors or TSU i.e. [AUTHORS/TSU]

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Chapter 6 has been allocated 20-34 pages in the SRREN. The actual chapter length (excluding references & cover page) is 35 pages: a total of 1 page over the allocated page number. Expert reviewers are therefore kindly asked to indicate where the Chapter could be shortened by 1 page in terms of text and/or figures and tables to reach the allocated length.

All monetary values provided in this document will be adjusted for inflation/deflation and converted to US$ for the base year 2005. If the necessary conversions have not yet been done, this is highlighted in the text.

Chapter 6: Ocean Energy

CONTENTS

EXECUTIVE SUMMARY

Ocean Energy can be defined as energy derived from technologies, which utilize seawater as their motive power or harness the chemical or heat potential of seawater. Technologies for harnessing ocean energy are probably the least mature of the six principal forms of renewable energy in this Special Report but the energy resources contained in the world's oceans easily exceed present human energy requirements. Ocean energy could be used not only to supply electricity but also for direct potable water production. Whilst some potential ocean energy resources, such as ocean currents and osmotic power from salinity gradients, are globally distributed, other forms of ocean energy have complementary distribution. Ocean thermal energy is principally distributed in the Tropics around the Equator (0° – 35°), whilst wave energy principally occurs between latitudes of 40° - 60°. Some forms of ocean energy, notably ocean thermal energy, ocean currents, salinity gradients and, to some extent, wave energy, may generate base load electricity.

With the exception of tidal rise and fall energy, which can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations, most ocean power technologies are presently immature. None can be truly characterized as commercially competitive with the other lowest cost forms of renewable energy – wind, geothermal and hydroelectric energy. Although basic concepts have been known for decades, if not centuries, ocean power technology development really began in the 1970s, only to languish in the post-oil price crisis period of the 1980s. Research and development on a wide range of ocean power technologies was rejuvenated at the start of the 2000s and some technologies – for wave and tidal current energy – have reached full-scale prototype deployments. Unlike wind turbine generators, there is presently no convergence on a single design for ocean power converters and, given the range of options for energy extraction, there may never be a single device design.

Worldwide developments of devices are accelerating with over 100 prototype wave and tidal current devices under development (US DoE, 2009). Principal investors in ocean energy R&D and deployments are national, federal and state governments, followed by major national energy utilities and investment companies. By contrast, the principal form of device developer is a private small- or medium-scale enterprise (SME). There is encouraging uptake and support from these major investors into the prototype products being developed by the SMEs.

National and regional governments are particularly supportive of ocean energy through a range of initiatives to support developments. These range from [TSU: sentence structure "from … to …", "to" missing] R&D and capital grants to device developers, performance incentives (for produced electricity), marine infrastructure development, standards, protocols and regulatory interventions for permitting, space and resource allocation. Presently the northwestern European coastal countries lead development of ocean power technologies with the North American, northwestern Pacific and Australasian countries also involved.

Environmental impacts of ocean energy converters can be forecast from maritime and other offshore industries. Ocean power technologies potentially present fewer environmental risks and thus community acceptance may be more likely than for other renewable energy developments. Social impacts are likely to be high, rejuvenating shipping and fishing industries, supplying electricity and/or drinking water to remote communities (at small-scale) or utility-scale deployments with transmission grid connections to displace aging fossil fuel generation plants. Critically, ocean power technologies do not generate greenhouse gases in operation, so they can significantly contribute to emissions reduction targets.

Although ocean energy technologies are at an early stage of development, there are encouraging signs that the capital cost of technologies (in $/kW) and unit cost of electricity generated (in $/kWh) will decline from their present non-competitive levels to reach the costs of wind, geothermal and hydroelectric technologies. When this occurs, the uptake of ocean energy can be expected to accelerate and ocean power technologies will create another power/water supply option for countries seeking to reduce their GHG emissions to meet internationally agreed targets for such reductions.

Ocean energy will be predominantly a utility-scale application, rather than a domestic-scale opportunity. This is particularly true for OTEC and salinity gradient plants. Small-scale, off-grid wave and tidal current technologies are likely for applications for island/remote communities and combined electricity generation/water production projects are being developed, particularly in Australia and India.

6.1 Introduction

This chapter discusses the contribution that useful energy derived from the ocean can make to the overall energy supply and hence its potential contribution to climate mitigation. The renewable energy resource in the ocean comes from five distinct sources, each with different origins and each requiring different technologies for conversion. These resources are:

- **Waves and Swells** – derived from wind energy kinetic energy input over the whole ocean,
- **Tidal Rise and Fall** – derived from gravitational forces of earth-moon-sun system,
- **Tidal and Ocean Currents** – derived from tidal energy or from wind driven / thermo-haline ocean circulation,
- **Ocean Thermal Energy Conversion (OTEC)** – derived from solar energy stored as heat in ocean surface layers and Submarine Geothermal Energy – hydrothermal energy at submarine volcanic centres,
- **Salinity Gradients** – derived from salinity differences between fresh and ocean water at river mouths (sometimes called ‘osmotic power’).

Aspects related to resource potential, environmental and social impacts, technology, costs and deployment are considered.

The conversion of resources available in the oceans to useful energy presents a significant engineering challenge. However, the reward may be high with many estimates of the potential energy exceeding world electricity demands (OES-IA, 2008). Even though the potential resources have been recognised for a long time, technologies for harnessing these potentials are only now becoming feasible and economically attractive, with the exception of tidal barrage systems - effectively estuarine hydro dams - of which a number of plants are operational worldwide (c. 265 MW worldwide).

6.2 Resource Potential

6.2.1 Wave Energy

Wave energy is a concentrated form of wind energy. Wind is generated by the differential heating of the atmosphere and, as it passes over the ocean, friction transfers some of the wind energy to the water, forming waves, which store this energy as potential energy (in the mass of water displaced from the mean sea level) and kinetic energy (in the motion of water particles). The size of the resulting waves depends on the amount of transferred energy, which is a function of the wind speed, the length of time the wind blows (order of days) and the size of the area affected by the wind (fetch). Wind-waves grow into open ocean swells by constructive interference, the difference being that wind-waves have periods of less than 10 seconds, whilst swells have greater periods.

The most energetic waves on earth are generated between 30º and 60º latitudes by extra-tropical storms (the so-called “Roaring Forties”). An attractive wave climate also occurs within ± 30º of the Equator (where trade-winds prevail most of the year): The wave energy resource is lower here but has less seasonal variability. However, doldrums occur in some Equatorial zones.

The total theoretical wave energy resource is very high (32,000 TWh; Mørk et al., 2010), roughly twice the global electrical energy consumption in 2006 (18,000 TWh; EIA, 2008). The map of the global offshore average annual wave power distribution (Figure 6.1) shows that the largest power levels occur off the west coasts of the continents in temperate latitudes, where the most energetic winds and greatest fetch areas occur.

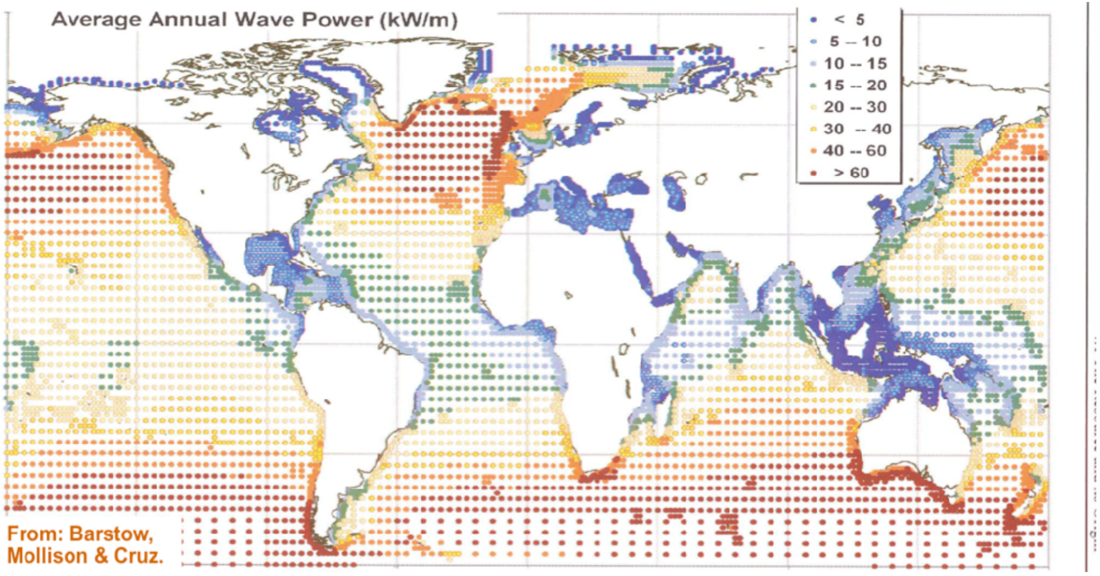

Figure 6.1: Global offshore annual wave power level distribution (Barstow, S., Mollison, D. and Cruz, J., in Cruz, 2008)

The regional distribution of the annual wave energy incident on the coasts of the respective countries or regions were obtained for areas, where theoretical wave power $P \geq 5$ kW/m and latitude ≤±66.5 º (Table 6.1). The total annual wave energy (29,500 TWh) is a decrease of 8% from the total theoretical wave energy resource above.

Table 6.1: Regional Theoretical Wave Power (Mørk et al., 2010)

REGION	Wave Energy (TWh)
Western and Northern Europe	2,800
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1,300
North America and Greenland	4,000
Central America	1,500
South America	4,600
Africa	3,500
Asia	6,200
Australia, New Zealand and Polynesia	5,600
TOTAL	29,500

Swell waves travel for very long distances (i.e., tens of thousands of kilometres) with minimal energy dissipation in deep water. Swells that generated in Antarctica, Australia and New Zealand have been observed in California (e.g., Khandekar, 1989). When the water depth (h) becomes less than half the wavelength, swell waves change due to friction with the seabed (e.g., Lighthill, 1978). Bottom friction can be significant when the continental shelf is wide and the sea bottom is rough, as in the west of Scotland, where some frequency components lose half of their energy between deep water and 42 m water depth (Mollison, 1985). Shoaling causes the waves to grow in height and refraction (similar to the optical phenomenon) causes wave crests to become parallel to the bathymetric contours. This, in turn, leads to energy concentration in convex zones (e.g., close to capes) and dispersion in concave zones (e.g., in bays). Shelter by nearshore islands or by the coast itself also reduces incident energy. Waves start to break, thus dissipating their energy, when wave height H > Kh, with the constant K having values of 0.79-0.87 (Sarpkaya and Isaacson, 1981).

A range of devices is used to measure swell waves. Wave measuring buoys are used in water depth greater than 20 m (see Allender et al., 1989). Seabed-mounted (pressure and acoustic) probes are used in shallower waters. Capacity/resistive probes or down-looking infrared and laser devices can be used, when offshore structures are available (e.g., oil/ gas platforms).

Satellite-based measurements have been made regularly since 1991 by altimeters that provide measurements of significant wave height (H_s) and wave period (T) with accuracies similar to wave buoys (Pontes and Bruck, 2008). The main drawback of satellite data is the long Exact Return Period (ERP), which is between 10 and 35 days, and the corresponding large distance between adjacent tracks (0.8º to 2.8 º along the Equator). Synthetic Aperture Radar (SAR) can provide directional spectra they [TSU: that] are not useful yet for wave energy resource mapping (Pontes et al., 2009).

The results of numerical wind-wave models are now quite accurate, especially for average wave conditions. Such models compute directional spectra over the oceans, taking as input wind-fields provided by atmospheric models; they are by far the largest source of wave information. The different types of wave information are complementary and should be used together for best results. For a review of wave data sources, atlases and databases, see Pontes and Candelária (2009).

6.2.2 Tide Rise and Fall

Tidal rise and fall is the result of gravitational attraction of the Earth / Moon and the Sun on the ocean. In most parts of the world there are two tides a day (called ‘semi-diurnal’), whilst in other places there is only one tide a day. During the year, the amplitude of the tides varies depending on the respective positions of the Earth, the Moon and the Sun. When the Sun, Moon and Earth are aligned (at full moon and at new moon) maximum tidal level occurs (i.e., spring tides). The opposite tides, called neap tides, occur when the gravitational forces of the Moon and the Sun are in quadrature; they occur during quarter moons.

The spatial distribution of the tides varies depending on global position and also on the shape of the ocean bed, the shoreline geometry, Coriolis acceleration and atmospheric pressure. Within a tidal system there are points where the tidal range is nearly zero, called amphidromic points (Figure 6.2). However, even at these points tidal currents may flow as the water levels on either side of the amphidromic point are not the same. This is a result of the Coriolis effect and interference within oceanic basins, seas and bays, creating a tidal wave pattern (called an amphidromic system), which rotates around the amphidromic point. See Pugh (1987) for more details.

Locations with the highest tidal ranges are in Canada (Bay of Fundy), Western Europe (France and United Kingdom), Russia (White Sea, Sea of Okhotsk, Barents Sea), Korea, China (Yellow Sea), India (Arabic Gulf) and Australia. There is a great geographical variability in the tidal range. Some places like the Baie du Mont Saint Michel in France or the Bay of Fundy in Canada experience very high tides (respectively, 13.5 m and 17 m), while in other places (e.g., Mediterranean Sea) the tides are hardly noticeable (Shaw, 1997; Usachev, 2008). The global distribution of the M2 constituent of the tidal level, the largest semi-diurnal tidal constituent that is one half of the full tidal range, shows that the major oceans have more than one amphidromic system.

Tidal rise and fall can be forecasted with a high level of accuracy – even centuries in advance. Although the resultant power is intermittent, there is little or no hydrological risk, which is a significant advantage when compared to conventional hydro, to wind or to solar energy (Ray, 2009). The world's theoretical tidal power potential is in the range of 3 TW with 1 TW located in relatively shallow waters (Charlier and Justus, 1993). The effect of climate change on tidal rise and fall is uncertain but, in the worst case, sea level rise should only result in translation of the mean ocean level, with possible impacts linked to shoreline changes, rather than to tidal range.

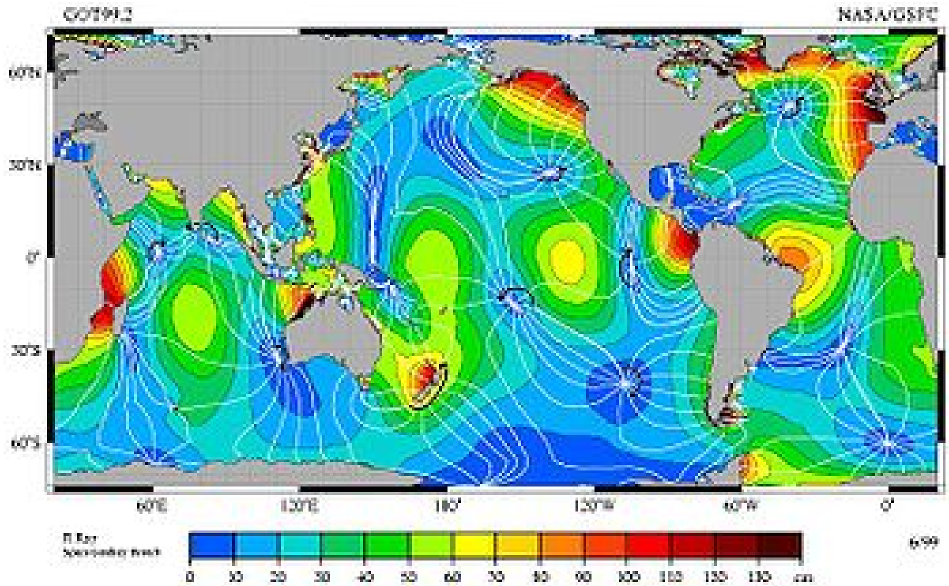

Figure 6.2 - TOPEX/Poseidon: Revealing Hidden Tidal Energy GSFC, NASA. [TSU: Source needs to be included in list of references, quotation-style needs to be adjusted.] The M2 tidal amplitude is shown in colour. White lines are cotidal lines, spaced at phase intervals of 30° (a bit over 1 hr). The amphidromic points are the dark blue areas where the cotidal [TSU: sentence incomplete]

6.2.3 Tidal Currents

Tidal currents are the ocean water mass response to tidal rise and fall. Tidal currents are generated by horizontal movements of water, modified by seabed bathymetry, particularly near coasts or other constrictions, e.g., islands. Tidal current flows result from the sinusoidal variation of various tidal components, operating on different cycles, although these flows can be modified by short-term weather fluctuations. The potential power of a tidal current is proportional to the cube of the current velocity. For near-shore currents, i.e., in channels between mainland and islands or in estuaries, current velocity varies sinusoidally with time, the period being related to the different tidal components. Potentially commercially attractive sites require a minimum average sinusoidal current velocity greater than 1.5 ms^{-1}. Below that value (1.0 – 1.5 ms^{-1}) evaluation should be on a site-by-site basis. For non-oscillating currents, the maximum current velocity should exceed 1.0 ms^{-1}, but in the range 0.5-1.0 ms^{-1}, its practical exploitation depends on site evaluation. [TSU: references missing]

A methodology for the assessment of tidal current energy resource has been proposed (Hagerman et al., 2006). An atlas of the wave energy and tidal resource has been developed for the UK, which includes tidal current energy (UK Department of Trade and Industry, 2004). Similar atlases have been published for the European Union (CEC, 1996; Carbon Trust Marine Energy Challenge, 2004) and for far-eastern countries (CEC, 1998).

In Europe tidal energy resource is of special interest for the UK, Ireland, Greece, France and Italy. Over 106 promising locations have been identified. Using present-day technologies, these sites could supply 48 TWh/y into the European electrical grid network. China has estimated that 7,000 MW of tidal current energy are available. Locations with high potential have also been identified in the Republic of Korea, Philippines, Japan, Australia, Northern Africa and South America. [TSU: references missing]

The predictability of tidal currents and the potentially high load factor (30-60%) are important positive factors for their utilization. Sites with oscillating flows can offer capacity factors in the 40-50% range. For non-oscillating flows, this range increases to the order of 80%. [TSU: references missing]

6.2.4 Ocean Currents

In addition to nearshore tidal currents, there are also significant current flows in the open ocean. Large-scale circulation of the oceans is concentrated in various regions, notably the western boundary currents associated with wind-driven circulations. Some of these offer sufficient current velocities (~2 ms^{-1}) to drive present-day current technologies (Leaman et al., 1987). These include the Agulhas/Mozambique Currents off South Africa, the Kuroshio Current off East Asia, the East Australian Current and the Gulf Stream off eastern North America (Figure 6.3). Other current systems may also have potential as improvements in turbine efficiency occur.

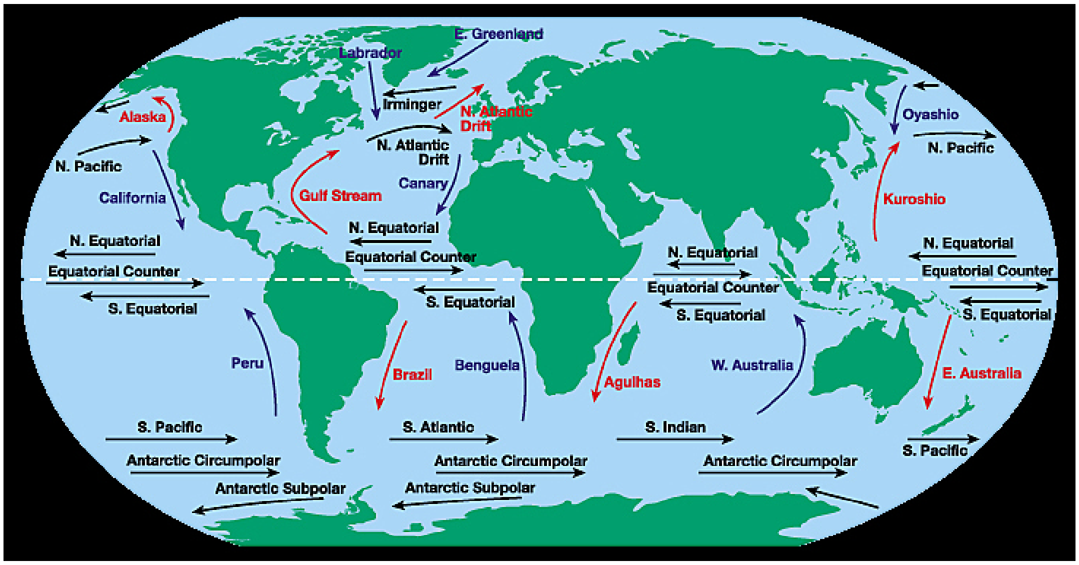

Figure 6.3: Surface ocean currents, showing warm (red) and cold (blue) systems (UCAR, 2000).

The power generation potential of the Florida Current of the Gulf Stream system was recognized decades ago (”MacArthur Workshop”; Stewart, 1974). The workshop concluded that the Florida Current had ~25 GW potential but its recommendations have languished, despite various oceanographic measurement programs confirming the potential (see Raye, 2001).

The Current has a core region, 15-30 km off the Florida coast and near surface, which represents the greatest potential for power generation. As the return flow of the Atlantic Ocean’s subtropical gyre, the Florida Current flows strongly year around, exhibiting variability on various time and space scales (Niiler & Richardson, 1973; Johns et al., 1999).

6.2.5 Ocean Thermal Energy Conversion

The most direct harnessing of ocean solar power is probably through an ocean thermal energy conversion (OTEC) plant. Among ocean energy sources, OTEC is one of the continuously available renewable resources which could contribute to base load power supply. The OTEC potential is considered to be much larger than for other ocean energy forms (UNDP, UNDESA, WEC, 2000). It also has a widespread distribution between the two tropics. An optimistic estimate of the global resource is 30,000 to 90,000 TWh (Charlier and Justus, 1993).

Only 15% of the total solar input to the ocean is retained as thermal energy, with absorption is concentrated at the top layers, declining exponentially with depth [TSU: sentence structure]. Sea surface temperature can exceed 25 °C in tropical latitudes, whilst 1 km below surface, sea temperature is between 5-10 °C. [TSU: references missing]

A minimum temperature difference of 20 °C is required to operate an OTEC power plant. [TSU: reference missing] Both coasts of Africa, the tropical west and southeastern coasts of the Americas and many Caribbean and Pacific islands have sea surface temperature of 25 – 30 °C, declining to 4 – 7 °C at depths varying from 750 to 1,000 m. An OTEC resource map showing annual average temperature differences between surface waters and the water at 1,000 meters depth shows a wide tropical area of potential 20+° C temperature differences (Figure 6.4). Almost everywhere in the Equatorial zone there is potential for installing OTEC facilities. A number of Pacific and Caribbean islands could develop OTEC plants, having an OTEC resource within one mile of their shores (UN, 1984).

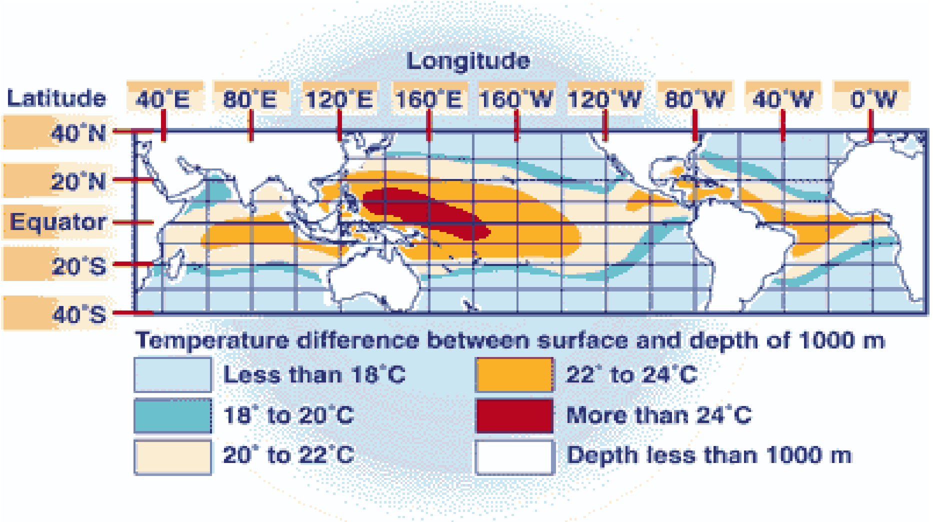

Figure 6.4: Ocean Thermal Energy Conversion Resource Map [TSU: reference missing]

6.2.6 Salinity Gradient

Since freshwater from rivers debouching into saline seawater is globally distributed, osmotic power could be generated and used in all regions - wherever there is a surplus of fresh water. Feasibility studies must be conducted before any osmotic power plant is constructed to ensure that each river discharging into the ocean can provide sufficient freshwater. Estuarine/deltaic environments are most appropriate, because of the potential for large, adjacent volumes of freshwater and seawater.

The first water quantity assessments for osmotic power potential were based on a methodology, which used average discharge and low flow discharge values. Low flow is defined as the 80th percentile of the flow regime, i.e., the low flow is exceeded 80% of the time. Freshwater extraction for electricity generation would not be possible in low flow conditions. [TSU: references missing]

Global generation capacity potential for osmotic power generation has been calculated as 1,600 – 1,700 TW (Scråmestø, personal communication, 2010). The annual generation potential has been calculated as 1,650 TWh (Scråmestø, Skilhagen and Nielsen, 2009). In Europe alone there is a potential to generate 180 TWh. Osmotic power will effectively generate base load electricity, which should make contributions to security of supply, portfolio diversity and grid strengthening.

6.3 Technology and Applications

6.3.1 Introduction

Ocean energy technologies range from the conceptual stage to the prototype stage, as few technologies have matured to commercial availability. Presently there are many technology options for each ocean energy source but, with the exception of tidal rise and fall barrages, the only one commercially available, technology convergence has not yet occurred, due to a fundamental lack of operating experience. Over the past four decades, other marine industries (primarily petroleum industry) have made significant advances in the fields of offshore materials, offshore construction, corrosion, submarine cables and communications. Ocean energy will directly benefit from these advances, rather than any new or major technological breakthrough. [TSU: references missing]

Competitive ocean energy technologies will emerge in the present decade, offering great promise beyond the near-term [TSU: references missing]. The abundance of globally distributed resources and the relatively high energy density of ocean energy resources make ocean energy a potentially widespread solution.

6.1.2 Wave Energy

Many wave energy technologies representing a range of operating principles have been conceived, and in many cases demonstrated, to convert energy from waves into a usable form of energy. Major variables include the method of wave interaction with respective device motions (heaving, surging, pitching) as well as water depth and distance from shore (shoreline, near-shore, offshore).

A generic scheme for both ocean wave and tidal current consists of primary, secondary and tertiary conversion stages as shown in (Figure 6.5). The primary subsystem represents fluid-mechanical processes and feeds mechanical power to the next stage. The intermediate subsystem is a short-term storage and the power processing can be facilitated before the electrical machine is operated. The final conversion utilizes electromechanical and electrical processes.

Recent reviews have identified over 50 wave energy devices at various stages of development (Falcão, 2009; Khan and Bhuyan, 2009 and DoE, 2009). The dimensional scale constraints of wave devices have not been fully investigated in practice. The dimension of wave devices in the direction of wave propagation is generally limited to lengths below the scale of the dominant wavelengths that characterize the wave power density spectrum at a particular site. Utility-scale electricity generation from wave energy will require device arrays, rather than larger devices and, as with wind turbine generators, devices will be tailored for specific site conditions.

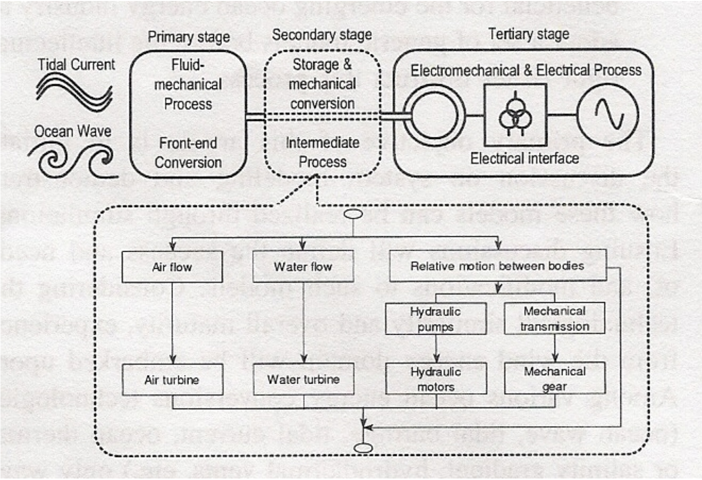

Figure 6.5: Conversion stages of ocean waves and tidal current devices (Khan et al., 2009)

Several methods have been proposed to classify wave energy systems (e.g., Falcão, 2009, Khan and Bhuyan, 2009 and DoE, 2009). The classification systems proposed by Falcão (Figure 6.6) are sorted mainly by the principle of operation. The first column is the genus, the second column is the location and the third column represents the mode of operation.

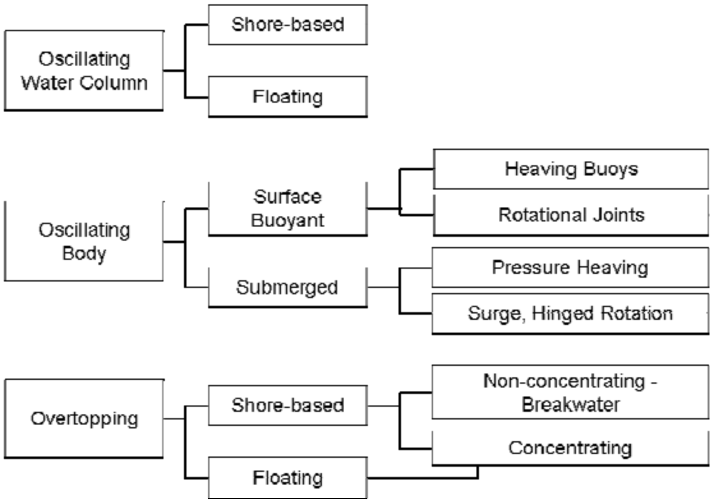

Figure 6.6: Wave energy technologies – Classification based on principles of operation (Falcão, 2009).

6.3.1.1 Oscillating Water Columns

Oscillating water columns (OWC) are wave energy converters, which use wave motion to induce different air pressure levels inside an air-filled chamber. High velocity compressed air exhausts through an air turbine, coupled to an electrical generator, which converts the kinetic energy into electricity. When the wave recedes, the airflow reverses and fills the chamber, generating another pulse of energy. The air turbine rotates in the same direction, regardless of the flow, through either its design or by variable pitch turbine blades. An OWC device can be a fixed structure located above the breaking waves – cliff-mounted or part of a breakwater, it can be bottom-mounted near shore or a floating system moored in deeper waters.

6.3.1.2 Oscillating-Body Systems

Oscillating-body (OB) wave energy conversion devices use the incident wave motion to induce differential oscillating motions between two bodies of different mass, which motions are then converted into a more usable form of energy. OBs can be surface devices or, more rarely, fully submerged. Commonly, axi-symmetric surface flotation devices (buoys) use buoyant forces to induce heaving motion relative to a secondary body that can be restrained by a fixed mooring. Generically, these devices are referred to as 'point absorbers', because they are non-directional. Another variation of floating surface device uses angularly articulating (pitching) buoyant cylinders linked together. The waves induce alternating rotational motions of the joints that are resisted by the power take-off device. Some OB devices are fully submerged and rely on oscillating hydrodynamic pressure to extract the wave energy.

6.3.1.3 Overtopping Devices

An overtopping device is a type of wave terminator that converts wave energy into potential energy by collecting surging waves into a water reservoir at a level above the free water surface. The reservoir drains down through a conventional low-head hydraulic turbine. These systems can be offshore floating devices or incorporated in shorelines or man-made breakwaters.

6.3.1.4 Power Take-off Devices

In most cases, converted kinetic energy is, in turn, converted to either electricity or to a pressurized working fluid via a secondary power take-off device. Real-time wave oscillations will produce corresponding electrical power oscillations that may degrade power quality to the grid. In practice, some method of short-term energy storage (durations of seconds) may be needed to smooth energy delivery. The cumulative power generated by several devices will be smoother than from a single device, so device arrays are likely to be common. Optimal wave energy absorption involves some kind of resonance, which requires that the geometry, mass or size of the structure must be linked to wave frequency. Maximum power can only be extracted by advanced control systems.

6.3.2 Tide Rise and Fall

The development of tidal rise and fall hydropower has been usually based on estuarine developments, where a barrage encloses an estuary, which creates a single reservoir (basin) behind it and incorporates generating units. More recently, new barrage configuration has been proposed based on dual-basin mode. One of the two basins fills at high tide, whilst the other is emptied at low tide. Turbines are located between the basins. Two-basin schemes may offer highly flexible power generation availability over normal schemes, such that it is possible to generate power almost continuously. Two-basin schemes are very expensive to construct due to the extra length of barrage.

The most recent advances focus now on offshore basins (single or multiple), located away from estuaries, called 'tidal lagoon', which offer greater flexibility in terms of capacity and output, with little or no impact on delicate estuarine environments.

The conversion mechanism most widely used to produce electricity from tidal rise and fall is the bulb-turbine (Bosc, 2007). At the 240 MW power plant La Rance, these units generate in both directions (on the ebb and flood tides) and may also offer the possibility of pumping, when the tide is high, in order to increase low head storage in the basin (Andre, 1976). The 254 MW Sihwa Barrage in the Republic of Korea employs the same type of turbine.

There are some favourable sites, such as very shallowly shelving coastlines, which are well suited to tide rise and fall power plants, like the Severn Estuary in southwest England. Current feasibility studies there include options, such as barrages and tidal lagoons. Conventional tidal rise and fall power stations will generate electricity for only part of each tide cycle. Consequently, the average capacity factor for tidal power stations varies from 25% to 35% (Charlier, 2003).

6.3.3 Tidal and Ocean Currents

Technologies to extract kinetic energy from tidal, river, and ocean currents are under development, with tidal energy converters the most common to date. The principal difference between tidal and river/ocean current turbines is that river and ocean currents flows are unidirectional, whilst tidal turbines reverse flow direction between ebb and flood cycles. Consequently, tidal turbines can generate in both directions to provide optimum power generation.

Several classification schemes for tidal and ocean current energy systems have been proposed (Khan et al., 2000; US DOE, 2009). Usually, they are classified based on the principle-of-operation, such as axial-flow turbines (Verdant, 2009[1]), cross-flow turbines (Li and Calisal, 2010; Ponte Di Archimede, 2009[2]) and reciprocating devices (Bernitsas et al., 2006[3]), (Figure 6.7).

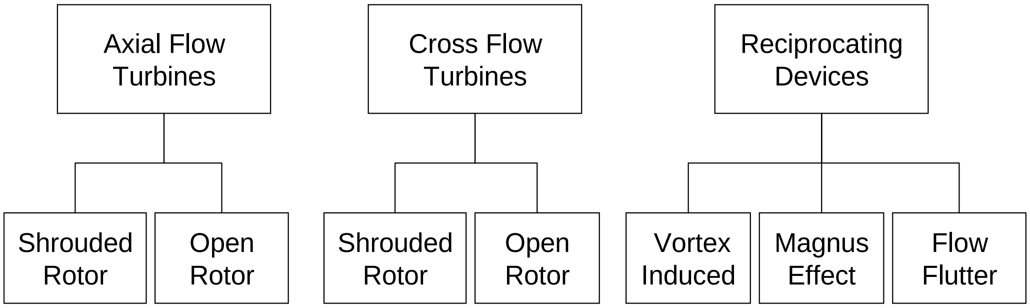

Figure 6.7: Classification of current tidal and ocean energy technologies (principles of operation) [TSU: reference missing]

Many of the water current energy conversion systems resemble wind turbine generators. However, the marine turbine designers must also take into accounts factors, such as reversing flows, cavitation and harsh underwater marine conditions (e.g., salt water corrosion, debris, fouling, etc). Axial flow turbines must be able to respond to reversing flow directions, while cross flow turbines continue to operate regardless of current flows. Axial-flow turbines will either reverse nacelle direction ~180º with each tide or, alternatively, the nacelle will have a fixed position but the rotor blades will accept flow from two directions - usually at some performance penalty.

Rotor shrouds (also known as cowlings or ducts) can enhance hydrodynamic performance by increasing the flow velocity through the rotor and reducing tip losses but the additional energy capture may not offset the cost of the shroud. The scale of water current devices in rivers and tidal currents will be driven by the external dimensions of the channel transects, in which they are installed and by navigational constraints that require minimum water clearance for vessels.

Capturing the energy of open-ocean current systems requires the same basic technology as for tidal flows but some of the infrastructure involved will differ. For deep-water applications, neutrally buoyant turbine/generator modules with mooring lines and anchor systems will replace fixed bottom support structures. Alternatively they can be attached to other structures, such as offshore platforms (Van Zwieten et al., 2005; Ponte Di Archimede, 2009[4]). Whether the turbines are bottom fixed or floating, it is likely that these modules will also have hydrodynamic lifting designs to allow optimal and flexible vertical positioning (Van Zwieten et al., 2005; Venezia and Holt, 1995; Raye,

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[1] www.verdantpower.com
[2] www.pontediarchimede.com
[3] http://www.vortexhydroenergy.com/
[4] http://www.pontediarchimede.it/language_us/

2001). In addition, open ocean currents will not impose a size restriction to the rotors due to lack of channel constraints. Therefore, ocean current systems may have larger rotors.

Reciprocating devices are generally based on basic fluid flow phenomena such as vortex shedding or passive and active flutter systems (usually hydrofoils), which induce mechanical oscillations in a direction transverse to the water flow. Most of these devices are in the conceptual stage of development and have not been evaluated in terms of cost or performance.

6.3.4 Ocean Thermal Energy Conversion

Ocean thermal energy conversion (OTEC) plants have three conversion schemes: open, closed and hybrid (Charlier and Justus 1993). In the open conversion cycle, seawater is the circulating fluid - warm surface water is flash-evaporated in a partial vacuum chamber. The steam produced passes through a turbine, generating power, after which it is condensed, using cooler, deep seawater. By employing an appropriate cycle, desalinated water can be obtained as an additional product.

Closed conversion cycles offer more efficient thermal performance. A secondary working fluid, such as ammonia, propane or Freon-type is vaporized and re-condensed continuously in a closed loop to drive a turbine (Figure 6.8).

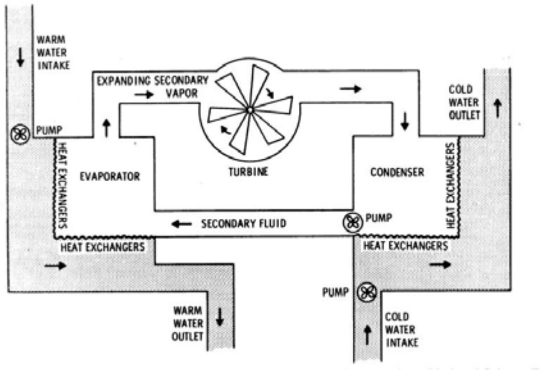

Figure 6.8: Diagram of a Closed-Cycle OTEC Plant (Charlier and Justus, 1993).

Warm seawater from the ocean surface is pumped through heat exchangers where a secondary working fluid is vaporized, causing a high pressure vapour to drive a turbine. The vapour flows to a surface condenser, cooled by seawater, to return it to a liquid phase. Closed-cycle turbines may be smaller than open cycle turbines, because the secondary working fluid operates at a higher operating pressure. A hybrid conversion cycle combines both open and closed cycles. Steam is generated by flash evaporation and then acts as the heat source for a closed Rankine cycle, using ammonia or other working fluid.

6.3.5 Salinity Gradient

It has been known for centuries that the mixing of freshwater and seawater releases energy, therefore, a river flowing into a saline ocean releases large amounts of energy (Scråmestø et al., 2009). The challenge is to utilise this energy, since the energy released from this mixing normally results in a very small increase in the local temperature of the water. During the last few decades at least two concepts for converting this energy into electricity instead of heat have been identified, these are Reversed Electro Dialysis (RED) and Pressure Retarded Osmosis (PRO).

6.3.5.1 Reversed Electro Dialysis

The RED process harnesses the difference in chemical potential between two solutions. Concentrated salt solution and freshwater are brought into contact through an alternating series of anion and cation exchange membranes (Figure 6.9). The chemical potential difference generates a voltage across each membrane; the overall potential of the system is the sum of the potential differences over the sum of the membranes. The first prototype to test this concept is being built in the Netherlands (Groeman and van den Ende, 2007).

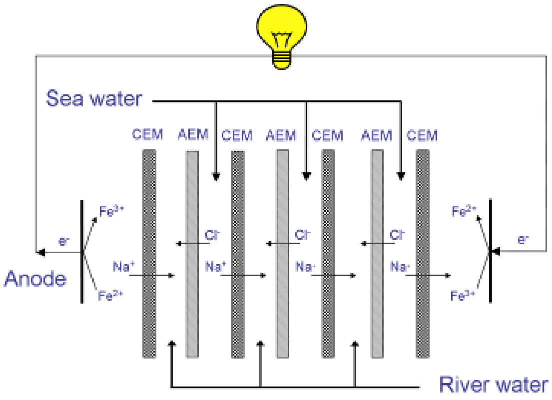

Figure 6.9: Reversed Electro Dialysis (RED) System (Groeman and Van den Ende, 2007)

6.3.5.2 Pressure Retarded Osmosis

Pressure Retarded Osmosis (PRO), also known as Osmotic Power, is a process where the chemical potential is exploited as pressure (Figure 6.10). Professor Sidney Loeb first proposed this principle in the early 1970s (Loeb and Norman, 1975).

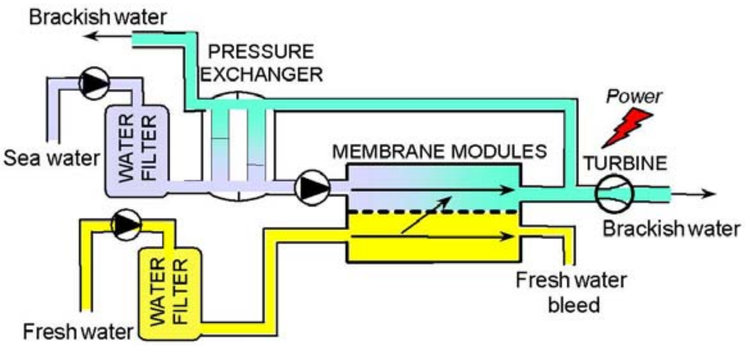

Figure 6.10: Pressure Retarded Osmosis (PRO) process (Scråmestø et al., 2009).

The osmotic power process utilises naturally occurring osmosis, caused by the difference in concentration of salt concentration between two liquids (for example, seawater and fresh water). Seawater and fresh water have a strong tendency to mix and this will occur as long as the pressure difference between the liquids is less than the osmotic pressure difference. For seawater and freshwater this will be in the range of 24 to 26 bars, depending on seawater salt concentration.

Before entering the PRO membrane modules, seawater is pressurized to approximately half the osmotic pressure, about 12 - 13 bars. In the membrane module freshwater migrates through the membrane and into pressurized seawater. The resulting brackish water [TSU: is] then split in two streams. One third is used for power generation (corresponding to approximately the volume of freshwater passing through the membrane) in a hydropower turbine, whilst the remainder passes through a pressure exchanger in order to pressurize the incoming seawater. The brackish water can be fed back to the river or into the sea, where the two original sources would have eventually mixed.

6.4 Global and Regional Status of Markets and Industry Development

6.4.1 Introduction

In the last 10 years marine energy technology developments have focussed on wave and tidal current technologies, probably because they are physically smaller and thus cheaper than major capital projects, such as tidal barrages and R&D projects in OTEC and salinity gradients. Presently, the only commercial ocean energy technology available is the tidal barrage, of which the best example is the La Rance Barrage in northwestern France (540 GWh/yr; de Laleu, 2009). Tidal barrages are usually large, capital-intensive constructions; complementary uses can justify development. These may include communication access, facilitating regional development, as at La Rance, or alleviation of environmental problems, such as at Sihwa Lake in Korea. [TSU: references missing]

Although some wave and tidal current devices are approaching commercial development, other technologies to develop the other ocean energy sources - ocean thermal energy conversion (OTEC), salinity gradients, ocean currents, submarine geothermal and marine biomass - are still at conceptual or early prototype stages. More than one hundred ocean power technologies are under development in over 30 countries (Khan and Bhuyan, 2009).

6.4.1.1 Markets

Apart from tidal barrages, all ocean energy technologies are conceptual, undergoing R&D or, at best, have reached pre-commercial prototype stage. Consequently, there is no commercial market for ocean energy technologies at present.

Some governments are using a range of initiatives and incentives to promote both ‘technology push’ and ‘market pull’ to promote and accelerate the uptake of ocean power technologies. These are fully described in section 6.4.7. The northeastern Atlantic coastal countries lead the development of the market for ocean power technologies and their produced electricity. Funding mechanisms such as the Clean Development Mechanism (CDM) or Joint Implementation (JI) projects enable developing country governments to secure additional external funding for ocean energy projects. The Sihwa barrage project in the Republic of Korea was funded, in part, by CDM finance. [TSU: references missing]

The introduction of emissions trading schemes and/or carbon taxes to promote emissions reductions may also promote uptake of ocean energy technologies, by effectively pricing in the cost of CO_2 emissions to fossil fuel technologies. This will make renewable energy technologies, such as wave and tidal stream technologies, which produce no emissions in operation, more competitive.

Since ocean energy technologies are being developed, which produce pressurized or potable water as well as or instead of electricity, markets for these products will develop in due course.

6.4.1.2 Industry Development

As the marine energy industry moves from its present R&D phase, capacity and expertise from existing industries, such as electrical and marine engineering and offshore operations, will be drawn in, promoting rapid growth of industry supply chains. [TSU: references missing]

An unusual feature of ocean energy is the emergence of a loose network of national marine energy testing centres, such as the European Marine Energy Centre in Orkney – the first of a growing number of testing centres worldwide – where device developers can test their prototypes, using existing infrastructure, power purchase agreements and permits. These centres are accelerating the development of a wide range of wave and tidal current technologies. [TSU: references missing]

Industry development road maps and supply chain studies have been developed for Scotland, the United Kingdom and New Zealand (MEG, 2009; UKERC, 2008; AWATEA, 2008); the US and Canada have begun road mapping exercises. These countries have begun to assess the market potential for ocean energy as an industry development or regional development initiative. Regions supporting industry cluster development, leading to development of scalable power developments, will attract concentrations of industry development. [TSU: references missing]

There are now a series of global and regional initiatives for collaborative development of ocean energy markets and industry. These are assisting in the development of international networks, information flow, removal of barriers and efforts to accelerate marine energy uptake. The presently active initiatives include the following:

- International Energy Agency's Ocean Energy Systems Implementing Agreement
- EquiMar – the Equitable Testing and Evaluation of Marine Energy Extraction Devices (a European Union-funded initiative to deliver a suite of protocols for evaluation of wave and tidal stream energy converters)
- WavePLAM – the WAVe Energy PLanning And Marketing project (a European industry initiative to address non-technical barriers to wave energy).

6.4.2 Wave Energy

Wave energy technologies started to be developed with appropriate scientific basis after the first oil crisis in 1974. Many different converter types have been and continue to be proposed and tested but we are still at the beginning of pre-commercial phase. It is usual to test devices at small-scale in laboratory test-tank facilities (~1:100) before the first open-sea prototype testing (1:10 – 1:4 scale). Pre-commercial testing may be at 1:2 or 1:1 scale before the final full-scale commercial version becomes commercially available. Presently only a handful of devices have been built and tested at full-scale. Pre-commercial trials of individual modules and small arrays began in recent years and are expected to accelerate through the next decade. Costs of electricity from these early projects are already lower than those for solar PV and efforts such as the Marine Energy Accelerator programme (Carbon Trust, 2007) and incentivised pilot markets are intended to accelerate the cost reduction experience to make wave energy technologies commercially competitive.

A coast-attached oscillating water column device has been operational in Portugal since 1999 and a somewhat similar device (Wavegen's LIMPET device[5]) has been operating almost continuously on the island of Islay in Scotland since 2000. Offshore oscillating water column devices have been tested at prototype scale in Australia (Energetech/Oceanlinx[6]) since 2006.

The most advanced oscillating-body device is the 750 kW Pelamis Wavepower[7] attenuator device, which has been tested in Scotland and deployed in Portugal. The Portuguese devices were sold as part of a commercial project. The other near-commercial oscillating-body technology is Ocean Power Technologies' PowerBuoy[8], a small (40 – 150 kW) vertical axis device, which has been

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[5] www.wavegen.co.uk

[6] www.oceanlinx.com

[7] www.pelamiswave.com

[8] www.oceanpowertechnologies.com

deployed in Hawaii, New Jersey and off the north Spanish coast. Other oscillating-body devices under development include the Irish device, Wavebob[9], and the WET-NZ device[10]. Two Danish overtopping devices have been built at prototype-scale (Wave Dragon[11] and WavePlane[12]).

6.4.3 Tide Rise and Fall

Presently, only estuary-type tidal power stations are in operation. They rely on a barrage, equipped with generating units, closing the estuary. The only industrial-scale tidal power station in the world to date is the 240 MW La Rance power station, which has been in successful operation since 1966. Other smaller projects have been commissioned since then in China, Canada and Russia. The 254 MW Sihwa barrage (South Korea) is expected to be commissioned in 2010 and will then become the largest tidal power station in the world. Sihwa power station is being retrofitted to an existing 12.7 km sea dyke that was built in 1994. The project will, when operational, generate electricity, while also improving flushing the reservoir basin to improve water quality. [TSU: references missing]

By the end of 2010, the world's installed capacity of tidal rise and fall will still be <600 MW (EDF, 2009). However, numerous projects have been identified, some of them with very large capacities, e.g., the Severn Estuary, White Sea and Sea of Okhotsk in Russia. Barrages are most common but some are tidal lagoon concepts (Figure 6.11). Total planned capacity is approximately 21.9 GW.

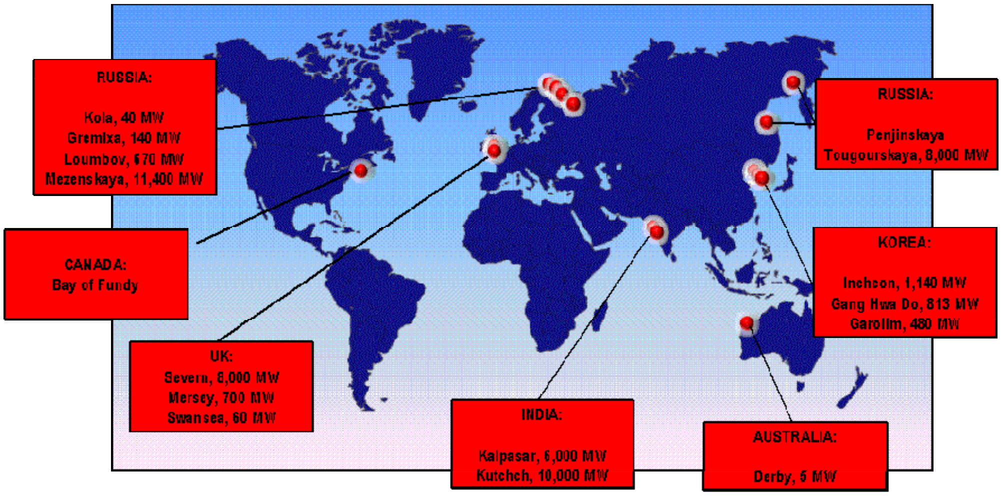

Figure 6.11: Tidal rise and fall power station proposed as of March 2009 (EDF, 2009)

6.4.4 Tidal and Ocean Currents

All tidal stream energy systems are in the proof of concept or prototype development stage, so large-scale deployment costs are not yet known. The most advanced example is the SeaGen tidal turbine, which was installed in Strangford Lough in Northern Ireland. This 'pre-commercial demonstrator' is now an accredited 'power station'. Most of these projections [TSU: context unclear] should be based on the available resources referenced in Section 6.2. From the global surveys, the best markets for tidal energy are in United Kingdom, USA, Canada, northeast Asia, and Scandinavia (EDF, 2009).

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[9] www.wavebob.com

[10] www.wavenergy.co.nz

[11] www.wavedragon.net

[12] www.waveplane.com

Tidal energy has some unique attributes that may enhance its market value. Tidal stream flows are often located near population centres, where the electricity delivery is not constrained by the further requirement for long transmission lines. Being largely submarine, tidal power plants are likely to have a very low visual impact, so can be located close to populations. Tidal flows are also very predictable, which is very valuable in utility generation planning and forecasting. [TSU: references missing]

The resource for tidal current energy is not widespread, being located at specific sites where current velocities are high enough for economic viability. The threshold for this velocity is at least 1.5 ms^{-1} but not enough is known about costs and this threshold will decline as technologies improve. Generally, the global resource and, hence, markets must be large enough to support sufficient deployments and experience for the technology to reach commercial maturity. Supported markets in Scotland, Ireland, UK, France, Spain and Portugal will launch development projects through the coming decade: the experience and scale up will drive down costs to a competitive level. [TSU: references missing]

Open ocean currents, such as the Gulf Stream, are being explored for their potential. Because they are slower moving and unidirectional, harnessing open ocean currents may require different technologies from those presently being developed for the faster, more restricted tidal stream currents (MMS, 2006). They do involve much larger water volumes, promising project scale.

6.4.5 Ocean Thermal Energy Conversion

Two floating ocean thermal energy conversion (OTEC) plants have been built in India. In 2005, a short 10-day experiment was conducted using an OTEC system mounted on a barge near Tuticorin (Ravindran, 2007). A barge was moored in water 400 m deep and successfully produced fresh water at a rate of 100,000 litres per day, using an ammonia-based closed-cycle system, created in co-operation with Saga University of Japan. The design was rated at 1 MW and apparently began construction in 2000 but was never completed.

In 2005, a land-based plant, capable of producing 100,000 litres per day of freshwater was built on the island of Kavaratti, using a 350 m long cold-water intake pipe (NIOT, 2007). The location gives access to water at 400 m depth only 400 m from shore, making it an ideal site for OTEC but the current plant does not incorporate electrical generation.

A small “Mini-OTEC” prototype plant was built in US in 1979 (Vega, 1999). The plant was built on a floating barge and used an ammonia-based closed cycle system. The 28,200 rpm radial inflow turbine gave the prototype a rated capacity of 53 kW but efficiency problems with the pumps limited to only 18 kW. In 1980 another floating OTEC plant, called OTEC-1, was built. It used the same closed-cycle system and was rated at 1 MW but it was primarily used for testing and demonstration and did not incorporate a turbine. It was operational for four months during 1981, during which time issues with the heat exchanger and water pipe were studied.

During 1992, an open-cycle OTEC plant was built in Hawaii (Ocean Thermal Energy, 2007). It operated from 1993 to 1998, and it had a rated capacity of 255 kW. Peak production was 103 kW and 0.4 l/s of desalinated water. Various difficulties were encountered, including out-gassing of the seawater in the vacuum chamber, the vacuum pump and varying output from the turbine/generator.

Several OTEC power plants have been built in Japan (Kobayashi et al., 2004). A 120 kW plant was built in the republic of Nauru, which used a closed-cycle system based on Freon and a cold water pipe with a depth of 580 m. The plant operated for several months and was connected to the power grid; it produced a peak of 31.5 kW of power. In 2006 the Institute of Ocean Energy (IOES) at Saga University created a small-scale 30 kW Hybrid OTEC plant. The prototype used a mixed water/ammonia working fluid, and successfully generated electrical power.

Sea Solar Power is developing a hybrid closed-cycle/open cycle OTEC system (Sea Solar Power, 2007). The design calls for the use of a propylene-based closed cycle-system, providing 10 MW of power in a shore-based plant or 100 MW in an offshore one. A parallel open-cycle system will provide fresh water and additional generation. Although conceptual plant designs have been created, it is unclear if any development is still occurring.

6.4.6 Salinity Gradient

Osmotic power is still a concept under development (Scråmestø et al., 2009). Utility sector and research groups initiated early development of osmotic power systems but, more recently, new groups have become engaged as the industry emerges. The parallel development of related technologies, such as desalination, will benefit the osmotic power industry.

Several governments and organisations are already supporting the development itself and consideration of necessary instruments to bring this source of renewable energy to the market. [TSU: references missing]

6.4.7 Ocean Energy-Specific Policies

[TSU: references missing in this section]

Because ocean energy technologies are relatively new but could offer emissions-free electricity generation and potable water production, numerous governments have introduced policy initiatives to promote and accelerate the uptake of marine energy. These policies range from funding initiatives, incentives to specifically promote marine energy deployments, industry and market develop and other regulatory initiatives to reward developers/users of marine energy technologies.

The government initiatives fall into five main categories (Table 6.2):

- Targets for installed capacity or contribution to future supply
- Capital grants and financial incentives, including prizes
- Market incentives, including feed-in tariffs and supply obligations
- Research and testing facilities and infrastructure
- Permitting/space/resource allocation regimes, standards and protocols

Most of the countries that have ocean energy-specific policies in place are also the most advanced with respect to technology developments and deployments. Government support for ocean energy is critical to the pace at which ocean energy is developed.

There are a variety of targets both aspirational and legislated. Most ocean energy-specific targets relate to proposed installed capacity targets, which complement other targets, such as for proportional increases in renewable energy generation or renewably generated electricity. Some European countries, such as Portugal, Ireland and Germany, have preferred ‘market pull’ mechanisms, such as feed-in tariffs (i.e., performance incentives for produced electricity from specific technologies). The United Kingdom has a Renewable Obligations Certificates (ROCs) scheme, i.e., tradable certificates awarded to generators of electricity using ocean energy technologies. More recently the Scottish Executive has introduced the Saltire Prize, a prize for the first device developer to meet a cumulative electricity generation target.

Most countries offer R&D grants for renewable energy technologies but some have ocean energy-specific grant programs. The United Kingdom and, since 2008, the United States have the largest and most sophisticated programs. Capital grant programs for device deployments have been implemented by both the United Kingdom and New Zealand as ‘technology push’ mechanisms.

1 **Table 6.2:** Ocean Energy-Specific Policies (modified after Huckerby & McComb, 2009).

Policy Instrument	Country	Example Description
Aspirational Targets and Forecasts	United Kingdom Basque Country, Spain, Canada	3% of UK electricity from ocean energy by 2020 5 MW off Basque coast by 2020 14,000 MW off Canada by 2050
Legislated Targets (total energy or electricity)	Ireland Portugal	Specific targets for marine energy installations 500 MW by 2020 off Ireland 550 MW by 2020 off Portugal
R&D programs/grants	United States	US DoE Hydrokinetic Program (capital grants for R&D and market acceleration)
Prototype Deployment Capital Grants	United Kingdom New Zealand	Marine Renewables Proving Fund (MRPF) Marine Energy Deployment Fund (MEDF)
Project Deployment Capital Grants	United Kingdom	Marine Renewables Deployment Fund (MRDF)
Feed-in Tariffs	Portugal Ireland/Germany	Guaranteed price (in $/kWh or equivalent) for ocean energy-generated electricity
Renewables Obligations	United Kingdom	ROCs scheme (tradable certificates (in $/MWh or equivalent) for ocean energy-generated electricity
Prizes	Scotland	E.g., Saltire Prize (GBP 10 million for first ocean energy device to deliver over 100 GWh of electricity over a continuous 2-year period)
Industry association support	Ireland New Zealand	Government financial support for establishment of industry associations
National Marine Energy Centres	United States	Two centres established (Oregon/Washington for wave/tidal & Hawaii for OTEC)
Marine Energy Testing Centres	Scotland, Canada and others	European Marine Energy Centre[13] and Fundy Ocean Resources Center, Canada
Offshore Hubs	United Kingdom	Wave hub, connection infrastructure for devices
Standards/protocols	International Electrotechnical Commission	Development of international standards for wave, tidal and ocean currents
Permitting Regimes	United Kingdom	Crown Estate competitive tender for Pentland Firth licences
Space/resource allocation regimes	United States	FERC/MMS permitting regime in US Outer Continental Shelf

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[13] www.emec.org.uk

6.5 Environmental and Social Impacts

6.5.1 Introduction

Since all ocean energy devices produce no CO_2 during operations, they are attractive for climate change mitigation purposes. Positive effects include strengthening of regional energy supply, regional economic growth, employment and eco-tourism. Negative effects may include reduction in visual amenity and loss of access to space for competing users. Project-specific effects will be different, depending on the environment where they are located and the communities that live near them and benefit from their outputs. Once operational, projects will have fewer and more limited effects than projects in operation [TSU: sentence unclear]. Most ocean energy projects will be long-lived (25 – 100 years), so the lasting effects of their development will be important. Given the high-energy nature of the ocean environment, the effects of some ocean energy projects should be completely reversible.

The general concerns comprise the effect of deployment, operation and maintenance (O&M) and decommissioning on local flora and fauna, and to a certain extent also the alteration of the physical environment. Noise impact is another issue. In addition, cabling the power generated to shore will involve bottom disturbances, including electromagnetic field hazards for some species.

More governments are undertaking Strategic Environmental Assessments (SEAs) to assess distribution of resources and to plan for potential environmental effects of ocean energy projects. Each new project proposal must then evaluate its own specific environmental impacts.

An ocean power station of any type becomes a source of eco-tourism and attraction in its own right, providing jobs in tourism and services [TSU: references missing]. Any type of ocean energy development will require extensive social and environmental impact assessments to fully evaluate all development options. A continuing program of public and stakeholder engagement is necessary to ensure that the concerns of various parties are duly considered in the development and operation of any project.

Social benefits may be national - creation of new industries, redirection of resources from declining industries, regional - developments of industry clusters, and individual - new employment opportunities, training for new skills and development of new capabilities. For example, the [TSU: delete] Scotland could create between 1,500 – 5,300 direct jobs in ocean energy by 2020 at present rates of marine energy technological and market development (MEG, 2009).

6.5.2 Wave Energy

Public concern over the environmental impacts of wave energy technologies comes from the lack of deployment experience with various wave energy conversion technologies. Good projections can be made using data from other offshore technologies, such as oil and gas and offshore wind. Potential impacts will [TSU: add “be”] similar to those of offshore wind turbines, which have now been monitored for several years. The potential effects on bird migration routes, feeding and nesting will not be relevant to ocean power technologies and the visual impacts of marine energy converters will be negligible, except where large arrays of devices are located nearshore.

Noise and vibration are potentially important impacts that need investigation. Noise and vibration are likely to be most disruptive during deployment and decommissioning but they will be longer-lasting during operations, so require R&D to understand, eliminate or mitigate. Electromagnetic fields around devices and electrical connection/export cables that connect arrays to the shore may be problematic to sharks and rays (elasmobranchs), which use electromagnetic fields to navigate and locate prey. Chemical leakage due to abrasion (of paints and anti-fouling chemicals) and leaks, e.g., oil leaks from hydraulic power-take-off systems (PTO)) will need to be eliminated or mitigated.

Energy capture and thus downstream effects could cause changes to sedimentation (e.g., seabed scouring or sediment accumulation) as well as wave height reductions, which are a potential concern to surfers. Wave energy farms could reduce swell conditions at adjacent beaches and modify wave dynamics along the shoreline. These aspects can be assessed through numerical and tank testing studies.

Large-scale implementation of wave farms will have positive impacts at general and local levels. In addition to electricity generation with rather small lifecycle greenhouse gases emission, it will decrease the import of fossil fuels (in those countries that do not possess such fuels) and will increase the local work of shipyards (devices construction and/or assembling), transportation, installation and maintenance. Exclusion areas for wave farms must be allocated, therefore creating refuges, which may be a net benefit to fishery resources.

6.5.3 Tide Rise and Fall

Estuaries are complex, unique and dynamic natural environments, which require very specific and careful attention. The impacts on the natural environment have to be addressed for both the construction phase and for future operations. For an estuary-type project, construction impacts will differ depending on the construction techniques employed: a total closure of the estuary during the construction period will affect fish life and biodiversity in the estuary whereas other methods such as floating caissons sunk in place for example will be less harmful.

At the La Rance power plant, although the estuary was closed for the construction period, biodiversity comparable to that of neighbouring estuaries was restored less than 10 years after commissioning, thanks to the responsible operating mode at the power station. The environmental impacts during construction of the Sihwa tidal power plant have been very limited. [TSU: references missing]

A barrage will affect the amplitude of the tides inside the basin and modify fish and bird life and habitat, water salinity and sediment movements in the estuary. Coastal processes may be disrupted. The need to ensure a minimum head between the basin and the sea will also lengthen the slack tidal times in the basin at high and low tides. A sound operational methodology is thus critical to mitigate the environmental impacts in the estuaries. In La Rance, two tides a day are systematically maintained by the operator inside the basin, which has resulted in the rapid restoration of a “natural” biodiversity in the basin. However, sediments accumulating towards the upstream end of the basin require regular dredging. [TSU: references missing]

Offshore tidal lagoons do not produce the same type of negative impacts. Being located offshore they do not have any impact on delicate nearshore ecosystems. Obviously they will have an impact on the area covered by the new basin, but provided this area is located away from sea currents, the impacts on marine life and biodiversity may be limited.

In terms of social impact, power plants constructed to date did not require any relocation of nearby inhabitants. This should continue to be so for future projects, as it is unlikely, even in the case of pumping, that the water level in the basin would be substantially higher than the water level at very high tides. Further these basins will be artificial installations at sites not previously inhabited.

Offshore tidal lagoons may have some impacts on fishing activities but this impact should be limited for locations away from sea currents. Lagoons may even be used to develop aquaculture to breed certain species of fish adapted to calm waters.

The construction phase usually requires large numbers of workers for the civil works, with significant investment and economic benefit to local communities. [TSU: references missing]

Estuary-type projects are often associated with the creation of new and shorter routes due to the use of the top of the barrage walls as roads linking locations originally with difficult access to each other. This will be positive in terms of improvement of socio-economic conditions for local communities. It should also lead to reductions in CO_2 emissions by reducing travel distances.

6.5.4 Tidal and Ocean Currents

6.5.4.1 Tidal Currents

The environmental impacts of tidal current technologies will be similar to those of wave energy converters. Tidal current technologies are likely to be large submarine structures, although some devices have surface-piercing structures. Environmental effects will be somewhat limited because devices are located in an already energetic, moving water environment.

A key concern with tidal current technologies is that they have rotating rotor blades or flapping hydrofoils - moving parts, which may harm marine life. To date there is no evidence of harm to marine life (such as whales, dolphins and sharks) from tidal current devices and this may in part be due to slow rotation speeds (relative to escape velocities of the marine fauna) compared with ship propulsion. On the positive side, arrays of tidal current turbines may act as de facto marine reserves, effectively creating new but protected habitats for some marine life.

6.5.4.2 Ocean Currents

Full-scale commercial deployments of open-ocean current electric generating systems could present certain environmental risks (Charlier, 1993; Van Walsum, 2003). These can be grouped into four broad categories: the physical environment (the ocean itself), benthic (ocean-bottom) communities, marine life in the water column and commerce.

Ocean current systems, with sufficient velocities to be cost-effective, are all associated with wind-driven circulation systems. Generation devices will not alter this circulation or its net mass transport. For example, the equator-ward Sverdrup drift in the wind-driven circulation, for which western boundary currents are the poleward return flow, is independent of the basin's dissipative mechanisms (e.g., Stommel, 1966). There could, however, be some alteration in meander patterns and in upper-ocean mixing processes, because the characteristics of the boundary current depend on dissipation. These effects need to be fully evaluated prior to full site development. Modelling studies of the Florida Current, using the HYCOM high-resolution regional simulation capability, are underway to assess these potential impacts (Chassignet et al., 2009).

Open-ocean power generation systems will operate below the draught of even the largest surface vessels, so hazards to commercial navigation will be minimal. Submarine naval operations could be impacted, although the stationary nature of the systems will make avoidance relatively simple. Underwater structures may affect fish habitats and behaviour and thus impact the attraction of sports fishing. Because underwater structures are known to become fish aggregating devices (FADs) (Relini et al., 2000), possible user conflicts, including line entanglement issues, must be considered. Associated alterations to pelagic habitats, particularly for large-scale installations, may become issues as well (Battin, 2004).

6.5.5 Ocean Thermal Energy Conversion

Potential changes in the regional properties of seawater due to ocean thermal energy conversion (OTEC) pumping operations are a major environmental concern. Large volumes of cold deep water and warm shallow water will be pumped to the heat exchangers and mixed. Mixing will modify the characteristics of the waters before discharge into ambient ocean water near the site. For this reason some shipboard OTEC projects, called ‘grazing’ projects, have been proposed so that the large volumes [TSU: singular] of discharged water does not have a long-term impact on the discharge site.

Under normal operating conditions, OTEC power plants will release few emissions to the atmosphere and will not adversely affect local air quality. The magnitude of possible climatic effects resulting from sea-surface temperature alterations by commercial OTEC development have not yet been ascertained and additional research on this theme is recommended.

Materials selection and design for operational flow rates, temperatures and pressures must be considered, together with aspects research on bio-fouling, corrosion and maintenance (Charlier and Justus (1993).

Marine organisms, mainly plankton and dissolved organic material, will be attracted by marine nutrients by the OTEC plant’s discharge pipe. Bacterial slimes will, which will [TSU: sentence structure] degrade heat exchanger performance, unless preventive procedures are implemented.

6.5.6 Salinity Gradient

Mixing of seawater and freshwater is a natural process that occurs all over the world. An osmotic power plant will extract the energy using this process without any significant interference with the environmental qualities of the site. Freshwater and seawater mixed in an osmotic power plant will be returned (to the sea) as brackish water, where they would have mixed naturally. Brackish water is the main waste product of the osmotic power plant but its concentrated discharge may alter the environment and result in changes for animals and plants living in the location. The impact of produced brackish water on the local marine environment will need to be monitored. Osmotic power will not produce any operational CO_2 emissions.

Assessments of the environmental optimisation and pre-environmental impact of an osmotic power plant located at an estuarine river mouth have not identified any serious obstacles. Major cities and industrial area [TSU: plural] are often sited at the mouths of major rivers, so osmotic power plants could be constructed on ‘brownfield’ sites. The plants can be constructed partly or completely underground to reduce their environmental footprint on the local environment.

6.6 Prospects for Technology Improvement, Innovation and Integration

6.6.1 Wave Energy

Wave energy technologies are still largely at a very nascent stage of development and all are pre-commercial (Falcão, 2009). Any cost or reliability projections are speculative with a high level of uncertainty, because they require assumptions to be made about optimized systems that have not yet been proven at or beyond the prototype level. ’Time in the water’ is critical for prototype wave devices so developers can gain enough operating experience to advance technology developments. As has happened with wind turbine generators, wave energy devices will iterate to the scale of the largest practical machine, to minimize the number of operation and maintenance (O&M) service visits, reduce installation and decommissioning costs and limit mooring requirements.

The largest cost reductions will come from maximizing power production by individual wave energy converters, even if deployed in arrays [TSU: references missing]. This will require efficient capture devices and dependable, efficient conversion systems. Performance and reliability will be top priorities for wave energy systems as commercialization and economic viability will depend on systems that require little servicing and can continue to produce energy reliably with minimal maintenance. The use of arrays will permit redundancy of single units and assist better maintenance/repair planning.

6.6.2 Tide Rise and Fall

Tidal rise and fall power projects rely on proven technologies in civil and electromechanical engineering, albeit built and operated in an estuarine, rather than a riverine environment. There are basically three areas where technology improvements can still be achieved [TSU: references missing]:

1. Development of cost-effective offshore tidal lagoons will allow the development of cost effective projects
2. Multiple tidal basins will increase the value of projects by reducing the intermittency of generation, thus allowing a better placement of the energy generated on the load curve.
3. Turbine efficiency improvements, particularly in bi-direction flows (including pumping).

Technologies may be further improved, for instance, with gears allowing different rotation speeds for the turbine and the generator or with variable frequency generation, allowing better outputs. Power plants may be built in situ within cofferdams or pre-fabricated in caissons (steel or reinforced concrete) and floated to site.

6.6.3 Tidal and Ocean Currents

Like wave energy converters, tidal current technologies are in an early stage of development. Extensive operational experience with horizontal- axis wind turbines may give axial flow water current turbines a developmental advantage, since the operating principles are similar. Future water current designs are likely to increase swept area (i.e., rotor diameter) to the largest practical machine size to increase generation capacity, minimize the number of O&M service visits, reduce installation and decommissioning costs and minimize substructure requirements.

Tidal device performance may be limited by the geometry of the specific channel transect dimensions and navigational requirements. The total tidal energy resource could be increased, if commercial threshold current velocities can be reduced. Tidal energy device optimization will follow a path of increasingly large turbines in lower flow regimes. A similar trend is well documented in the wind energy industry in the United States, where wind turbine technology developments targeted less energetic sites, creating a 20-fold increase in the available resource.

As with wave energy, performance and reliability will be top priorities for future tidal energy systems as commercialization and economic viability will depend on systems that need minimal servicing, producing power reliably without costly maintenance. New materials, which resist degradation caused by corrosion, cavitation, water absorption, and debris impact, will be needed.

6.6.4 Ocean Thermal Energy Conversion

The heat exchanger system is one of the key components of closed-cycle ocean thermal energy conversion (OTEC) power plants. Evaporator and condenser units must efficiently convert the working fluid from liquid to gaseous phase and back to liquid phase with low temperature differentials. Thermal conversion efficiency is highly dependent on heat exchangers, which can cause substantial losses in terms of power production and reduce economic viability of systems.

Evaporator and condenser units represent 20 - 40% of the plant total cost, so most research efforts are directed toward improving heat exchanger performance. Materials selection for the heat exchanger system is important. One of the best options is corrosion-resistant titanium but, due to its high cost, aluminium is substituted. This requires regularly scheduled planned maintenance. Copper-nickel alloys and stainless steel alloys are also candidate materials for the heat exchanger.

A second key component of an OTEC plant is the large diameter pipe, which carries deep coldwater to the surface. Experience obtained in the last decade with large-diameter risers for offshore oil and gas production can be easily transferred to the cold water pipe design.

A number of options are available for the closed-cycle working fluid, which has to boil at a low temperature (of warm surface water) and condense at a slightly lower temperature (of deep sea cold water). Three major candidates are ammonia, propane and a commercial refrigerant R-12/31. The main advantages are high evaporation and high thermal conductivity, especially in the liquid phase. Non-compatibility with copper alloys should be taken into account during design.

6.6.5 Salinity Gradient

The first osmotic power prototype plant became operational in October 2009 at Tofte, near Oslo in southeastern Norway. The prototype location is within an operational pulp factory, which gives good access to existing infrastructure. The location has sufficient access to seawater and fresh water from a nearby lake (Scråmestø, Skilhagen and Nielsen, 2009).

The main objective of the prototype is to confirm that the designed system can produce power on a reliable 24-hour/day production. After the start-up, initial operation and further testing, experience gained will be based on both operational changes as well as changes to the system and replacement of parts. These changes will be designed to increase the efficiency and optimise power generation. If the results of the prototype and the technology development are as expected, the R&D programme will lead to a commercial technology within a few years. [TSU: references missing]

The plant will be used for further testing of technology developed to increase the efficiency. These activities will focus on membrane modules, pressure exchanger equipment and power generation (i.e., the turbine and generator). Further development of control systems, water pre-treatment equipment and the water inlets and outlets is needed (Scråmestø, Skilhagen and Nielsen, 2009).

6.7 Cost Trends

6.7.1 Introduction

Commercial markets are not yet driving marine energy technology development. Government-supported technology R&D and national policy incentives are the key motivation for most technology development and deployment (US DoE, 2009). The cost of most ocean energy technologies is difficult to assess, because very little fabrication and deployment experience is available for validation of cost assumptions (Table 6.3).

Key variables that were taken into account in conducting some of the cost analysis include:

- Total installed capital cost (CAPEX),
- Reliability (i.e., operations and maintenance (O&M)),
- Annual Energy Production or Performance (AEP)[14]
- Learning curve (based on total industry wide deployment),
- Economies of scale (based on project size, production capacity),
- Impact of R&D and value engineering (innovation and implementation)

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[14] This term is widely accepted in the industry, even though 'energy production' is incorrect

Table 6.3: Cost Summary for All Ocean Energy Technology Sub-types

		Current Cost Parameters[1]					Future Cost Parameters			
Source of Cost Data	**Type of Ocean Energy Technology**	**Capex (US$/kW)**	**O&M Costs (US$/kW)**	**Discount Rate in %**	**Capacity Factor in %**	**LCOE (US¢/kWh)**	**LCOE (US¢/kWh)**	**Required Cumulative Capacity in MW**	**Learning Rate**	**Notes**
Vega (2002)	OTEC	12,300	NA	-	-	0.22	-	-	-	100 MW closed-cycle, 400 km from shore
SERI (1989)		12,200	NA	-	-	-	-	-	-	40 MW plant planned at Kahe Point, Oahu
Cohen (2009)		8,000 - 10,000	NA	-	-	0.16 - 0.20	0.08 - 0.16	-	-	100 MW early commercial plant
Francis (1985)		5,000 - 11,000	NA	-	-	-	-	-	-	-
Lennard (2004)		9,400	NA	-	-	0.18 (0.11)	-	-	-	10 MW closed-cycle; LCOE in parenthesis apply if also producing potable water
SERI (1989)		7,200	NA	-	-	-	-	-	-	Onshore, open-cycle
Vega (2002)		6,000	NA	-	-	0.10	-	-	-	100 MW closed-cycle, 100 km from shore
Vega (2002)		4,200	NA	-	-	0.07	-	-	-	100 MW closed-cycle, 10 km from shore
Scråmestø et al., 2009	Salinity Gradient Power	High	-	-	70%	0.05 - 0.10	-	-	-	[TSU: LCOE are in EUR/kWh. Will be converted in US$/kWh.]
CEC (2009)	Tidal Current	-	-	-	-	0.10 - 0.30	-	-	-	Cost estimate for California
Callaghan (2006)		8,571 - 14,286	-	-	-	0.16 - 0.32	0.046	2,800	-	Prototype, cost assessment for UK
Callaghan (2006)	Wave Energy	7,679 - 16,071	-	-	-	0.21 - 0.79	-	-	-	Prototype and pre-commercial devices, cost assessment for UK
Previsic (2004)		2620	123	7.5	38%	-	0.13 (2020)	-	-	106.5 MW capacity, 213 devices x 500 kW, 20-year life, 95% availability, R&D improvement

[1] Cost estimates for OTEC technologies are in different-year dollars and cover a range of different technologies and locations. Many are also highly speculative.

6.7.2 Wave and Tidal Energy

Several cost studies have estimated costs for wave and tidal energy devices by extrapolating from available prototype cost data (BBV, 2001; Li and Florig, 2006; Previsic, 2004; Callaghan, 2006; IEA, 2008). A recent study undertaken for the California Renewable Energy Transmission Initiative showed that tidal current generation (deployed in California) would cost US$100-300/MWh (CEC, 2009)[15]. Wave and current devices are at approximately the same early stage of development. CAPEX costs will potentially decline with experience to costs achieved by other renewable energy technologies such as wind energy (Bedard et al., 2006). This can only be demonstrated by extrapolation at present, since there is limited actual operating experience. Present CAPEX estimates are derived from operating prototypes, whose costs exceed commercial devices.

The US Electric Power Research Institute (EPRI) commissioned a study to examine theoretical commercial-scale project costs, using Pelamis wave energy converters off the California coast (Previsic, 2004). Overall plant size was assumed to be 213 x 500 kW devices (106.5 MW). Costs were based on a full 20-year life, 95% availability and forecast economies of scale. Energy capture

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[15] http://www.energy.ca.gov/reti/index.html.

potential would take advantage of near-term R&D improvement opportunities not yet realized but which were thought to be achievable at current CAPEX costs. The study concluded that a levelized cost of energy (LCOE) of 0.134 US$/kWh could be achieved, based upon a CAPEX cost of US$ 279 M, discount rate of 7.5%, capacity factor of 38%, and annual O&M costs of US$ 13.1 M (i.e., US$ 0.44/kWh).

In 2006 the UK Carbon Trust published the results of a survey of current costs for prototype and pre-commercial wave and tidal energy converters. Wave energy converters had CAPEX values ranging from £ 4,300 - 9,000/kW (US$ 7,679 - 16,071/kW) with a midpoint of US$ 11,875/kW (Callaghan 2006). Similarly, prototype tidal stream energy generator costs ranged from £ 4,800 - 8,000/kW (US$ 8,571 - 14,286/kW) with a midpoint of £ 6,400/kW (US$ 11,428/kW). Some current device concepts may have even greater CAPEX costs, which may be offset by future cost reductions. The same study estimated that energy from early UK wave energy farms would have LCOEs between 12 – 44 p/kWh (21.4 - 78.8 US¢/kWh) whilst early tidal stream farms had estimated LCOEs between 9 – 18 p/kWh (16.1 - 32.1 US¢/kWh). The studies did not account for economies of scale, R&D improvements or learning curve effects.

These theoretical analyses provide plausible benchmarks to demonstrate that wave energy projects could have lower LCOEs than wind energy did in the 1980s. Early wind turbines had numerous deployment problems and high ‘infant mortality rates’ that drove up early wind LCOE estimates, which may be avoided by early marine energy devices. The greatest uncertainties in estimating the LCOE of ocean energy are annual energy production (AEP) and operation and maintenance (O&M) costs. To achieve competitive costs, future ocean energy AEP and O&M must be estimated assuming increased efficiency and reliability.

There is also a high degree of uncertainty in estimating future CAPEX for mature, reliable systems from prototype data (Previsic et al., 2004; Buckley, 2005). Learning curve effects are an important downward cost driver for LCOE. As deployments multiply and installed capacity rises, costs reduce along the learning curve, due to natural production efficiency gains and assimilated experience. Early learning curve decline rates will be high but reduce over time. Learning curve rates for wind turbine generators ranged from 10% to 27% per doubling of installed capacity (see review of learning curve literature in Chapter 7, Table 7.8.2). Limiting this analysis to studies that span the full development of the wind industry (i.e., the three decades from 1980s to the present day), the learning curve effect converges to about 11% per doubling, without including an R&D factor (Wiser and Bolinger, 2009). Future ocean energy industries (wave, tidal current, ocean current and OTEC) could follow the same 11% learning curve as the wind industry. A CAPEX learning curve for wave and tidal current technologies, beginning with the midpoints for the CAPEX costs given by the Carbon Trust (2006), shows a rapid decline with increased installed capacity (Figure 6.12).

CAPEX costs for wave and tidal energy technologies will reduce to a range from US$ 2,600/kW to US$ 5,400/kW (average: US$ 4,000/kW), assuming worldwide deployments of 2-5 GW by 2020 and a learning rate of 11%. Electricity production from ocean energy technologies will exceed 667.5 TWh/yr from an installed capacity for all technologies of approximately 220 GW (assuming a nominal capacity factor of 35% and deployment estimates to 2050 (Table 6.4 or Chapter 10)). CAPEX costs will reduce to US$ 1,800 - 3,500, depending on the other market achievements of the individual ocean energy subtypes, assuming that aggregated energy output is roughly allocated at 50 GW per major technology subtype (Figure 6.12).

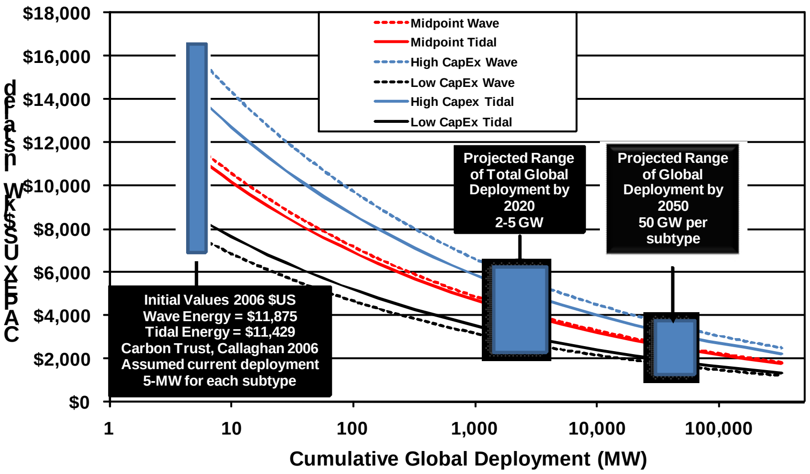

Figure 6.12: Learning curve reductions in CAPEX for wave and tidal energy devices based on current cost and 11% cost reduction per doubling of capacity (Callaghan, 2006).

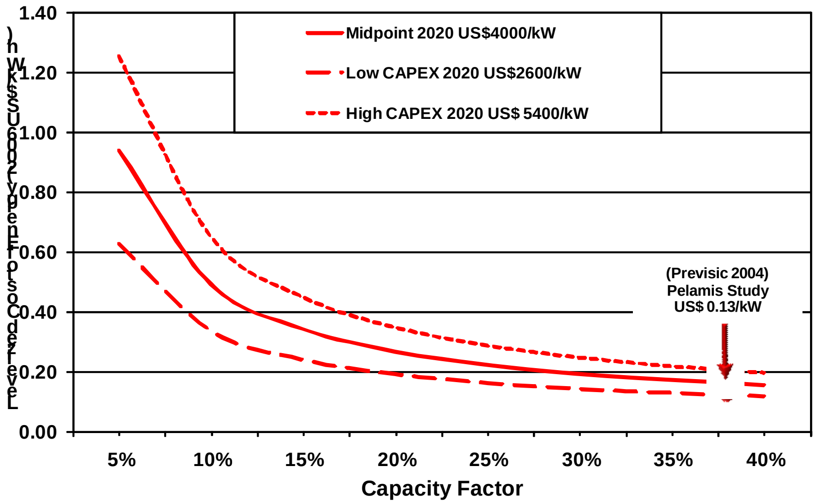

Figure 6.13: Capacity factor effect on LCOE for 2020 ocean energy CAPEX showing theoretical EPRI design, using Pelamis 500 kW machines at 38% capacity factor (Previsic, 2004).

Figure 6.13 shows projections of LCOE for wave and tidal energy as function of capacity factor, using a calculation worksheet provided by IPCC wind modelling group (Wiser, 2009). The three curves correspond to the calculated high, mid and low learning rate curves, i.e., US$ 5,600/kW, US$ 4,000/kW and US$ 2,600/kW, taken in the year 2020 (Figure 6.12). Marine devices operating with high capacity factors (i.e., 30% to 40%) can potentially generate electricity at rates competitive with other technologies. Devices must be reliable and located in a high quality wave or tidal current resource to achieve such capacity factors. Cost reductions will derive from manufacturing economies, new technology designs, knowledge and experience transfer from other industries and design modifications realized through operation and experience. All will contribute to rapid LCOE reductions. The cost and economics for open-ocean current technologies should track closely the evolution of tidal stream energy technologies. No definitive cost studies are available in the public domain for ocean current technologies.

6.7.3 Tide Rise and Fall

Tidal rise and fall projects usually require a very high capital investment, with relatively long construction periods. Civil construction in the marine environment - with additional infrastructure to protect against the harsh sea conditions - is complex and expensive. Consequently, capital costs associated with tidal rise and fall technologies are high, when compared to other sources of energy. Innovative techniques including construction of large civil components onshore and flotation to the site will allow substantial reduction in risks and costs. Tidal rise and fall projects tend, therefore, to be large-scale, as the scale reduces the unit cost of generation.

Tidal rise and fall projects may be eligible for Clean Development Mechanism (CDM) credits, as was the case for the Sihwa project in the Republic of Korea or, as in the UK, for the award of two Renewable Obligation Certificates (ROCs) for tidal energy, worth £ 105 (US$ 191) per MWh each.

6.7.4 Ocean Thermal Energy Conversion

Because there has been no sustained field experience with commercial ocean thermal energy conversion (OTEC) operations, it is hard to predict cost trends. Costs for individual projects are presently high, so iterative development has been slow. Published cost estimates are generally high. These range from: $ 4,200/kW, $ 6000/kW and $ 12,300 for a 100 MW closed-cycle power plant (10 km, 100 km, and 400 km, respectively from shore, corresponding to $ 0.07/kWh, $ 0.10/kWh, and $ 0.22/kWh (Vega, 2002 and 2009); $ 9,400/kW or $ 0.18/kWh for a 10 MW closed-cycle pilot plant, dropping to $ 0.11/kWh, if also producing potable water (Lennard, 2004); and $ 8,000-$ 10,000/kW for an early commercial 100-MW plant, corresponding to $ 0.10 - 0.20/kWh, dropping to $ 0.08 - 0.16/kWh, once enough plants have been built; an initial 75-MWe commercial floating plant off Puerto Rico will cost approximately $600 million, will produce 600 million kWh of electricity annually for about $ 0.15/kWh (Plocek et al., 2009) [TSU: not included in Table 6.3]. These speculative estimates are in different-year dollars and cover a range of different technologies and locations.

Perhaps the most reliable current costs are the Lockheed-Martin pilot plant estimates: $32,500/kW for a 10 MW pilot plant to $10,000/kW for a commercial 100 MW plant (Cooper et al., 2009) [TSU: not included in Table 6.3]. Advances in new materials and construction techniques in other fields in recent years, however, improve OTEC economics and technical feasibility. Offshore construction experience for wind turbines, undersea electrical cables, and oil drilling platforms, in particular, will prove helpful to future OTEC installations. Potentially important work specific or directly applicable to OTEC includes a congressionally mandated U.S. Navy contract expected to be awarded soon for development of high-efficiency, low-cost heat exchangers and industry and university work on lower-cost turbines. Costs will decrease dramatically with deployments.

6.7.5 Salinity Gradient

The estimated costs of producing osmotic power, based on a number of detailed investment analyses, are expected to be in the range of Euro 50 -100 per MWh [TSU: All monetary values will be converted to 2005 US$](Scråmestø et al., 2009). Full-scale cost estimates are based on current hydropower knowledge, general desalination (reversed osmosis) engineering and a specific membrane target as a prerequisite. Capital costs are expected to be high, compared to other renewable energy sources, and dependent on development of reliable, large-scale and low-cost membranes. However, capacity factors are expected to be approximately 70% [AUTHORS: This number was inferred from the claim that osmotic power could produce twice what a wind turbine could make. Please verify and provide a reference to support this claim.], based on preliminary calculations, which will yield relatively high AEP.

6.8 Deployment Potential

[TSU: Plenary-approved heading: Potential Deployment]

Individual ocean energy technology subtypes (i.e., tidal, wave, OTEC, ocean current) were aggregated to perform the initial analyses presented in Chapter 10 (Krewitt, 2009). These aggregated values yield estimates for world ocean energy deployments - with relatively high uncertainties. Further analysis is required to break down capital costs, resource technical potential, capacity factor and regional distribution of the resource for each technology.

Technical potential for aggregated ocean energy resources were estimated to be 0.207 EJ/yr (57.5 TWh/yr) by 2020, but increasing to 2.437 EJ/yr (677.5 TWh/yr), by 2050 as new technology is introduced (see section 6.4 to obtain specific data on current installations). This is a significant proportion of the world's energy consumption. The proportion of ocean energy deployments in the world's energy use portfolio is expected to continue to grow well beyond the 2050 horizon.

Significant growth in the decade 2010 – 2020 will see a substantial increase in ocean energy's contribution to energy/electricity supply and thus climate change reductions (Table 6.4). However, the total contribution will still be small. From 2020 mature technology deployments will effectively treble the proportion of energy/electricity production, with an effective doubling for the succeeding decades. These generation figures were generated from ocean energy runs of the MESAP/PlanNet - Energy [R]evolution Scenario model (Krewitt 2009, SRREN Database 2010). This analysis is preliminary, since ocean energy has only recently been included in some IPCC scenario modelling. The magnitude and diversity of ocean energy resources indicate that ocean energy can offer significant potential for carbon emission reductions before 2050 and beyond but near-term deployments (10 years) are unlikely to have a significant impact on global climate change.

Table 6.4: Ocean Energy Deployment from MESAP/PlanNet - Energy [R]evolution Scenario

	2010		2020		2030		2040		2050	
	TWh/yr	EJ/yr	TWh/yr	EJ/yr	TWh/yr	EJ/yr	TWh/yr	EJ/yr	TWh/yr	EJ/yr
World	2.5	0.009	57.5	0.207	151.2	0.544	338.6	1.218	677.5	2.437
Brazil	0.0	0.000	0.2	0.001	0.9	0.003	1.7	0.006	2.0	0.007
China	0.0	0.000	5.0	0.018	25.0	0.090	75.1	0.270	260.2	0.936
EU	0.6	0.002	3.4	0.012	13.0	0.047	34.0	0.122	55.0	0.198
India	0.0	0.000	4.2	0.015	9.0	0.032	19.0	0.068	37.0	0.133
Japan	1.2	0.004	7.0	0.025	18.0	0.065	29.0	0.104	35.0	0.126
Russia	0.0	0.000	13.0	0.047	17.0	0.061	21.0	0.076	25.0	0.090
USA	0.70	0.0025	8.0	0.029	27.0	0.097	71.1	0.256	115.1	0.414

6.8.1 Near-term Forecasts

Most near-term deployment will be policy driven in countries where government-sponsored research programs and policy incentives have been implemented to promote ocean energy development. Some countries have proposed non-binding deployment targets and timelines to achieve prescribed ocean energy capacity. The United Kingdom government has a target of 2 GW by 2020 (UKERC, 2008). Canada, USA, Portugal and Ireland have announced, or are working on establishing, independent deployment targets in a similar timeframe. However, most countries with significant ocean resources have not yet quantified their ocean energy resource potentials and have not established national deployment goals. In general, the near-term forecast for ocean energy does not envisage a substantial contribution to near-term carbon mitigation.

6.8.2 Long-term Deployment in the Context of Carbon Mitigation

The long-term deployment potential for ocean energy is significant in terms of future carbon mitigation. Substantial technology development is expected over the next 10 years, making ocean energy's proportionate larger in longer-term scenarios. Ocean technology scenario modelling need to be refined by disaggregation into the technology sub-types, better resource and cost information. The validity of scenario model projections depends on cost and resource assumptions for individual technologies, which, to date, have had only limited actual deployments. As deployments proliferate, model inputs will improve and scenario modelling will iterate towards better accuracy.

6.8.2.1 Resource Potential

- Wave energy sites are globally dispersed over all coastal boundaries, but mid-latitude sites (30 – 60º) are more favourable. Seasonal variations are much larger in the northern hemisphere than in the southern hemisphere, an important advantage for southern hemisphere deployments. The technical resource potential is present on coasts where incident wave energy exceeds an average of 20 kW/m but may be limited to nearshore sites (< 50 km) near coastal load centres. Availability of suitable sites may become a barrier in some regions under high penetration scenarios or in populated areas with competing uses.
- Tidal rise and fall is most likely in enclosed bays, where the regional tidal range is adequate for deployment. Limited site availability may prevent widespread deployment but tidal power plants are likely to be large to capture economies of scale.
- Tidal currents energy is globally distributed but is locally limited to sites, where local bathymetry accelerates existing currents. Average current speeds must exceed 1.5 ms^{-1} for present technologies. Sites with current speeds of at least 1.0 ms^{-1} may become viable as technologies mature.
- OTEC resources are limited to tropical regions where thermal differences of c. 20º C occur in close proximity to load centres. Coasts and islands with steep gradients – to bring deep water close to shore – are ideal locations. OTEC has potential for Indian, Pacific and Caribbean coast and island sites.
- The potential of ocean currents is limited to sites where relatively fast-moving global circulation currents come reasonably close to land, e.g., Florida Gulf Stream. The technical resource is abundant and could support substantial local or regional deployment.
- The technical potential for salinity gradient technology is probably limited to large river mouths, where large volumes of fresh water debouch into the sea.

6.8.2.2 Regional Deployment

Ocean energy technology is under development in countries bordering the North Atlantic, North Pacific and Southern Ocean, where government-sponsored programmes support R&DD and deployments, whilst pro-active policy incentives to promote early-stage projects [TSU: sentence structure].

6.8.2.3 Supply Chain Issues

There are no foreseeable supply chain issues that will limit the manufacture or deployment of ocean energy devices.

6.8.2.4 Technology and Economics

Successful demonstration of ocean energy technologies are limited to electric energy generating facilities located close to shore, where power delivery and grid integration issues do not significantly exceed the knowledge base of other variable output renewable energy sources, like offshore wind. The technical performance of ocean energy technologies will improve steadily over time as experience is gained and new technologies will be able to access poorer quality resources.

Technical improvements will enhance capacity factors, give access to more remote sites and tolerance of poorer quality resources (poorer wave climates or lower average current velocities).

6.8.2.5 Integration and transmission

Ocean energy deployments are likely to occur where network/grid access is available with sufficient nearby load demand. Small-scale off-grid applications are also possible. Large-scale deployment scenarios will require forecasting capability (which may be good in some instances), matching generation variability with load demand and power quality. Variability will differ by technology from relatively steady base-load generation from [TSU: sentence incomplete]. Ocean currents, OTEC and osmotic power plants will produce base load power, whilst tidal currents and tidal rise and fall will produce cyclical but predictable generation. Even the more stochastic nature wave generation has forecastable characteristics on longer-term variability than wind or solar insulation [TSU: sentence structure].

6.8.2.6 Social and Environmental Impacts

The social and economic impacts of ocean energy projects are being evaluated as actual deployments multiply (Section 6.5). Risk analysis and mitigation, using environmental impacts assessments, will be part of early deployments. Competitive uses may preclude the availability of some good resources sites. A balanced approach to engaging energy end-users in coastal communities will be necessary, whilst maintaining a fair and responsible respect for existing coastal uses.

6.8.3 Conclusions Regarding Deployment

The preliminary estimation of aggregated ocean energy deployment presented here is the first attempt to include ocean energy in any of the IPCC scenario modelling. Ocean power technologies have promising potential to mitigate long-term climate change by offsetting GHG emissions with predicted deployments resulting in energy delivery of 2.437 EJ/yr (677.5 TWh/yr) by 2050 (based on the preliminary analysis provided by the MESAP/PlanNet - Energy [R]evolution analysis). The modelling process established here will allow future scenarios to include ocean energy to be disaggregated into individual technologies, with better performance and cost data, to provide more rigorous and accurate analyses in [TSU: the] future.

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Chapter 7

Wind Power

Chapter:	7				
Title:	Wind energy				
(Sub)Section:	All				
Author(s):	CLAs:	Ryan Wiser, Zhenbin Yang			
	LAs:	Maureen Hand, Olav Hohmeyer, David Infield, Peter Hjuler Jensen, Vladimir Nikolaev, Mark O’Malley, Graham Sinden, Arthouros Zervos			
	CAs:	Naim Darghouth, Dennis Elliott, Hannele Holttinen, Jason Jonkman, Andrew Mills, Patrick Moriarty, Sara Pryor, Charles Smith			
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COMMENTS ON TEXT BY TSU TO REVIEWER

Yellow highlighted – original chapter text to which comments are references

Turquoise highlighted – inserted comment text from Authors or TSU e.g. [AUTHOR/TSU:…]

Chapter 7 has been allocated a maximum of 68 (with a mean of 51) pages in the SRREN. The actual chapter length (excluding references & cover page) is 71 pages: a total of 3 pages over the maximum (20 over the mean, respectively). Government and expert reviewers are kindly asked to indicate where the chapter could be shortened in terms of text and/or figures and tables.

All monetary values provided in this document either have been or will be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 7: Wind energy

CONTENTS

EXECUTIVE SUMMARY

Wind energy offers significant potential for near- and long-term carbon emissions reduction. Though there are a number of different wind energy technologies available within a range of applications, the primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either on- or off-shore. Focusing on these technologies, the wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050 if ambitious efforts are made to reduce carbon emissions and to mitigate the other barriers to increased wind energy deployment. On-shore wind energy is already being deployed at a rapid pace in many countries, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. Moreover, though average wind speeds vary considerably by location, ample technical potential exists in most regions of the world to enable significant wind energy development. In areas with particularly good wind resources, the cost of wind energy can be competitive with fossil generation but, in most regions of the world, policy measures are required to make wind energy economically attractive. Nonetheless, continued advancements in both on- and off-shore wind energy technology are expected, further reducing the cost of wind energy and improving wind energy’s carbon emissions mitigation potential.

The wind energy market has expanded rapidly. Modern wind turbines have evolved from small, simple machines to large, highly sophisticated devices, driven in part by more than three decades of basic and applied R&D. The resulting cost reductions, along with government policies to expand RE supply, have led to rapid market development, demonstrating the commercial and economic viability of the technology. From a cumulative capacity of 14 GW by the end of 1999, the global installed wind power capacity increased twelve-fold in ten years to reach almost 160 GW by the end of 2009. Most additions have been on-shore, but 2.1 GW of off-shore wind power capacity was installed by the end of 2009, with European countries embarking on ambitious programmes of off-shore wind energy deployment. From 2000 through 2009, roughly 11% of global net electric capacity additions came from new wind power plants; in 2009 alone, that figure was likely more than 20%. Total investment in wind power installations in 2009 equaled roughly US$57 billion, while direct employment in the wind energy sector has been estimated at 500,000. Nonetheless, wind electricity remains a relatively small fraction of worldwide electricity supply, and growth has been concentrated in Europe, Asia, and North America (Latin America, Africa and the Middle East, and the Pacific regions have installed relatively little wind power capacity). The top five countries in cumulative installed capacity by the end of 2009 were the U.S., China, Germany, Spain, and India; the top five countries in terms of wind electricity supply as a proportion of total electricity consumption were Denmark, Portugal, Spain, Ireland, and Germany. In the late 2000s, the U.S. and then China became the locations for the greatest annual capacity additions. Policy frameworks continue to play a significant role in wind energy utilization, and expansion of wind energy, especially in regions of the world with little wind energy development to date and in off-shore locations, is likely to require additional policy measures.

The global wind energy resource is sizable. A growing number of global wind resource assessments have demonstrated that the world’s technical potential for wind energy exceeds global electricity demand. Estimates of global technical potential range from a low of 70 EJ/y (excluding off-shore) to a high of 1,000 EJ/y (including on- and off-shore); estimates of the potential for off-shore wind energy alone range from 15 EJ/y to 130 EJ/y. Although the global potential for wind energy is not fixed (but is instead related to the status of the technology, the economics of wind energy, and subjective judgments on other constraints to wind energy development) and further

advancements in wind resource assessment methods are needed, the technical potential for the resource itself is unlikely to be a limiting factor on global wind energy development. Instead, economic constraints associated with the cost of wind energy, the institutional constraints and costs associated with transmission grid access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute global technical resource limits are encountered. Ample potential also exists in most regions of the world to enable significant wind energy development. That said, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the needs of every country. Additionally, the wind resource is not uniformly located near population centres – some of the resource is therefore economically less feasible. Research into the effects of global climate change on the geographic distribution and variability of the wind resource is nascent, as is research on the possible impacts of climate change on extreme weather events and therefore wind turbine operating environments. Research to date, however, suggests that global climate change will alter the geographic distribution of the wind resource, but that those effects are unlikely to be of a magnitude to greatly impact the global potential for wind energy to reduce carbon emissions.

Analysis and experience demonstrate that successful integration of wind energy is achievable. Wind energy has characteristics that pose new challenges to electric system planners and operators, such as variable electrical output, reduced predictability, and locational dependence. Nonetheless, wind electricity has been successfully integrated into existing electricity supply systems without compromising system security and reliability; in some countries, wind energy supplies in excess of 10% of aggregate annual electricity demand. Because the characteristics of the existing electric system determine the ease of integrating wind energy, acceptable wind electricity penetration limits and the operational costs of integration are system-specific. Nevertheless, theoretical analyses and practical experience suggest that, at low to medium levels of wind electricity penetration (under 20% of total electricity demand), the operational integration of wind energy generally poses no insurmountable technical barriers and is economically manageable. That said, concerns about (and the costs of) wind energy integration will grow with wind energy deployment and, even at medium penetration levels, integration issues must be addressed both at the local and system levels through stability and balancing requirements. Active management through a broad range of strategies is anticipated, including the use of flexible power generation technologies, wind energy forecasting and output curtailment, and increased coordination and interconnection between electric systems; demand-side management, energy storage technologies, and geographic diversification of wind power plant siting will also become increasingly beneficial as wind electricity penetration rises. Finally, significant new transmission infrastructure, both on-shore and off-shore, would be required to access areas with the best wind resource conditions. Both cost and institutional barriers would need to be overcome to develop this infrastructure. At low to medium levels of wind electricity penetration, the available literature suggests that the additional costs of managing electric system variability and uncertainty, ensuring resource adequacy, and adding new transmission to accommodate wind energy will generally not exceed 30% of the generation cost of wind energy.

Environmental and social issues will affect wind energy deployment opportunities. Wind energy has significant potential to reduce (and is already reducing) GHG emissions, together with the emissions of other air pollutants. The energy used and emissions produced in the manufacture and installation of wind turbines are small compared to the energy generated and emissions avoided over the lifetime of wind power plants (the carbon intensity of wind energy is estimated to range from 4.6 to 27 gCO_2/kWh, whereas energy payback times are between 3 to 9 months). In addition, managing the variability of wind power production has not been found to significantly degrade the carbon emissions benefits of wind energy. Alongside these benefits, however, wind energy also has the potential to produce some negative impacts on the environment and on human beings.

Prominent environmental concerns about wind energy include bird and bat collision fatalities and habitat and ecosystem modifications, while prominent social concerns include visibility and landscape impacts as well various nuisance effects and radar interference. Modern wind energy technology involves large structures, so wind turbines are unavoidably visible in the landscape, and planning wind power plants often creates local public concern. Appropriate siting of wind turbines is important in minimizing the impact of wind energy development on local communities, and engaging local residents in consultation during the planning stage is often an integral aspect of the development process. The construction and operation of both on- and off-shore wind power plants also impacts wildlife through bird and bat collisions and through habitat and ecosystem modifications, with the nature and magnitude of those impacts being site- and species-specific. Attempts to measure the relative impacts of various electricity supply technologies suggest that wind energy generally has a comparatively small environmental footprint, but impacts do exist, and techniques for assessing, minimizing, and mitigating those concerns could be improved. Though community and scientific concerns should be addressed, streamlined planning, siting, and permitting procedures may be required to enable more-rapid growth in wind energy utilization.

Technology innovation and underpinning research can further reduce the cost of wind energy. Current wind turbine technology has been developed largely for on-shore applications, and has converged to three-bladed upwind rotors, with variable speed operation. Though on-shore wind energy technology is reasonably mature, continued incremental advancements are expected to yield improved design procedures, increased reliability and energy capture, reduced O&M costs, and longer component life. In addition, as off-shore wind energy gains more attention, new technology challenges arise, and more-radical technology innovations are possible (e.g., floating turbines). Advancements can also be gained through more-fundamental research to better understand the operating environment in which wind turbines must operate. The cost of wind energy is affected by five fundamental factors: annual energy production, installation costs, operating and maintenance costs, financing costs, and the assumed economic life of the power plant. Though the cost of wind energy has declined significantly since the beginnings of the modern wind energy industry in the 1980s, in most regions of the world, policy measures are required to make wind energy economically attractive. In areas with particularly good wind resources or particularly costly alternative forms of energy supply, however, the cost of wind energy can be competitive with fossil generation. For on-shore wind power plants built in 2009, levelized costs in good to excellent wind resource regimes averaged US$50-100/MWh; levelized costs can reach US$150/MWh in lower resource areas. Off-shore wind energy had typical levelized costs that ranged from US$100/MWh to US$200/MWh. It is estimated that continued R&D, testing, and operational experience could yield reductions in the levelized cost of on-shore wind energy, relative to these 2009 levels, of 7.5-25% by 2020, and 15-35% by 2050. The available literature suggests that off-shore wind energy has greater potential for cost reductions: 10-30% by 2020 and 20-45% by 2050.

Wind energy offers significant potential for near- and long-term carbon emissions reduction. Given the commercial maturity and cost of on-shore wind energy technology, increased utilization of wind energy offers the potential for significant near-term carbon emissions reductions: this potential is not conditioned on technology breakthroughs, and related systems integration challenges are manageable. As technology advancements continue, especially for off-shore wind energy, greater contributions to carbon emissions reduction are possible in the longer term. Based on a review of the carbon and energy scenarios literature, wind energy's contribution to global electricity supply could rise from 1.8% by the end of 2009 to 13% by 2050 in the median scenario, and to 21-26% by 2050 at the 75th percentile of scenarios, if ambitious efforts are made to reduce carbon emissions. Achieving the higher end of this range of global wind energy utilization would likely require not only economic support policies of adequate size and predictability, but also an expansion of wind energy utilization regionally, increased reliance on off-shore wind energy in some regions, technical and institutional solutions to transmission constraints and operational integration concerns, and proactive efforts to mitigate and manage social and environmental concerns associated with wind energy deployment. Though R&D is expected to lead to incremental cost reductions for on-shore wind energy technology, enhanced R&D expenditures may be especially important for off-shore wind energy technology. Finally, for those markets with good wind resource potential but that are new to wind energy deployment, both knowledge (e.g., wind resource mapping expertise) and technology (e.g., to develop local wind turbine manufacturers and to ease grid integration) transfer may help facilitate early wind power installations.

7.1 Introduction

This chapter addresses the potential role of wind energy in reducing GHG emissions. Wind energy (in many applications) is a mature renewable energy (RE) source that has been successfully deployed in many countries, is technically and economically capable of significant continued expansion, and its further exploitation may be a crucial aspect of global GHG reduction strategies. Though average wind speeds vary considerably by location, the world's technical potential for wind energy exceeds global electricity demand, and ample potential exists in most regions of the world to enable significant wind energy development.

Wind energy relies, indirectly, on the energy of the sun. A small proportion of the solar radiation received by the earth is converted into kinetic energy (Hubbert, 1971), the main cause of which is the imbalance between the net outgoing radiation at high latitudes and the net incoming radiation at low latitudes. The earth's rotation, geographic features, and temperature gradients affect the location and nature of the resulting winds (Burton *et al.*, 2001). The use of wind energy requires that the kinetic energy of moving air be converted to useful energy. Because the theoretically-extractable kinetic energy in the wind is proportional to the cube of wind speed, the economics of using wind for electricity supply are highly sensitive to local wind conditions.

Wind energy has been used for millennia (for historical overviews, see, e.g., Gipe, 1995; Ackermann and Soder, 2002; Pasqualetti *et al.*, 2004). Sailing vessels relied on the wind from at least 3,100 BC, with mechanical applications of wind energy in grinding grain, pumping water, and powering factory machinery following, first with vertical axis devices and subsequently with horizontal axis turbines. By 200 B.C., for example, simple windmills in China were pumping water, while vertical-axis windmills were grinding grain in Persia and the Middle East. By the 11th century, windmills were used in food production in the Middle East; returning merchants and crusaders carried this idea back to Europe. The Dutch refined the windmill and adapted it for draining lakes and marshes in the Rhine River Delta. When settlers took this technology to the New World in the late 19th century, they began using windmills to pump water for farms and ranches. Industrialization and rural electrification, first in Europe and later in America, led to a gradual decline in the use of windmills for mechanical applications. The first successful experiments with the use of wind to generate electricity are often credited to Charles Brush (1887) and Poul la Cour (1891). Use of wind electricity in rural areas and, experimentally, in larger-scale applications, continued throughout the mid-1900s. However, the use of wind to generate electricity on a commercial scale began in earnest only in the 1970s, first in Denmark on a relatively small scale, then on a much larger scale in California (1980s), and then in Europe more broadly (1990s).

The primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either in a great number of smaller wind power plants or a smaller number of much larger plants. As of 2010, such turbines typically stand on tubular towers of 50-100 meters in height, with three-bladed rotors of 50-100 meters in diameter; machines with rotor diameters and tower heights of 130 meters were operating, and even larger machines are under development. Wind power plants are commonly sited on land: by the end of

2009, wind power plants sited in shallow and deeper water off-shore were a relatively small proportion of global wind power installations. Nonetheless, as wind energy deployment expands and as the technology becomes more mature, off-shore wind energy is expected to become a more significant source of overall wind energy supply.

Due to their potential importance to climate change mitigation, this chapter emphasizes grid-connected on- and off-shore wind turbines for electricity production. Notwithstanding this focus, wind energy has served and will continue to meet other energy service needs. In remote areas of the world that lack centrally provided electricity supplies, smaller wind turbines can be deployed alone or alongside other technologies to meet individual household or community electricity demands; small turbines of this nature also serve marine energy needs. Small-island or remote electricity grids can also employ wind energy, along with other energy sources. Even in urban settings that already have ready access to electricity, smaller wind turbines can, with careful siting, be used to meet a portion of building energy needs. New concepts for higher-altitude wind energy machines are also under consideration and, in addition to electricity supply, wind energy can meet mechanical and propulsion needs in specific applications. Though not the focus of this chapter, these additional wind energy applications and technologies are briefly summarized in Text Box 7.1.

Drawing on available literature, this chapter begins by describing the size of the global wind energy resource, the regional distribution of that resource, and the possible impacts of climate change on the resource (Section 7.2). The chapter then reviews the status of and trends in modern on-shore and off-shore wind energy technology (Section 7.3). Following that, the chapter discusses the status of the wind energy market and industry developments, both globally and regionally, and the impact of policies on those developments (Section 7.4). Near-term issues associated with the integration of wind energy into electricity supply systems are addressed (Section 7.5), as is available evidence on the environmental and social impacts of wind energy (Section 7.6). The prospects for further technology improvement and innovation are summarized (Section 7.7), and historical, current, and potential future cost trends are reviewed (Section 7.8). The chapter concludes with an examination of the potential future deployment of wind energy, focusing on the carbon mitigation and energy scenarios literature (Section 7.9).

Box 7.1. Alternative wind energy applications and technologies.

Beyond the use of large, modern wind turbines for electricity supply, a number of additional wind energy applications and technologies are currently employed or are under consideration. Though these technologies and applications are at different phases of market development, and each holds a certain level of promise for scaled deployment, none are likely to compete with traditional large on- and off-shore wind energy technology from the perspective of carbon emissions reduction, at least in the near- to medium-term.

Small wind turbines for electricity supply. Smaller-scale wind turbines are used in a wide range of applications. Though wind turbines from hundreds of watts to tens of kilowatts in size do not benefit from the economies of scale that have helped reduce the cost of larger wind turbines, they can be economically competitive with other supply alternatives in areas that do not have access to centrally provided electricity supply (Byrne *et al.*, 2007). For rural electrification or isolated areas, small wind turbines can be used on a stand-alone basis for battery charging or can be combined with other supply options (e.g., solar and/or diesel) in hybrid systems. As an example, China had 57 MW of cumulative small (<100 kW) wind power capacity installed by the end of 2008 (Li and Ma, 2009); 33 MW were reportedly installed in China in 2009. Small wind turbines are also employed in grid-connected applications for both residential and commercial electricity customers. Though the use of wind energy in these disparate applications can provide economic and social development benefits, the current and future size of this market makes it an unlikely source of significant long-term carbon emissions reductions; AWEA (2009b) estimates annual global installations of <100 kW wind turbines from leading manufacturers at under 40 MW in 2008. In addition, in urban settings where the wind resource is highly site-specific and can be poor, the carbon emissions savings associated with the displacement of grid electricity can be low or even zero once the manufacture and installation of the turbines are taken into account (Carbon Trust 2008a; Allen *et al.*, 2008).

Wind energy to meet mechanical and propulsion needs. Among the first technologies to harness the energy from the wind are those that directly used the kinetic energy of the wind as a means of marine propulsion, grinding of grain, and water pumping. Though these technologies were first developed long ago, there remain opportunities for the expanded use of wind energy to meet mechanical and propulsion needs (e.g., Purohit, 2007). New concepts to harness the energy of the wind for propulsion are also under development, such as using large kites to complement diesel engines for marine transport. Demonstration projects and analytic studies have found that these systems may yield fuel savings of up to 50%, though this depends heavily on the technology and wind conditions (O'Rourke, 2006; Naaijen and Koster, 2007).

Higher-altitude wind electricity. Higher-altitude wind energy systems have recently received some attention as an alternative approach to generating electricity from the wind (Roberts *et al.*, 2007; Argatov *et al.*, 2009; Archer and Caldeira, 2009; Kim and Park, 2010; Argatov and Silvennoinen, 2010). A principal motivation for the development of this technology is the sizable wind resource present at higher altitudes. There are two main approaches to higher-altitude wind energy that have been proposed: (1) tethered wind turbines that transmit electricity to earth via cables, and (2) base stations that convert the kinetic energy from the wind collected via kites to electricity at ground level. A variety of concepts are under consideration, operating at altitudes of less than 500 meters to more than 10,000 meters. Though some research has been conducted on these technologies and on the size of the potential resource, the technology remains in its infancy, and scientific, economic, institutional challenges must be overcome before a realistic estimate of the carbon emissions reduction potential of higher-altitude wind energy can be developed.

7.2 Resource potential

The global resource potential for wind energy is not fixed, but is instead related to the status of the technology, the economics of wind energy, and the assumptions made regarding other constraints to wind energy development. Nonetheless, a growing number of global wind resource assessments have demonstrated that the world's technical potential for wind energy exceeds global electricity demand, and that ample potential exists in most regions of the world to enable significant wind energy development. However, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the needs of every country. This section summarizes available evidence on the size of the global technical resource potential for wind energy (7.2.1), the regional distribution of that resource (7.2.2), and the possible impacts of climate change on wind energy resources (7.2.3). This section focuses on long-term average annual technical resource potential; for a discussion of seasonal and diurnal patterns, as well as shorter-term wind power variability, see Section 7.5.

7.2.1 Global technical resource potential

A number of studies have estimated the global technical resource potential for wind energy. In general, two methods can be used to make these estimates: first, available wind speed measurements can be interpolated to construct a surface wind distribution; and second, physics-based numerical weather prediction models can be applied. Studies of the global wind energy resource have used varying combinations of these two approaches, and have typically used relatively simple analytical techniques with coarse spatial and temporal resolution.[1] Additionally, it is important to recognize that estimates of the resource potential for wind energy should not be viewed as fixed – they will change as wind energy technology develops and as more is learned about technical, environmental, and social concerns that may influence development.

Synthesizing the available literature, the IPCC's Fourth Assessment Report identified 600 EJ/y of on-shore wind energy technical resource potential (IPCC, 2007), just 0.95 EJ (0.2%) of which was being used for wind energy supply in 2005. The IPCC (2007) estimate appears to derive from a study authored by Grubb and Meyer (1993). Using the direct equivalent method of deriving primary energy equivalence (where electricity supply, in TWh, is translated directly to primary energy, in EJ; see Chapter 1), the IPCC (2007) estimate of on-shore wind energy potential is 180 EJ/y (50,000 TWh/y), almost three times greater than global electricity demand in 2007 (19,800 TWh).[2]

Since the Grubb and Meyer (1993) study, a number of analyses have been undertaken to estimate the global technical potential for wind energy. The methods and results of these assessments are summarized in Table 7.1.

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[1] Wind power plant developers may rely upon global and regional wind resource estimates to obtain a general sense for the locations of potentially promising development prospects. However, on-site collection of actual wind speed data at or near turbine hub heights remains essential for most wind power plants of significant scale.

[2] The IPCC (2007) cites Johansson *et al.* (2004), which obtains its data from Goldemberg (2000), which in turn references WEC (1994) and Grubb and Meyer (1993). To convert from TWh to EJ, the documents cited by IPCC (2007) use the standard conversion, and then divide by 0.3 (i.e.., the "substitution" method of energy accounting in which RE supply is assumed to substitute the primary energy of fossil fuel inputs into conventional power plants, accounting for plant conversion efficiencies). The direct equivalent method does not take this last step, and instead counts the electricity itself as primary energy (see Chapter 1), so this chapter reports the IPCC (2007) figure at 180 EJ/y, or roughly 50,000 TWh/y. This figure is close to that estimated by Grubb and Meyer (1993).

Table 7.1. Global assessments of technical wind energy resource potential.

Study	**Scope**	**Methods and Assumptions***	**Results****
Krewitt *et al.* (2009)	On-shore & Off-shore	Updated Hoogwijk and Graus (2008), itself based on Hoogwijk *et al.* (2004), by revising off-shore wind power plant spacing by 2050 to 16 MW/km^2	*Technical:* 121,000 TWh/y 440 EJ/y
Lu *et al.* (2009)	On-shore & Off-shore	>20% capacity factor (Class 1); 100m hub height; 9 MW/km^2 spacing; based on coarse simulated model dataset; exclusions for urban and developed areas, forests, inland water, permanent snow/ice; off-shore assumes 100m hub height, 6 MW/km^2, <92.6 km from shore, <200m depth, no other exclusions	*Technical (limited constraints):* 840,000 TWh/y 3,050 EJ/y
Hoogwijk and Graus (2008)	On-shore & Off-shore	Updated Hoogwijk *et al.* (2004) by incorporating off-shore wind energy, assuming 100m hub height for on-shore, and altering cost assumptions; for off-shore, study updates and adds to earlier analysis by Fellows (2000); other assumptions as listed below under Hoogwijk *et al.* (2004); technical potential defined in economic terms separately for on-shore and off-shore	*Technical/Economic:* 110,000 TWh/y 400 EJ/y
Archer and Jacobson (2005)	On-shore & Near-Shore	>Class 3; 80m hub height; 9 MW/km^2 spacing; 48% average capacity factor; based on wind speeds from surface stations and balloon-launch monitoring stations; constrained technical potential = 20% of total potential	*Technical (limited constraints):* 627,000 TWh/y 2,260 EJ/y *Technical (more constraints):* 125,000 TWh/y 450 EJ/y
WBGU (2004)	On-shore & Off-shore	Multi-MW turbines; based on interpolation of wind speeds from meteorological towers; exclusions for urban areas, forest areas, wetlands, nature reserves, glaciers, and sand dunes; local exclusions accounted for through corrections related to population density; off-shore to 40m depth, with sea ice and minimum distance to shore considered regionally; sustainable potential = 14% of technical potential	*Technical:* 278,000 TWh/y 1,000 EJ/y *Sustainable:* 39,000 TWh/y 140 EJ/y
Hoogwijk *et al.* (2004)	On-shore	>4 m/s at 10m (some less than Class 2); 69m hub height; 4 MW/km^2 spacing; assumptions for availability / array efficiency; based on interpolation of wind speeds from meteorological towers; exclusions for elevations >2000m, urban areas, nature reserves, certain forests; reductions in use for many other land-uses; economic potential defined here as <US$100/MWh (2005$)	*Technical:* 96,000 TWh/y 350 EJ/y *Economic:* 53,000 TWh/y 190 EJ/y
Fellows (2000)	On-shore & Off-shore	50m hub height; 6 MW/km^2 spacing; based on upper-air model dataset; exclusions for urban areas, forest areas, nature areas, water bodies, and steep slopes; additional maximum density criterion; off-shore assumes 60m hub height, 8 MW/km^2 spacing, to 40m depth, 5-40 km from shore, with 75% exclusion; technical potential defined here in economic terms: <US$230/MWh (2005$) in 2020; focus on four regions, with extrapolations to others; some countries omitted altogether	*Technical/Economic:* 46,000 TWh/y 170 EJ/y
WEC (1994)	On-shore	>Class 3; 8 MW/km^2 spacing; 23% average capacity factor; based on an early global wind resource map;	*Technical (limited constraints):*

		constrained technical potential = 4% of total potential	484,000 TWh/y 1,740 EJ/y *Technical (more constraints):* 19,400 TWh/y 70 EJ/y
Grubb and Meyer (1993)	On-shore	>Class 3; 50m hub height; assumptions for conversion efficiency and turbine spacing; based on an early global wind resource map; exclusions for cities, forests, and unreachable mountain areas, as well as for social, environmental, and land use constraints, differentiated by region (results in constrained technical potential = ~10% of total potential, globally)	*Technical (limited constraints):* 498,000 TWh/y 1,800 EJ/y *Technical (more constraints):* 53,000 TWh/y 190 EJ/y

* Where used, wind resource classes refer to the following wind densities at a 50 meter hub height: Class 1 (<200 W/m2), Class 2 (200-300 W/m2), Class 3 (300-400 W/m2), Class 4 (400-500 W/m2), Class 5 (500-600 W/m2), Class 6 (600-800 W/m2), and Class 7 (>800 W/m2).

** Reporting of resource potential and conversion between EJ and TWh are based on the direct equivalent method (see Chapter 1). Definitions for theoretical, technical, economic, and sustainable potential are provided in the glossary of terms, though individual authors cited in Table 7.1 often use different definitions of these terms.

Among all of these studies, the global (constrained) technical resource potential for wind energy ranges from a low of 70 EJ/y (excluding off-shore) to a high of 1,000 EJ/y (including on- and off-shore), or from 19,400 to 278,000 TWh/y. (Excluded here are those assessments that applied limited development constraints; if those assessment are included, the absolute range of technical potential would expand to 70 EJ/y to 3,050 EJ/y). This range equates to between one and 14 times 2007 global electricity demand. Results vary based on whether off-shore wind energy is included, the wind speed data that are used, the areas assumed available for wind energy development, the rated output of wind turbines installed per unit of land area, and the assumed performance of wind power plants, which itself is related to hub height and turbine technology. Estimates of technical potential are dependent on technical assumptions as well as subjective judgements of development constraints.

There are three main reasons to believe that many of the studies reported in Table 7.1 may understate the global technical resource potential for wind energy. First, several of the studies are dated, and considerable advances have occurred in both wind energy technology and resource assessment methods. In part as a result, the six most-recent studies listed in Table 7.1 calculate larger technical resource potentials than the earlier studies (i.e., WBGU, 2004; Hoogwijk *et al.*, 2004; Archer and Jacobson, 2005; Hoogwijk and Graus, 2008; Krewitt *et al.*, 2009; Lu *et al.*, 2009). Second, a number of the studies included in Table 7.1 exclude the technical potential of off-shore wind energy. Though research has consistently found the technical potential for off-shore wind energy to be smaller than for on-shore wind energy and to be highly dependent on assumed technology developments, the potential for off-shore wind energy is nonetheless sizable, at 15-130 EJ/y (4,000-37,000 TWh/y).[3] Finally, even some of the more-recent studies reported in Table 7.1

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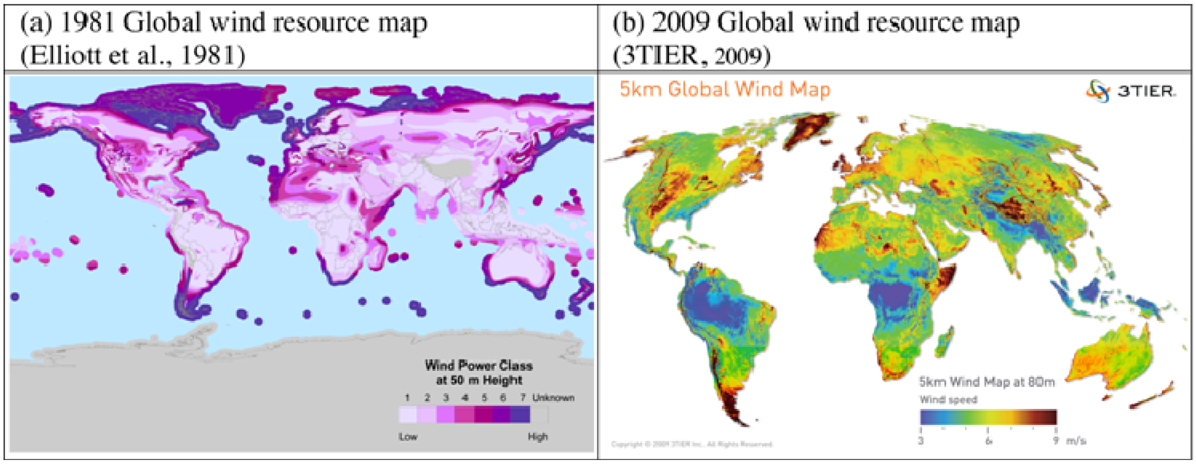
[3] The size of the off-shore wind energy resource is, at least theoretically, enormous, and constraints are primarily economic rather than technical. In particular, water depth, accessibility, and grid interconnection may limit development to relatively near-shore locations in the medium term, though technology improvements are expected, over time, to enable deeper-water and more-remote installations. Relatively few studies have investigated the global off-shore technical wind energy resource potential, and neither Archer and Jacobson (2005) nor WBGU (2004) report off-shore potential separately from the total potential reported in Table 7.1. In one study of global potential, Leutz *et al.* (2001) estimate an off-shore wind energy potential of 130 EJ/y (37,000 TWh/y) at depths less than 50m. Building from Fellows (2000) and Hoogwijk and Graus (2008), Krewitt *et al.* (2009) estimate a global off-shore wind energy potential of 57 EJ/y by 2050 (16,000 TWh/y) [Fellows (2000) provides an estimate of 15 EJ/y, or more than 4,000 TWh/y, whereas Hoogwijk and Graus (2008) estimate 23 EJ/y, or 6,100

likely understate the global technical potential for wind energy due to methodological limitations.[4] Enabled in part by an increase in computing power, more sophisticated and finer-geographic-resolution atmospheric modelling approaches are beginning to be applied (and increasingly validated with higher-quality measurement data) on a country or regional basis, as described in more depth in Section 7.2.2. Experience shows that these techniques have often identified greater actual wind energy resource potential than the earlier global assessments had estimated (see Section 7.2.2). As visual demonstration of these advancements, Figure 7.1(a,b) presents two global wind resource maps, one created in 1981 (Elliot *et al.*, 1981) and another in 2009 (3Tier, 2009).[5]


(a) 1981 Global wind resource map (Elliott et al., 1981)

(b) 2009 Global wind resource map (3TIER, 2009)

Figure 7.1(a,b). Example global wind resource maps from 1981 and 2009.

Despite the limitations of the available literature, it can be concluded that the IPCC (2007) estimate of 180 EJ/y likely understates by at least a factor of two the technical potential for wind energy, and that the global wind resource is unlikely to be a limiting factor on global wind energy development. Instead, economic constraints associated with the cost of wind energy, the institutional constraints and costs associated with transmission grid access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute global technical resource limits are encountered.

TWh/y]. In another study, Siegfriedsen *et al.* (2003) calculate the technical potential of off-shore wind energy outside of Europe as 17 EJ/y (4,600 TWh/y). Lu *et al.* (2009) estimate an off-shore wind energy resource potential of 540 EJ/y (150,000 TWh/y), of which 150 EJ/y (42,000 TWh/y) is available at depths of less than 20m, though this study does not consider as many development constraints as the other estimates listed here. A number of regional studies have been completed as well, including (but not limited to) those that have estimated the size of the off-shore wind energy resource in the EU (Matthies and Garrad, 1995; Delft University *et al.*, 2001), the U.S. (Kempton *et al.*, 2007; Jiang *et al.*, 2008; Heimiller *et al.*, 2010), and China (CMA, 2006).

[4] The global assessments described in this section often use relatively simple analytical techniques with coarse spatial resolutions, rely on interpolations of wind speed data from a limited number (and quality) of surface stations, and apply limited validation from wind speed measurements in prime wind resource areas.

[5] Although there are a variety of reasons to believe that global wind resource assessments have, to date, understated the actual size of the technical potential for wind energy, there is at least one methodological issue that would suggest the opposite. In particular, the assessments summarized here use point-source estimates of the wind resource, and assess the global potential for wind energy by summing local wind resource potential. Large-scale atmospheric dynamics, thermodynamic limits, and array effects, however, may bound the aggregate amount of energy that can be extracted by wind power plants on a regional or global basis. Relatively little is known about the nature of these constraints, though early research suggests effect sizes that are unlikely to significantly constrain the use of wind energy in the electricity sector (see Section 7.6.2.3).

7.2.2 Regional technical resource potential

7.2.2.1 Global assessment results, by region

The global assessments presented in Section 7.2.1 come to varying conclusions about the relative technical potential for on-shore wind energy among different regions, and Table 7.2 summarizes results from a sub-set of the global assessments, by region. Differences among these studies are due to variations in wind speed data and key input parameters, including the minimum wind speed assumed to be exploitable, land-use constraints, density of wind energy development, and assumed wind power plant performance (Hoogwijk *et al.*, 2004); differing regional categories also complicate comparisons. Nonetheless, the resource in North America and Eastern Europe/CIS are found to be particularly sizable, while some areas of Asia and OECD Europe appear to have more limited on-shore potential. Visual inspection of Figure 7.1 also demonstrates limited resource potential in certain areas of Latin America and Africa, though other portions of those continents have significant potential. Caution is required in interpreting these results, however, as other studies find significantly different regional allocations of global technical potential (e.g., Fellows, 2000), and more detailed country and regional assessments have come to differing conclusions on, for example, the wind energy resource in East Asia and other regions (Hoogwijk and Graus, 2008)**.**

Table 7.2. Regional allocation of global technical on-shore wind energy resource potential* [TSU: table width needs to be adjusted].

Grubb and Meyer (1993)		**WEC (1994)**		**Krewitt *et al.* (2009) ****		**Lu *et al.* (2009)**	
Region	%	Region	%	Region	%	Region	%
Western Europe	9%	Western Europe	7%	OECD Europe	5%	OECD Europe	4%
North America	26%	North America	26%	OECD North America	42%	North America	22%
Latin America	10%	L. America & Carib.	11%	Latin America	10%	Latin America	9%
E. Europe & FSU	20%	E. Europe & CIS	22%	Transition Economies	17%	Non-OECD Europe & FSU	26%
Africa	20%	Sub-Saharan Africa	7%	Africa and Middle East	9%	Africa and Middle East	17%
Australia	6%	M. East & N. Africa	8%	OECD Pacific	14%	Oceania	13%
Rest of Asia	9%	Pacific	14%	Rest of Asia	4%	Rest of Asia	9%
		Rest of Asia	4%				

* Some regions have been combined to improve comparability among the four studies.
** Hoogwijk and Graus (2008) and Hoogwijk et al. (2004) show similar results.

Hoogwijk *et al.* (2004) also compare *on-shore* technical potential against regional electricity consumption in 1996. In most of the 17 regions evaluated, technical on-shore wind energy potential exceeded electricity consumption in 1996. The multiple was over five in 10 regions: East Africa, Oceania, Canada, North Africa, South America, Former Soviet Union (FSU), Central America, West Africa, United States, and the Middle East. Areas in which on-shore wind energy resource potential was estimated to be less than a 2x multiple of 1996 electricity consumption were South Asia (1.9), Western Europe (1.6), East Asia (1.1), South Africa (1), Eastern Europe (1), South East Asia (0.1), and Japan (0.1), though again, caution is warranted in interpreting these results. More recent resource assessments and data on regional electricity consumption would alter these figures.

The estimates reported in Table 7.2 ignore *off-shore* wind energy potential. Krewitt *et al.* (2009), however, estimate that of the 57 EJ/y (16,000 TWh/y) of technical off-shore resource potential by 2050, the largest opportunities exist in OECD Europe (22% of global potential), Rest of Asia (21%), Latin America (18%), and the Transition Economies (16%), with lower but still significant potential in North America (12%), OECD Pacific (6%), and Africa and the Middle East (4%).

Overall, these studies find that ample potential exists in most regions of the world to enable significant wind energy development. However, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the energy needs and GHG reduction demands of every region or country.

7.2.2.2 Regional assessment results

The global wind resource assessments described above have historically relied primarily on relatively coarse and imprecise estimates of the wind resource, sometimes relying heavily on measurement stations with relatively poor exposure to the wind (Elliott, 2002; Elliot *et al.*, 2004). The regional results from these global assessments, as presented in Section 7.2.2.1, should therefore be viewed with caution, especially in areas where wind measurement data are of limited quantity and quality. In contrast, specific country and regional assessments have benefited from: wind speed data collected with wind resource estimation in mind; sophisticated numerical wind resource prediction techniques; improved model validation; and a dramatic growth in computing power. These advancements have allowed the most-recent country and regional resource assessments to capture smaller-scale terrain features and temporal variations in predicted wind speeds, and at a variety of possible turbine heights.

These techniques were initially applied in the EU[6] and the U.S.[7], but there are now publicly available high-resolution wind resource assessments covering a large number of regions and countries. The United Nations Environment Program's Solar and Wind Energy Resource Assessment (SWERA), for example, provides wind resource information for a large number of its partner countries around the world[8]; the European Bank for Reconstruction and Development has developed RE assessments in its countries of operation (Black and Veatch, 2003); the World Bank's Asia Sustainable and Alternative Energy Program has prepared wind resource atlas' for the Pacific Islands and Southeast Asia[9]; and wind resource assessments for portions of the Mediterranean region are available through Observatoire Méditerranéen de l'Energie.[10] A number of other publicly available country-level assessments have been produced by the U.S. National Renewable Energy Laboratory[11], Denmark's Risø DTU[12], and others[13]. Text Box 7.2 presents details on the status of wind resource assessment in China and Russia.

These more-detailed assessments have generally found the actual size of the wind resource to be greater than estimated in previous global or regional assessments. This is due primarily to improved data, spatial resolution, and analytic techniques, but is also the result of wind turbine technology developments, e.g., higher hub heights and improved machine efficiencies (see, e.g., Elliott, 2002; Elliot *et al.*, 2004). Nevertheless, even greater spatial and temporal resolution and enhanced validation of model results with observational data are needed, as is an expanded geographic coverage of these assessments (see, e.g., IEA, 2008; Schreck *et al.*, 2008; IEA, 2009a). These developments will allow further refinement of estimates of the technical potential for wind energy, and will likely highlight regions with high-quality potential that have not previously been identified.

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[6] For the latest publicly available European wind resource map, see http://www.windatlas.dk/Europe/Index.htm. Publicly available assessments for individual EU countries are summarized in EWEA (2009).

[7] A large number of publicly available U.S. wind resource maps have been produced at the state level, many of which have subsequently been validated by the National Renewable Energy Laboratory (see http://www.windpoweringamerica.gov/wind_maps.asp).

[8] See http://swera.unep.net/index.php?id=7

[9] http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/EASTASIAPACIFICEXT/EXTEAPASTAE/0,,contentMDK:21084082~menuPK:3031665~pagePK:64168445~piPK:64168309~theSitePK:2822888,00.html

[10] See http://www.omenergie.com/

[11] See http://www.nrel.gov/wind/international_wind_resources.html

[12] See http://www.windatlas.dk/World/About.html

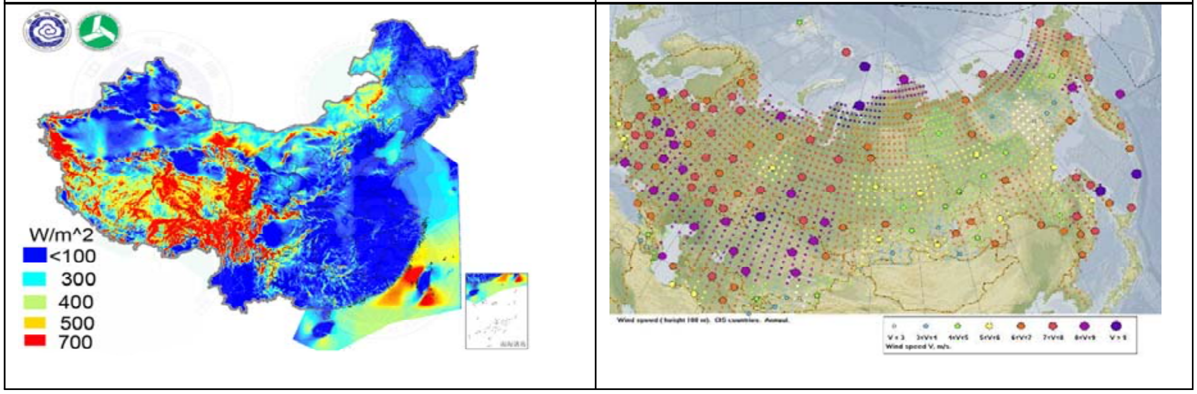
[13] A number of companies offer wind resource mapping assessments for a fee.

Box 7.2. Advancements in wind resource assessment in China and Russia

As demonstration of the growing use of sophisticated wind resource assessment tools outside of the EU and U.S., historical and ongoing efforts in China and Russia to better characterize their wind resources are described here. In both cases, the wind energy resource has been found to be sizable compared to present electricity consumption, and recent analyses offer enhanced understanding of the size and location of those resources.

China's Meteorological Administration (CMA) completed its first wind resource assessment in the 1970s. In the 1980s, a second wind resource investigation was performed based on data from roughly 900 meteorological stations, and a spatial distribution of the resource was delineated. The CMA estimated the availability of 253 GW (510 TWh/y at a 23% average capacity factor) of on-shore wind energy potential (Xue *et al.*, 2001). A third assessment was based on data from 2,384 meteorological stations, supplemented with data from other sources. Though still mainly based on measured wind speeds at 10m, most data covered a period of over 50 years, and this assessment led to an estimate 297 GW (600 TWh/y at a 23% average capacity factor) of on-shore wind energy potential (CMA 2006). More recently, improved mesoscale atmospheric models and access to higher-elevation meteorological station data have facilitated higher-resolution assessments. Figure 7.2(a) shows the results of a recent investigation, focused on on-shore wind resources and off-shore resources at 5-25m water depth. Based on this research, the CMA now estimates 2,380 GW of on-shore (4,800 TWh/y at a 23% average capacity factor) and 200 GW of off-shore (610 TWh/y at a 35% average capacity factor) wind energy potential (CMA, 2010). Other recent research has similarly estimated far-greater potential than past assessments (see, e.g., McElroy *et al.*, 2009).

Considerable progress has also been made in understanding the magnitude and distribution of the wind energy resource in Russia (as well as the other CIS countries, and the Baltic countries), based in part on data from approximately 3,600 surface meteorological stations and 150 upper-air stations. A recent assessment by Nikolaev *et al.* (2008) uses these data and meteorological and statistical modeling to estimate the distribution of the wind resource in the region (Figure 7.2(b)). Based on this work and after making assumptions on the characteristics and placement of wind turbines, Nikolaev *et al.* (2008) estimate that the technical potential for wind energy in Russia is more than 14,000 TWh/y, 15-times that of Russia's electricity consumption in 2006. The more promising regions of Russia for wind energy development are in the Western part of the country, the South Ural area, in Western Siberia, and on the coasts of the seas of the North and Pacific Oceans.



(a) China wind resource map (CMA, 2010)

(b) Russia, CIS, Baltic wind resource map (Nikolaev *et al.*, 2008)

Figure 7.2(a,b). Wind resource maps for China and Russia/CIS/Baltic.

7.2.3 Possible impact of climate change on resource potential

There is increasing recognition that global climate change may alter the geographic distribution and/or the inter- and intra-annual variability of the wind resource, or alter the prevalence of extreme weather events that may impact wind turbine design and operation. Research in this field is nascent, however, and Global and Regional Climate Models (GCMs and RCMs) do not fully reproduce contemporary wind climates (Goyette *et al.*, 2003) or historical trends (Pryor *et al.*, 2009). Additional uncertainty in wind resource projections under global climate change scenarios derive, in part, from substantial variations in simulated circulation and flow regimes when using different RCMs and GCMs (Pryor *et al.*, 2005, 2006; Bengtsson *et al.*, 2009; Pryor and Schoof, 2010). Nevertheless, based on research to date, it appears unlikely that multi-year annual mean wind speeds and energy densities will change by more than a maximum of ±25% over most of Europe and North America during the present century (Breslow and Sailor, 2002; Pryor *et al.*, 2005, 2006; Walter *et al.*, 2006; Bloom *et al.*, 2008; Sailor *et al.*, 2008; Pryor and Schoof, 2010). Prior research from the UK indicates high historical variability and weak evidence for slight increases in the wind resource based on output from one GCM run under one climate forcing scenario (Palutikof *et al.*, 1987, 1992). Brazil, meanwhile, has a large wind resource that was shown in one study to be relatively insensitive to (and perhaps even increase as a result of) global climate change (de Lucena *et al.*, 2009), and simulations for the west coast of South America showed increases in mean wind speeds of up to +15% (Garreaud and Falvey, 2009).

In addition to the possible impact of climate change on long-term average wind speeds, impacts on intra-annual, inter-annual, and inter-decadal variability in wind speeds are also of interest. Wind climates in northern Europe, for example, exhibit seasonality with the highest wind speeds during the winter (Rockel and Woth, 2007), and some analyses in the Northeast Atlantic (1874-2007) have found notable differences in temporal trends in winter and summer (Wang *et al.*, 2009). Internal climate modes have been found to be responsible for relatively high intra-annual, inter-annual, and inter-decadal variability in wind climates in the mid-latitudes (e.g., Petersen *et al.*, 1998; Pryor *et al.*, 2009). The ability of climate models to accurately reproduce these conditions in current and possible future climates is the subject of intense research (Stoner *et al.*, 2009). Equally, the degree to which historical variability and change in near-surface wind climates is attributable to global climate change or to other factors (Pryor *et al.*, 2009; Pryor and Ledolter, 2010), and whether that variability will change as the global climate continues to evolve, are also being investigated.

Finally, the prevalence of extreme winds and the probability of icing have implications for wind turbine design and operation (Wang *et al.*, 2009). Preliminary studies from northern and central Europe show some evidence of increased wind speed extremes (Pryor *et al.*, 2005; Haugen and Iversen, 2008; Leckebusch *et al.*, 2008), though changes in the occurrence of inherently rare events are difficult to quantify, and further research is warranted. Sea ice, and particularly drifting sea ice, potentially enhances turbine foundation loading for off-shore plants, and changes in sea ice and/or permafrost conditions may also influence access for wind power plant [TSU: operation and maintenance] (O&M) (Laakso *et al.*, 2003). One study conducted in northern Europe found substantial declines in the occurrence of both icing frequency and sea ice extent under reasonable climate change scenarios (Claussen *et al.*, 2007). Other meteorological drivers of turbine loading may also be influenced by climate change but are likely to be secondary in comparison to changes in resource magnitude, weather extremes, and icing issues (Pryor and Barthelmie, 2010).

Additional research on the possible impact of climate change on the size, geographic distribution, and variability of the wind resource is warranted, as is research on the possible impact of climate change on extreme weather events and therefore wind turbine operating environments. Overall, however, research to date suggests that these impacts are unlikely to be of a magnitude that will greatly impact the global potential of wind energy to reduce carbon emissions.

7.3 Technology and applications

7.3.1 Introduction

Modern grid-connected wind turbines have evolved from small, simple machines to large-scale, highly sophisticated devices. Scientific and engineering expertise, as well as computational tools and design standards, have supported these technology developments. As a result, wind turbine nameplate capacity ratings have increased dramatically since the late 1970s and early 1980s (from under 25 kW to 1.5 MW and larger), while the cost of wind energy production has declined by a factor of five (EWEA, 2009).

On-shore wind energy technology is already being manufactured and deployed on a commercial basis. Nonetheless, additional R&D advancements are anticipated, and are expected to further reduce the cost of wind energy. Off-shore wind energy technology is still developing, with greater opportunities for additional advancement. This section summarizes the historical development and technology status of large grid-connected on-shore and off-shore wind turbines (7.3.2), discusses international wind energy technology standards (7.3.3), and reviews grid connection issues (7.3.4); a later section (7.7) describes opportunities for further technical advancements.

7.3.2 Technology development and status

Generating electricity from the wind requires that the kinetic energy of moving air be converted to mechanical and then electrical energy, and the engineering challenge for the wind energy industry is to design efficient wind turbines to perform this conversion. The amount of energy in the wind that is available for extraction increases with the cube of wind speed. However, a turbine only captures a portion of that available energy, with the Lanchester-Betz limit providing a theoretical upper limit (59%) on the amount of energy that can be extracted.

Modern, large wind turbines employ rotors that start extracting energy from the wind at speeds of roughly 3-5 m/s (cut-in speed). The turbine increases power production until it reaches its rated power level, corresponding to a wind speed of about 12-15 m/s. At still-higher wind speeds, control systems limit power output to prevent overloading the wind turbine, either through stall control or through pitching the blades. Turbines stop producing energy at wind speeds of approximately 25-30 m/s (cut-out speed) to limit loads on the rotor and prevent damage to the turbine's structural components. When the power in the wind exceeds the wind speed for which the mechanical and electrical system of the machine has been designed (the rated power of the turbine), excess energy is allowed to pass through the rotor uncaptured (see Figure 7.3).

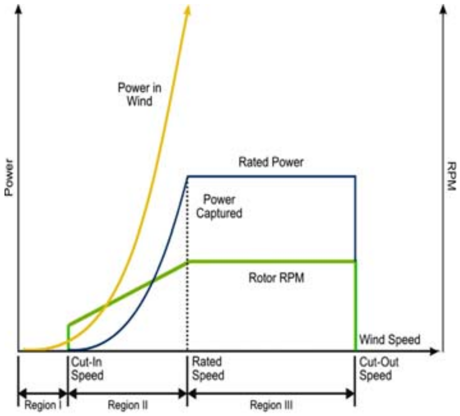


Figure 7.3. Conceptual power curve for a modern variable-speed wind turbine (US DOE, 2008).

In general, the speed of the wind increases with height above the ground, encouraging engineers to design taller and larger wind turbines while minimizing the cost of materials. Wind speeds also vary geographically and temporally, influencing the location of wind power plants, the economics of those plants, and the implications of increased wind energy on electric system operations.

7.3.2.1 On-shore wind energy technology

In the 1970s and 1980s, a variety of wind turbine configurations were investigated, including both horizontal- and vertical-axis designs (see Figure 7.4). Gradually, the horizontal axis design came to dominate, although configurations varied, in particular the number of blades and whether those blades were oriented upwind or downwind of the tower. After a period of further consolidation, turbine designs centred (with some notable exceptions) around the 3-blade, upwind rotor; locating the turbine blades upwind of the tower prevents the tower from blocking wind flow onto the blades and producing extra aerodynamic noise and loading. The three blades are attached to a rotor, from which power is transferred (sometimes through a gearbox, depending on design) to a generator. The gearbox and generator are contained within a housing called the nacelle. Figure 7.5 shows the components in a modern wind turbine with a gearbox; in wind turbines without a gearbox, the rotor is mounted directly on the generator shaft.

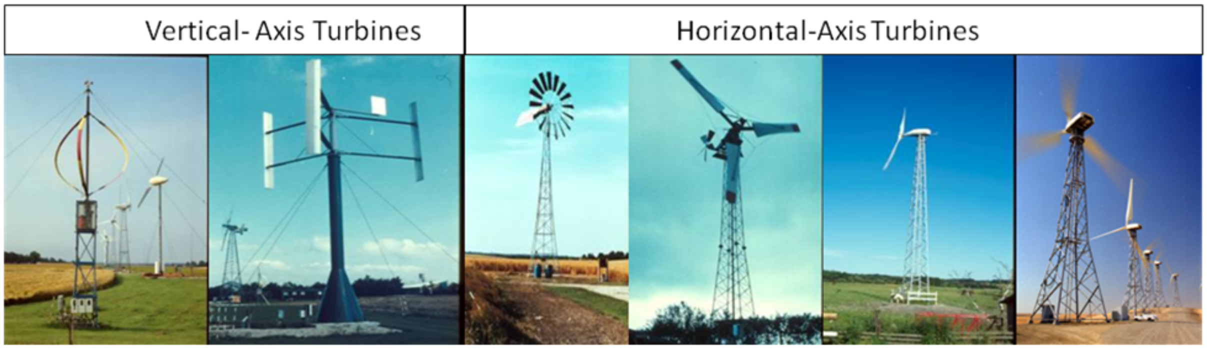


Figure 7.4. Early wind turbine designs, including vertical- and horizontal-axis turbines. Source: Risø DTU

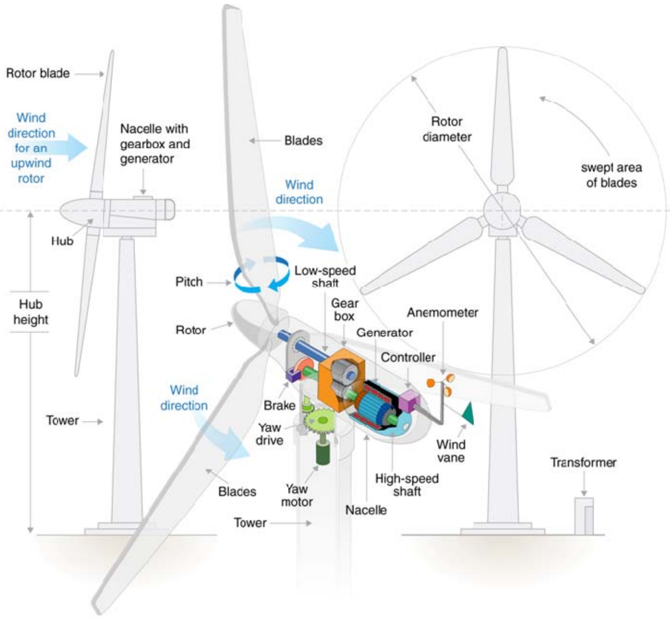


Figure 7.5. Basic components of a modern, horizontal-axis wind turbine with a gearbox. Source: NREL

In the 1980s, larger machines were rated at around 100 kW and primarily relied on aerodynamic blade stall to regulate power production from the fixed blades. These turbines generally operated at one or two rotational speeds. As turbine size increased over time, development went from stall control to full-span pitch control in which turbine output is controlled by pitching (i.e., rotating) the blades along their long axis. In addition, the advent of inexpensive power electronics allowed variable speed wind turbine operation. Initially, variable speeds were used to smooth out the torque fluctuations in the drive train caused by wind turbulence and to allow more efficient operation in variable and gusty winds. More recently, almost all electric system operators require the continued operation of large wind power plants during electrical faults, together with being able to provide reactive power: these requirements have accelerated the adoption of variable speed operation with power electronic conversion (see Section 7.5 for a fuller discussion of electric system integration issues). Today, wind turbines typically operate at variable speeds using full-span blade pitch control. Blades are commonly constructed with composite materials, and the towers are usually tubular steel structures that taper from the base to the nacelle at the top.

Over the past 30 years, average wind turbine size has grown significantly (Figure 7.6), with the largest fraction of land-based wind turbines installed globally in 2009 having a rated capacity of 1.5 MW to 2.5 MW; the average size of turbines installed in 2009 was 1.6 MW (BTM, 2010). As of 2010, such turbines typically stand on 50-100 meter towers, with rotors that are often 50-100 meters in diameter; larger machines with rotor diameters and tower heights of 130 meters are operating, and even larger machines are in use and under development. Modern turbines operate with rotational speeds of about 10 RPM, which compares to the faster and potentially more visually disruptive speeds exceeding 60 RPM common of the smaller turbines installed during the 1980s. The main reason for the continual increase in turbine size has been to minimize the levelized cost of wind energy by increasing electricity production (taller towers provide access to a higher-quality wind resource, and larger rotors allow a greater exploitation of those winds as well as more cost-effective exploitation of lower wind resource sites), reducing installed costs per unit of capacity (installation of a fewer number of larger turbines can, to a point, also reduce installed costs), and reducing O&M costs (larger turbines can reduce maintenance costs per unit of capacity). For land-based turbines, however, additional growth in turbine size may be limited due to the logistical constraints of transporting the very large blades, tower, and nacelle components by road, as well as the cost of and difficulty in obtaining large cranes to lift the components in place.

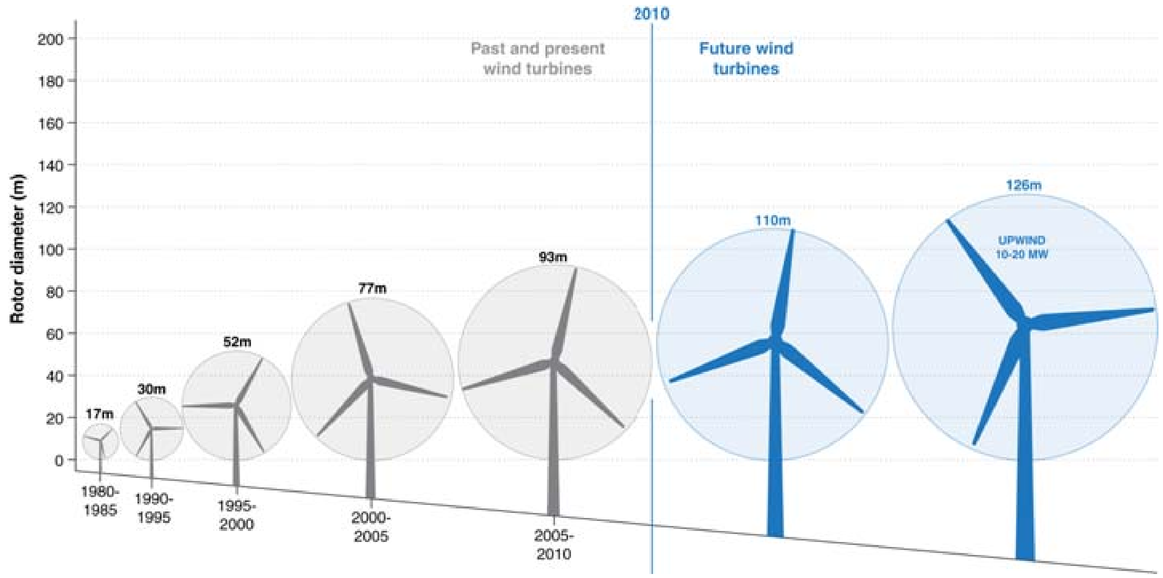


Figure 7.6. Growth in size of commercial wind turbines. Source: NREL

Modern on-shore wind turbines are typically grouped together into [TSU: word(s) missing?] wind power plants, sometimes called wind projects or wind farms. These wind power plants are often 5 MW to 300 MW in size, though smaller and larger plants do exist.

As a result of the above developments, on-shore wind energy technology is already viable for large-scale commercial deployment. Moreover, modern wind turbines have nearly reached the theoretical maximum of aerodynamic efficiency, with the coefficient of performance rising from 0.44 in the 1980s to about 0.50 by the mid 2000s.[14] The value of 0.50 is near the practical limit dictated by the drag of aerofoils and compares with a theoretical limit of 0.59 known as the Lanchester-Betz limit. The design requirement for wind turbines is normally 20 years, with 4,000 to 7,000 hours of operation each year depending on the characteristics of the local wind resource. By comparison, a domestic car that travels 20,000 km per year at an average speed of 30 km per hour operates 666 hours each year. O&M teams work to maintain high plant availability despite component failure rates that have, in some instances, been higher than expected. Though domestically manufactured wind turbines in China are reportedly under-performing (Li, 2010), data collected through 2008 show that modern wind turbines in mature markets can achieve an availability of 97% or more (Blanco, 2009; EWEA, 2009; IEA, 2009a).

These results are encouraging, and the technology has reached sufficient commercial maturity to allow large-scale manufacturing and deployment. Nonetheless, additional advancements to improve reliability, increase electricity production, and reduce costs are anticipated, and are discussed in Section 7.7. Additionally, most of the historical technology developments have occurred in developed countries. Increasingly, however, developing countries are investigating the potential installation of wind energy technology, and opportunities for technology transfer in wind turbine design, component manufacturing, and wind power plant siting exist. Moreover, extreme environmental conditions, such as icing or typhoons, may be more prominent in some of these markets, providing impetus for continuing research. Other aspects unique to less developed countries, such as minimal transportation infrastructure, could also influence wind turbine designs as these markets develop.

7.3.2.2 Off-shore wind energy technology

The first off-shore wind power plant was built in 1991 in Denmark, and consisted of eleven 450 kW wind turbines. By the end of 2009, many of the off-shore installations had taken place in the UK and Denmark, but significant development activity exists in other EU countries, in the U.S., in China, and elsewhere (e.g., Mostafaeipour, 2010). The off-shore wind energy sector remains relatively immature, however, and, by the end of 2009, about 2,100 MW of off-shore wind power capacity was installed globally, just 1.3% of total installed wind power capacity (GWEC, 2010b).

Interest in off-shore wind energy is the result of several factors: the higher-quality wind resources located at sea (e.g., higher average wind speeds, lower turbulence, and lower shear near hub height); the ability to use even-larger wind turbines due to avoidance of certain land-based transportation constraints and the potential to thereby gain further economies of scale; the ability to use more-flexible turbine designs given the uniqueness of the off-shore environment (e.g., lower turbulence, less wind shear near hub height, fewer constraints on noise); a potential reduction in the need for new, long-distance, land-based transmission infrastructure[15]; the ability to build larger power plants

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[14] Wind turbines achieve maximum aerodynamic efficiency when operating at wind speeds corresponding to power levels below the rated power level. Aerodynamic efficiency is reduced when operating at wind speeds above the rated power level (see Figure 7.3).

[15] Of course, transmission infrastructure would be needed to connect off-shore wind power plants with electricity demand centres, and the per-km cost of off-shore transmission typically exceeds that for on-shore lines. Whether off-shore transmission needs are more or less extensive than that needed to access on-shore wind energy varies by location.

than on-shore, gaining plant-level economies of scale; and the potential reduction of visual impacts and mitigation of siting controversies if wind power plants are located far-enough from shore (Carbon Trust, 2008b; Twidell and Gaudiosi, 2009; Snyder and Kaiser, 2009b). These factors, combined with a significant off-shore wind resource potential, have created considerable interest in off-shore wind energy technology in the EU and, increasingly, in other regions as well.

Wind turbine sizes of 2 MW to 5 MW were common for off-shore wind power plants built from 2007 through 2009, with even larger turbines under development. Off-shore wind power plants installed from 2007-09 were typically 20-120 MW in size, with a clear trend towards larger turbines and power plants over time. Water depths for most off-shore wind turbines installed through 2005 were less than 10 meters, but from 2006-09 water depths from 10 to more than 20 meters were common (EWEA, 2010a). As experience is gained, water depths are expected to increase further and more exposed locations with higher winds will be utilized.

To date, off-shore turbine technology has been very similar to on-shore designs, with some modifications and with special foundations (Musial, 2007; Carbon Trust, 2008b). The mono-pile foundation is the most common, though concrete gravity-based foundations have also been used with some frequency; a variety of other foundation designs are being considered and in some instances used, especially as water depths increase, as discussed in Section 7.7. In addition to differences in foundations, modification to off-shore turbines (relative to on-shore) include structural upgrades to the tower to address wave loading; air conditioned and pressurized nacelles and other controls to prevent the effects of corrosive sea air from degrading turbine equipment; and personnel access platforms to facilitate maintenance. Additional design changes for marine navigational safety (e.g., warning lights, fog signals) and to minimize expensive servicing (e.g., more extensive condition monitoring, on-board service cranes) are common. Wind turbine tip-speed is often greater than for on-shore turbines because concerns about noise are reduced for off-shore power plants and higher tip speeds can sometimes lead to lower torque and lighter drive train components for the same power output. In addition, tower heights are often lower due to reduced wind shear (i.e., wind speed does not increase with height to the same degree as on-shore).

Off-shore wind energy technology is still under development, and lower power plant availabilities and higher O&M costs have been common for the early installations (Carbon Trust, 2008b). Wind energy technology specifically tailored for off-shore applications will become more prevalent as the off-shore market expands, and it is expected that larger turbines in the 5-10 MW range may come to dominate this market segment (EU, 2008).

7.3.3 International wind energy technology standards

Wind turbines in the 1970s and 1980s were designed using simplified design models, which in some cases led to machine failures and in other cases resulted in design conservatism. The need to address both of these issues, combined with advancements in computer processing power, motivated designers to improve their calculations during the 1990s (Quarton, 1998; Rasmussen *et al.*, 2003). Improved design and testing methods have been codified in International Electrotechnical Commission (IEC) standards, and the rules and procedures for Conformity Testing and Certification of Wind Turbines (IEC, 2008a) relies upon these standards. These certification procedures provide for third-party conformity evaluation of a wind turbine type, a major component type, or one or more wind turbines at a specific location. Certification agencies rely on accredited design and testing bodies to provide traceable documentation of the execution of rules and specifications outlined in the standards in order to certify turbines, components, or entire wind power plants. The certification system assures that a wind turbine design or wind turbines installed in a given location meet common guidelines relating to safety, reliability, performance, and testing. Figure 7.7(a) illustrates the design and testing procedures required to obtain a wind turbine type certification. Project certification, shown in Figure 7.7(b), requires a type certificate for the turbine and includes procedures for evaluating site conditions and turbine design parameters associated with that specific site, as well as other site-specific conditions including soil properties, installation, and plant commissioning.

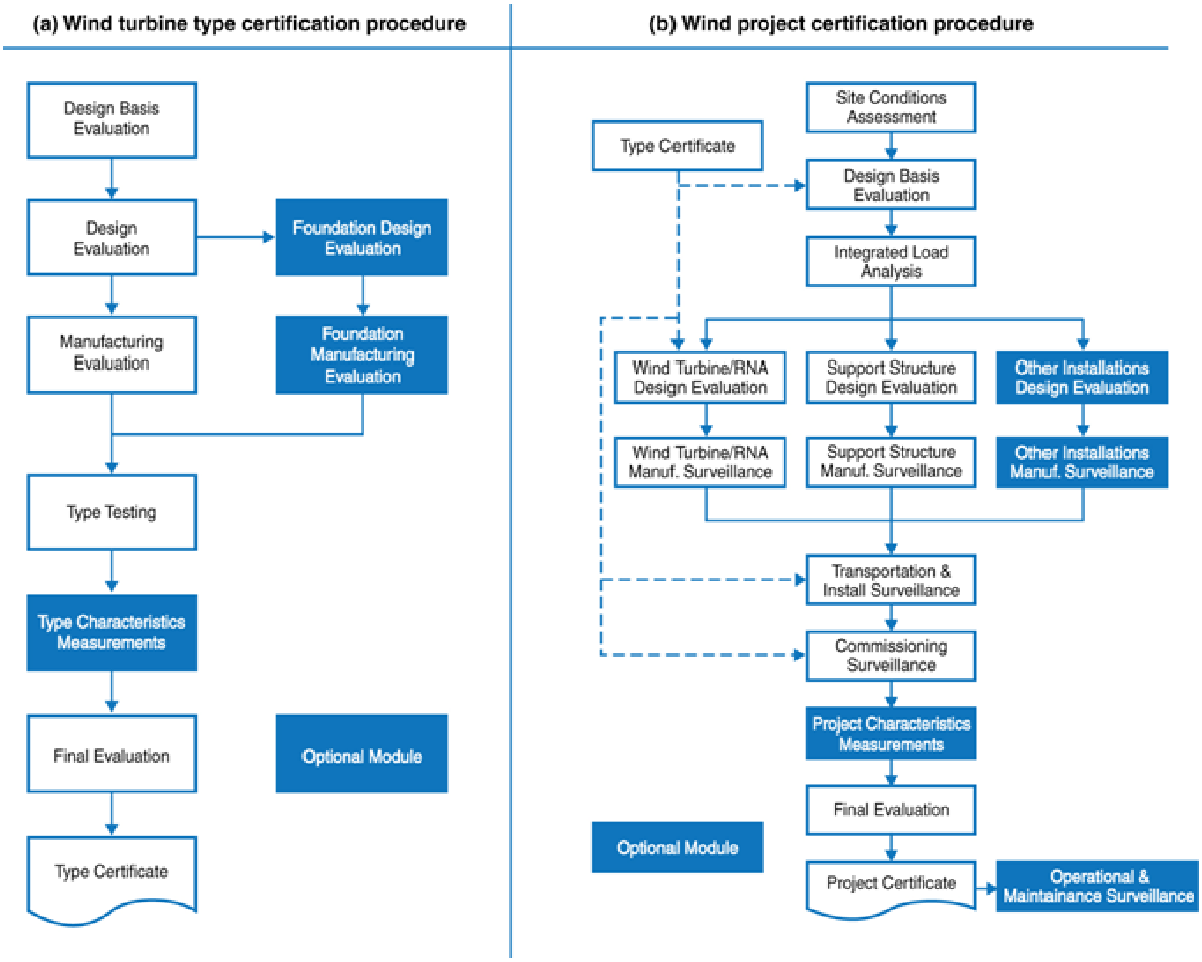

Figure 7.7(a,b). Modules for (a) type certification and (b) project certification (IEC, 2008a).

Insurance companies, financing institutions, and power plant owners normally require some form of certification for plants to proceed. These standards provide a common basis for certification to reduce uncertainty and increase the quality of wind turbine products available in the market. In emerging markets, the lack of highly qualified testing laboratories and certification bodies limits the opportunities for manufacturers to obtain certification according to IEC standards and may lead to lower-quality products. As markets mature and design margins are compressed to reduce costs, reliance on internationally recognized standards will likely become even more widespread to assure consistent performance, safety, and reliability of wind turbines.

7.3.4 Power conversion and related grid connection issues

From an electric system reliability perspective, an important part of the wind turbine is the electrical conversion system. For large grid-connected turbines, electrical conversion systems come in three broad forms. Fixed-speed induction generators were popular in earlier years for both stall regulated and pitch controlled turbines; in these arrangements, wind turbines were net consumers of reactive power that had to be supplied by the electric system. For new turbines, these designs have now been largely replaced with variable speed machines. Two arrangements are common, doubly-fed induction generators (DFIG) and synchronous generators with a full power electronic convertor, both of which are almost always coupled to pitch controlled rotors. These turbines can provide real and reactive-power control and some fault ride-through capability, which are increasingly being required for electric system reliability (further discussion of these requirements and the institutional elements of wind energy integration are addressed in Section 7.5, with a more general discussion of RE integration covered in Chapter 8). These variable speed designs essentially decouple the rotating masses of the turbine from the electric system, thereby offering a number of power quality advantages over earlier turbine designs (Ackermann, 2005; EWEA, 2009). These designs, however, differ from the synchronous generators found in most conventional power plants in that they result in no intrinsic inertial response capability. The lack of inertial response is an important consideration for electric system planners because less overall inertia makes the maintenance of stable system operation more challenging (Gautam *et al.*, 2009). Wind turbine manufacturers have recognized this lack of intrinsic inertial response as a possible long term impediment to wind energy and are actively pursuing a variety of solutions; for example, additional turbine controls can be added to provide inertial response (Mullane and O'Malley, 2005; Morren *et al.*, 2006).

7.4 Global and regional status of market and industry development

This section summarizes the global (7.4.1) and regional (7.4.2) status of wind energy development, discusses trends in the wind energy industry (7.4.3), and highlights the importance of policy actions for the wind energy market (7.4.4). As documented in this section, the wind energy market has expanded substantially in the 2000s, demonstrating the commercial and economic viability of the technology and industry, and the importance placed on wind energy development by a number of countries through policy support measures. Wind energy expansion has been concentrated in a limited number of regions, however, and the wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of global electricity demand. Further expansion of wind energy, especially in regions of the world with little wind energy development to date and in off-shore locations, is likely to require additional policy measures.

7.4.1 Global status and trends

Wind energy has quickly established itself as part of the mainstream electricity industry. From a cumulative capacity of 14 GW by the end of 1999, the global installed capacity increased twelve-fold in ten years to reach almost 160 GW by the end of 2009, an average annual increase in cumulative capacity of 28% (see Figure 7.8). Global annual wind power capacity additions equalled more than 38 GW in 2009, up from 26 GW in 2008 and 20 GW in 2007, and this despite the global financial crisis that led to fears of a slow-down in market growth (GWEC, 2010a).

The majority of the capacity has been installed on-shore, with off-shore installations constituting a small proportion of the total market. About 2.1 GW of off-shore wind turbines were installed by the end of 2009; 0.6 GW were installed in 2009, including the first off-shore wind power plant outside of Europe, in China (GWEC, 2010a). Off-shore wind energy is expected to develop in a more-significant way in the years ahead as the technology becomes more mature and as on-shore wind energy sites become constrained by local resource availability and/or siting challenges in some regions (BTM, 2010; GWEC, 2010a).

In terms of economic value, the total cost of new wind power generating equipment installed in 2009 was US$57 billion (2005$, GWEC, 2010a). Direct employment in the wind energy sector in 2009 has been estimated at roughly 190,000 in the EU and 85,000 in the United States. Worldwide, direct employment has been estimated at approximately 500,000 (GWEC, 2010a).

Despite these trends, wind energy remains a relatively small fraction of worldwide electricity supply. The total wind power capacity installed by the end of 2009 would, in an average year, meet roughly 1.8% of worldwide electricity demand, up from 1.5% by the end of 2008, 1.2% by the end of 2007, and 0.9% by the end of 2006 (Wiser and Bolinger, 2010).

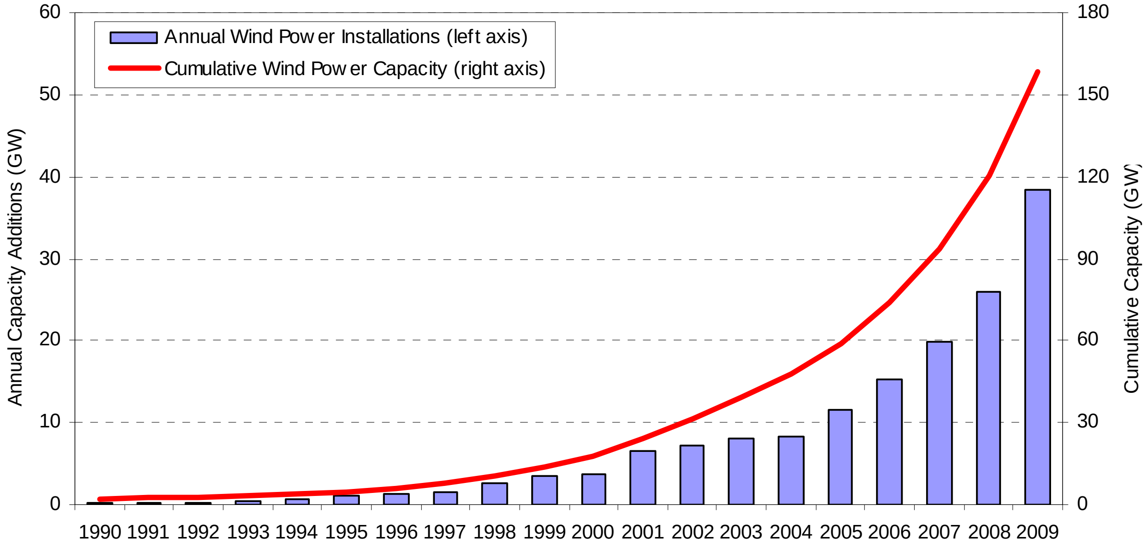

Figure 7.8. Global annual wind power capacity additions and cumulative capacity (GWEC, 2010a; Wiser and Bolinger, 2010).

7.4.2 Regional and national status and trends

The countries with the highest total installed wind power capacity by the end of 2009 were the United States (35 GW), China (26 GW), Germany (26 GW), Spain (19 GW), and India (11 GW). After its initial start in the United States in the 1980s, wind energy growth centred on countries in the EU and India during the 1990s and the early 2000s. In the late 2000s, however, the U.S. and then China became the locations for the greatest annual capacity additions (Figure 7.9).

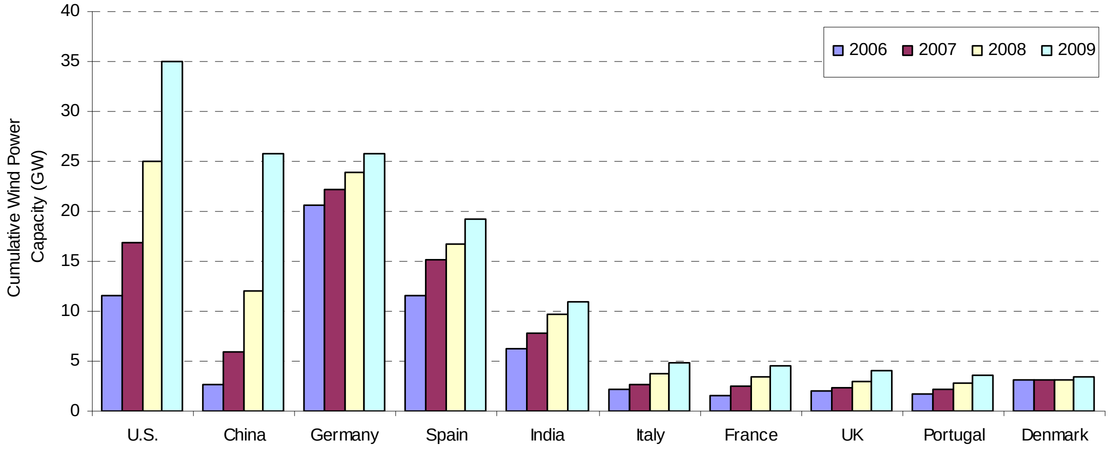

Figure 7.9. Top-10 countries in cumulative wind power capacity (GWEC, 2010a).

Regionally, Europe continues to lead the market with 76 GW of cumulative installed wind power capacity by the end of 2009, representing 48% of the global total (Asia represented 25%, while North America represented 24%). Notwithstanding the continuing growth in Europe, the trend over time has been for the wind energy industry to become less reliant on a few key markets, and other regions of the world have increasingly become the dominant markets for wind energy growth. The annual growth in the European wind energy market in 2009, for example, accounted for just 28% of the total new wind power additions in that year, down from over 60% in the early 2000s (GWEC, 2010a). More than 70% of the annual wind power capacity additions in 2009 occurred outside of Europe, with particularly significant growth in Asia (40%) and North America (29%) (Figure 7.10). Even in Europe, though Germany and Spain have been the strongest markets during the 2000s, there is a trend towards less reliance on these two countries.

Despite the increased globalization of wind power capacity additions, the market remains concentrated regionally. Latin America, Africa and the Middle East, and the Pacific regions have installed relatively little wind power capacity. And, even in the regions of significant growth, most of that growth has occurred in a limited number of countries. In 2009, for example, 90% of wind power capacity additions occurred in the 10 largest markets, and 62% was concentrated in just two countries: China (14 GW, 36%) and the United States (10 GW, 26%).

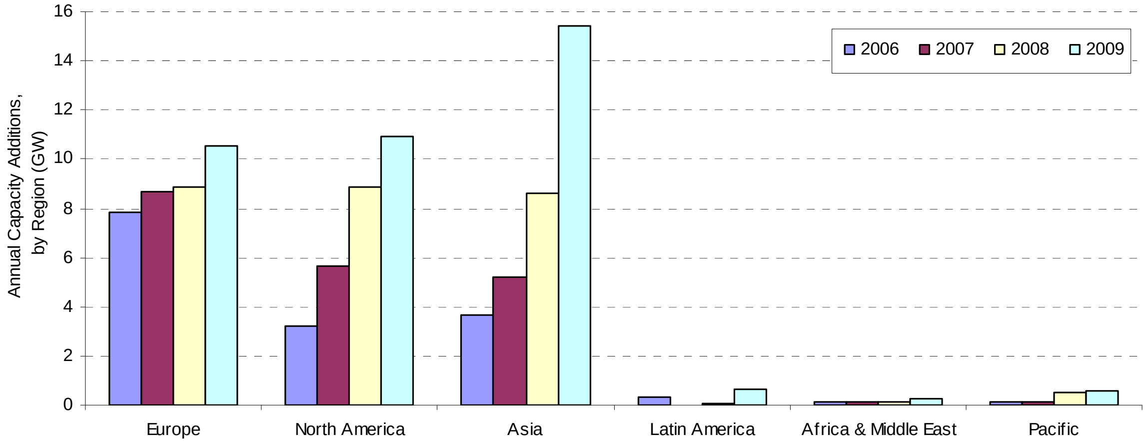

Figure 7.10. Annual wind power capacity additions by region (GWEC, 2010a).

In both Europe and the United States, wind energy represents a major new source of electric capacity additions. From 2000 through 2009, wind energy was the second-largest new resource added in the U.S. (10% of all gross capacity additions) and EU (33% of all gross capacity additions) in terms of nameplate capacity, behind natural gas, but ahead of coal. In 2009, 39% of all capacity additions in the U.S. and 39% of all additions in the EU came from wind energy (Figure 7.11). In China, 5% of the net capacity additions from 2000-2009 and 16% of the net additions in 2009 came from wind energy. On a global basis, from 2000 through 2009, wind energy represented roughly 11% of total net capacity additions; in 2009 alone, that figure was likely more than 20%.[16]

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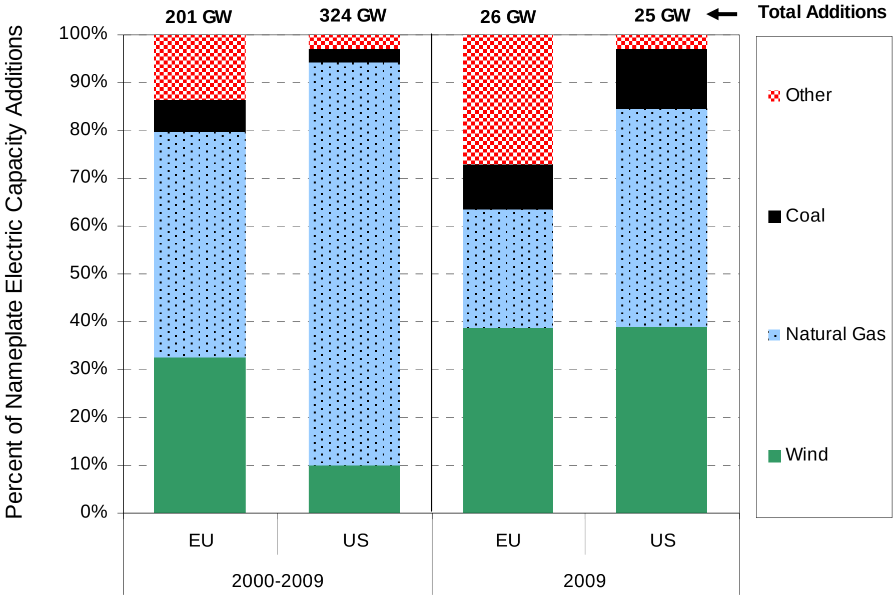
[16] Worldwide capacity additions from 2000 through 2007 come from historical data from the U.S. Energy Information Administration. Capacity additions for 2008 and 2009 are estimated based on historical capacity growth from 2000-2007.



Note: The "other" category includes other forms of renewable energy, nuclear energy, and fuel oil.

Figure 7.11. Relative contribution of electricity supply types to gross capacity additions in the EU and U.S. (EWEA, 2010b; Wiser and Bolinger, 2010).

As a result of this expansion, though wind energy remains a modest contributor to global electricity supply, a number of countries are beginning to achieve relatively high levels of wind electricity penetration in their respective electric systems. Figure 7.12 presents data on end-of-2009 (and end-of-2006/07/08) installed wind power capacity, translated into projected annual electricity supply, and divided by electricity consumption. On this basis, and focusing only on the 20 countries with the greatest cumulative wind power capacity, end-of-2009 wind power capacity is projected to be capable of supplying electricity equal to roughly 20% of Denmark's electricity demand, 14% of Portugal's, 14% of Spain's, 11% of Ireland's, and 8% of Germany's (Wiser and Bolinger, 2010).[17]

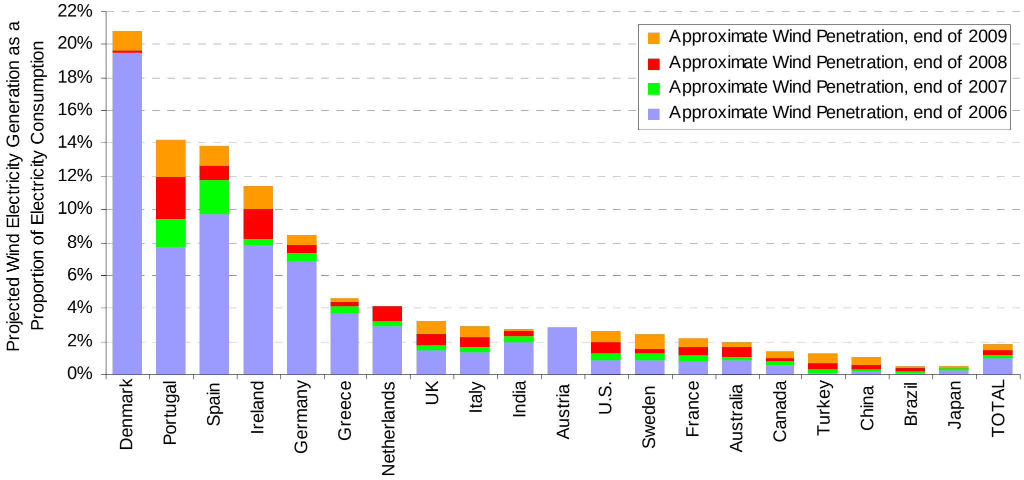


Figure 7.12. Approximate wind electricity penetration in the twenty countries with the greatest installed wind power capacity (Wiser and Bolinger, 2010).

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[17] Because of grid interconnections among electricity grids, these percentages do not necessarily equate to the amount of wind electricity consumed within each country.

7.4.3 Industry development

The growing maturity of the wind energy sector is illustrated not only by wind power capacity additions, but also by trends in the wind energy industry. In particular, companies from outside the traditional wind energy industry have become increasingly involved in the sector. For example, there has been a shift in the type of companies developing, owning, and operating wind power plants, from relatively small independent power plant developers towards large power generation companies (including electric utilities) and large independent power plant developers, often financed by investment banks. On the manufacturing side, the increase in the size of the wind energy market, along with manufacturing localization requirements in some countries, has brought in new players. The involvement of these new players has, in turn, encouraged a greater globalisation of the industry. Manufacturer product strategies are shifting to address larger scale power plants, higher capacity turbines, and lower wind speeds. More generally, the significant contribution of wind energy to new electric generation capacity investment in several regions of the world has attracted a broad range of players across the industry value chain, from local site-focused engineering firms to global vertically integrated utilities. The industry's value chain has also become increasingly competitive as a multitude of firms seek the most profitable balance between vertical integration and specialization (BTM, 2010; GWEC, 2010a).

Despite these trends, the global wind turbine market remains somewhat regionally segmented, with just six countries hosting the majority of wind turbine manufacturing (China, Denmark, India, Germany, Spain, and the U.S.). With markets developing differently, market share for turbine supply has been marked by the emergence of national industrial champions, entry of highly focused technology innovators, and the arrival of new start-ups licensing proven technology from other regions (Lewis and Wiser, 2007). Regardless, the industry continues to globalize: Europe's turbine and component manufacturers have begun to penetrate North America and Asia, and the growing presence of Asian manufacturers in Europe and North America is expected to become more pronounced in the years ahead. Chinese wind turbine manufacturers, in particular, are dominating their home market, are among the world's top manufacturers, and will increasingly seek export opportunities in the years ahead. Wind turbine sales and supply chain strategies are therefore expected to continue to take on a more international dimension as volumes increase.

Amidst the growth in wind power capacity also come challenges. From 2005 through 2008, supply chain difficulties caused by growing demand strained the industry, and prices for wind turbines and turbine components increased to compensate for this imbalance; commodity price increases and other factors also played a role in pushing wind turbine prices higher (see Section 7.8). Overcoming supply chain difficulties is not simply a matter of ramping up the production of wind turbine components to meet the increased levels of demand. After all, large-scale investment decisions are more easily made based on a sound long-term outlook for the industry. In most markets, however, both the projections and actual demand for wind energy depend on a number of factors, some of which are outside of the control of the industry, such as political frameworks and policy measures.

7.4.4 Impact of policies

The deployment of wind energy must overcome a number of barriers that vary in type and magnitude depending on the wind energy application and region. The most significant barriers to wind energy development are summarized here. Perhaps most importantly, in many regions of the world, wind energy remains more expensive than fossil-fuel generation options, at least if environmental impacts are not internalized and monetized (NRC, 2010b). Additionally, a number of other barriers exist that are at least somewhat unique to wind energy. The most critical of these barriers include: (1) concerns about the impact of wind energy's variability on electricity reliability; (2) challenges to building the new transmission infrastructure both on- and off-shore (and within country and cross-border) needed to enable access to the most-attractive wind resource areas; (3) cumbersome and slow planning, siting, and permitting procedures that impede wind energy development; (4) the relative immaturity and therefore high cost of off-shore wind energy technology; and (5) lack of institutional and technical knowledge in regions that have not experienced substantial wind energy development to this point.

As a result of these issues, growth in the wind energy sector is affected by and responsive to political frameworks and a wide range of government policies. During the past two decades, a significant number of developed countries and, more recently, a growing number of developing nations have laid out RE policy frameworks that have played a major role in the expansion of the wind energy market. These efforts have been motivated by the environmental, fuel diversity, and economic development impacts of wind energy deployment. An early significant effort to deploy wind energy at commercial scale occurred in California, with a feed-in tariff and aggressive tax incentives spurring growth in the 1980s (Bird *et al.*, 2005). In the 1990s, wind energy deployment moved to Europe, with feed-in tariff policies initially established in Denmark and Germany, and later expanding to Spain and then a number of other countries (Meyer, 2007); renewables portfolio standards have been implemented in other European countries and, more recently, European renewable energy policies have been motivated in part by the EU's binding 20%-by-2020 target for renewable energy. In the 2000s, growth in the U.S. (Bird *et al.*, 2005; Wiser and Bolinger, 2009), China (Li *et al.*, 2007; Li, 2010), and India (Goyal, 2010) was based on varied policy frameworks, including renewables portfolio standards, tax incentives, feed-in tariffs, and government-overseen bidding. Still other policies have been used in a number of countries to directly encourage the localization of wind turbine and component manufacturing (Lewis and Wiser, 2007).

Though economic support policies differ, and a healthy debate exists over the relative merits of different approaches, a key finding is that both policy transparency and predictability are important (see Chapter 11). Moreover, though it is not uncommon to focus on economic policies for wind energy, as noted above and as discussed elsewhere in this chapter and in Chapter 11, experience shows that wind energy markets are also dependent on a variety of other factors. These include local resource availability, site planning and approval procedures, operational integration concerns, transmission grid expansion, wind energy technology improvements, and the availability of institutional and technical knowledge in markets unfamiliar with wind energy (IEA, 2009a). For the wind energy industry, these issues have been critical in defining both the size of the market opportunity in each country and the rules for participation in those opportunities; many countries with sizable wind resources have not deployed significant amounts of wind energy as a result of these factors. Successful frameworks for the deployment of wind energy have generally included the following elements: support systems that offer adequate profitability and that ensure investor confidence; appropriate administrative procedures for wind energy planning, siting, and permitting; a degree of public acceptance of wind power plants to ease implementation; access to the existing transmission system and strategic transmission planning and new investment for wind energy; and proactive efforts to manage wind energy's inherent output variability and uncertainty. In addition, research and development by government and industry has been essential to enabling incremental improvements in on-shore wind energy technology and to driving the improvements needed in off-shore wind energy technology. Finally, for those markets that are new to wind energy deployment, both knowledge (e.g., wind resource mapping expertise) and technology (e.g., to develop local wind turbine manufacturers and to ease grid integration) transfer can help facilitate early installations.

7.5 Near-term grid integration issues

7.5.1 Introduction

As wind electricity penetration levels have increased so too have concerns about the integration of that energy into electric systems (e.g., Fox *et al.*, 2007). The nature and magnitude of the integration challenge will be system specific and will vary with the degree of wind electricity penetration. Nonetheless, the existing literature generally suggests that, at low to medium levels of wind electricity penetration (under 20% of total electricity demand), the integration of wind energy is technically and economically manageable, though institutional constraints will need to be overcome. Moreover, increased operating experience with wind energy along with improved technology and additional research should facilitate the integration of even greater quantities of wind energy without degrading electric system reliability.

The integration issues covered in this section include how to address wind power variability and uncertainty, how to provide adequate transmission capacity to connect wind power plants to electricity demand centres, and the development of connection standards and grid codes. The focus is on those issues faced at low to medium levels of wind electricity penetration (under 20%). Even higher levels of penetration may depend on the availability of additional flexibility options, such as mass-market demand response, large-scale deployment of electric vehicles and their associated contributions to system flexibility through controlled battery charging, increased deployment of other storage technologies, and improvements in the interconnections between electric systems; the deployment of a diversity of RE technologies may also help facilitate overall electric system integration. These options relate to broader developments within the energy sector that are not specific to wind energy, however, and are therefore addressed in Chapter 8.

This section begins by describing the specific characteristics of wind energy that present integration challenges (7.5.2). The section then discusses how these characteristics impact issues associated with the planning (7.5.3) and operation (7.5.4) of electric systems to accommodate wind energy, including experience in systems with high wind electricity penetration. The final section (7.5.5) summarizes the results of various integration studies that have sought to better quantify the technical and economic integration issues associated with increased wind electricity supply.

7.5.2 Wind energy characteristics

Integrating wind energy into electric systems relies on the same basic planning and operating tools that are used to ensure the reliable operation of electric systems without wind energy. Several important characteristics of wind energy are different from those of conventional generation, however, and these characteristics must be considered in electric system planning and operation.

First, the quality of the wind resource and therefore the cost of wind energy are location dependent. Because regions with the highest-quality wind energy resources may not be situated near high demand areas, additional transmission infrastructure is often needed to bring wind energy from the best wind resource sites to electricity demand centres (see Section 7.5.5).

Second, wind energy is weather dependent and therefore variable. The power output of a wind power plant varies from zero to its rated capacity depending on prevailing weather conditions; Figure 7.13 illustrates this variability by showing the output of an individual wind turbine, a small collection of wind power plants, and a large collection of wind power plants in Germany over ten consecutive days. The most relevant characteristic of wind power variability for electric system *operation* is the rate of change in wind power output over different time periods; Figure 7.13 demonstrates that the aggregate output of multiple wind power plants changes much more dramatically over longer periods (multiple hours) than over very short periods (minutes). The most relevant characteristic of wind power variability for the purpose of electric sector *planning*, on the other hand, is the correlation of wind power output with the periods of time when electric system reliability is at greatest risk, typically periods of high electricity demand. This correlation affects the capacity credit assigned by system planners to wind power, as discussed further in Section 7.5.3.4.

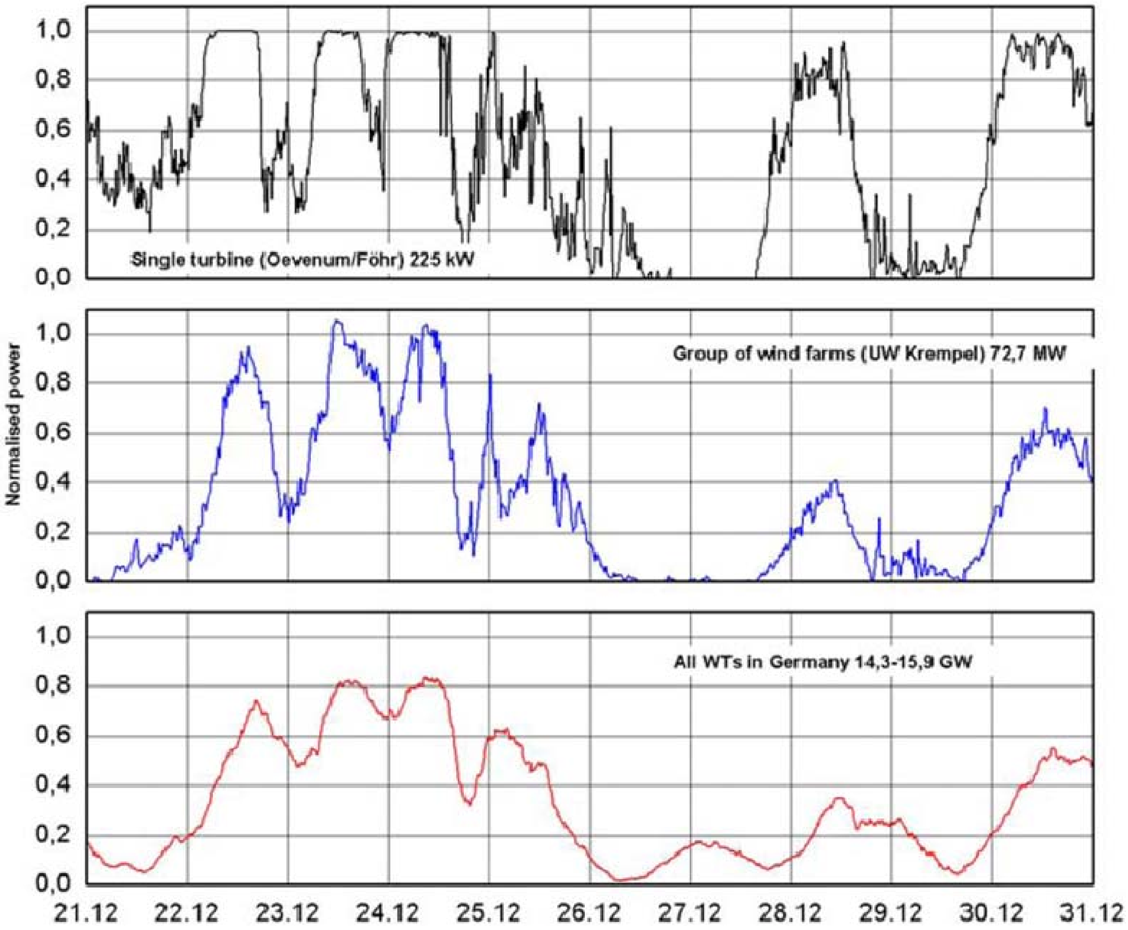

Figure 7.13. Example time series of wind power output normalised to wind power capacity for a single wind turbine, a group of wind power plants, and all wind power plants in Germany over a 10-day period in 2004 (Holttinen et al., 2009)

Third, in comparison with conventional power plants, wind power output has lower levels of predictability. Forecasts of wind power output use various approaches and have multiple goals, and significant improvements in forecast accuracy have been achieved in recent years (e.g., Costa *et al.*, 2008). Despite those improvements, however, forecasts are less accurate over longer forecast horizons (multiple hours to days) than over shorter periods (e.g., Madsen *et al.*, 2005 [TSU: reference missing]), which has implications for the ability of electric systems to manage wind power variability and uncertainty (Usaola, 2009; Weber, 2010).

The aggregate variability and uncertainty of wind power output depends, in part, on the degree of correlation in the output of geographically dispersed wind power plants. This correlation, in turn, depends on the geographic deployment of wind power plants and the regional characteristics of weather patterns, and especially wind speeds. Generally, the output of wind power plants that are further apart are less correlated, and variability over shorter time periods (minutes) is less correlated than variability over longer time periods (multiple hours) (e.g., Wan *et al.*, 2003; Sinden, 2007; Holttinen *et al.*, 2009; Katzenstein *et al.*, 2010). The output smoothing benefits of geographic diversity are illustrated in Figure 7.13: if the output of multiple wind turbines and power plants was perfectly correlated, then the aggregate variability would be equivalent to the scaled variability of a single wind turbine. Since correlation decreases with distance, however, the aggregate scaled variability shown for groups of wind power plants over a region is less than the scaled output of a single wind turbine. This output smoothing effect has implications for the variability of aggregate wind power output that electric systems must accommodate, and also influences forecast accuracy because accuracy improves with the number and diversity of wind power plants considered (e.g., Focken *et al.*, 2002).

7.5.3 Planning electric systems with wind energy

Ensuring the reliable operation of electric systems in real-time requires detailed system planning over the time horizons required to build new generation or transmission infrastructure. Planners must evaluate the adequacy of transmission to allow interconnection of new generation and the adequacy of generation to maintain a balance between supply and demand under a variety of operation conditions. Four planning issues deserve attention when considering increased reliance on wind energy: the need for accurate electric system models of wind turbines and power plants, the creation of interconnection standards (i.e., power quality and grid codes) that account for the characteristics of wind energy, the transmission infrastructure needs of wind energy, and the maintenance of overall resource adequacy with increased wind electricity penetration.

7.5.3.1 Electric system models

Computer-based simulation models are used extensively to evaluate the ability of the electric system to accommodate new generation, changes in demand, and changes in operational practices. An important role of electric system models is to demonstrate the ability of an electric system to recover from severe events or contingencies. Generic models of conventional synchronous generators have been developed and validated over a period of multiple decades. These models are used inside industry standard software tools (e.g., PSSE, DigSilent, etc.) to study how the electric system and all its components will behave during system events or contingencies. Similar generic models of wind turbines and wind power plants are in the process of being developed and validated. Because wind turbines are non-standard when compared to conventional synchronous generators, this modelling exercise requires significant effort. As a result, though considerable progress has been made, this progress is not complete and increased deployment of wind energy will require improved and validated models to allow planners to better assess the capability of electric systems to accommodate additional wind power plants (Coughlan *et al.*, 2007; NERC, 2009).

7.5.3.2 Power quality and grid codes

As wind power capacity has increased, so too has the need for wind power plants to become more active participants in maintaining (rather than passively depending on) the operability and power quality of the electric system. Focusing here primarily on the technical aspects of grid interconnection, the electrical performance of wind turbines in interaction with the grid is often verified in accordance with IEC 61400-21, in which methods to assess the impact of one or more wind turbines on power quality are specified (IEC, 2008b). Additionally, an increasing number of electric system operators have implemented minimum interconnection requirements (sometimes called “grid codes”) that wind turbines and/or wind power plants (and other power plants) must meet when connecting to the grid to prevent equipment or facilities from adversely affecting the electric system during normal operation and contingencies. Electric system models and operating experience are used to develop these requirements, which can then typically be met through modifications to wind turbine design or through the addition of auxiliary equipment such as power conditioning devices. In some cases, the unique characteristics of specific generation types are addressed in grid codes, resulting in wind-specific grid codes (e.g., Singh and Singh, 2009).

Grid codes often require “fault ride-through” capability, or the ability of a wind power plant to remain connected and operational during brief but severe changes in electric system voltage (Singh and Singh, 2009). The imposition of fault ride-through requirements on wind power plants responded to the increasing penetration of wind energy and the significant size of individual wind power plants. Electric systems can typically maintain reliable operation when small individual power plants shut-down or disconnect from the system for protection purposes in response to fault conditions. When a large amount of wind power capacity disconnects in response to a fault, however, that disconnection can exacerbate the fault conditions. Electric system planners have therefore increasingly specified that wind power plants should continue to remain operational during faults and meet minimum fault ride-through standards similar to other large conventional power plants. System wide approaches have also been adopted: in Spain, for example, wind power output may be curtailed in order to avoid potential reliability issues in the event of a fault; the need to employ this curtailment, however, is expected to decrease as fault ride-through capability is added to new and existing wind power plants (Rivier Abbad, 2010). Reactive power control to help manage voltage is also often required by grid codes, enabling wind turbines to improve voltage stability margins particularly in weak parts of the electric system (Vittal *et al.*, 2010). Requirements for wind turbine inertial response to improve system stability after disturbances are less common, but are increasingly being considered (Hydro-Quebec TransEnergie, 2006; Doherty *et al.*, 2010). Finally, active power control (including ramp-rate limits) and frequency control are sometimes required (Singh and Singh, 2009).

7.5.3.3 Transmission infrastructure

As noted earlier, the addition of large quantities of wind energy will require upgrades to the transmission system, in part because the strongest wind resources (whether on- or off-shore) are often located at a distance from load centres. Accurate transmission adequacy evaluations must account for the locational dependence of the wind resource, the relative smoothing benefits of aggregating wind power plants over large areas, and the transmission capacity required to manage the variability of wind energy (Burke and O'Malley, 2010). One of the primary challenges with transmission expansion to accommodate increased wind energy development is the long time it takes to plan, site, permit, and construct new transmission infrastructure relative to the relatively shorter period of time it takes to add new wind power plants. The institutional challenges of transmission expansion, including cost allocation and siting, can be substantial (e.g., Vajjhala and Fischbeck, 2007; Benjamin, 2007; Swider *et al.*, 2008). Enabling high penetrations of wind electricity may therefore require proactive rather than reactive transmission planning (Schumacher *et al.*, 2009). Estimates of the cost of the new transmission required to achieve low to medium levels of wind electricity penetration in a variety of locations around the world are summarized in Section 7.5.5.

7.5.3.4 Resource adequacy

Resource adequacy evaluations are used to assess the capability of generating resources to reliably meet electricity demand. Planners evaluate the long-term reliability of the electric system by estimating the probability that the system will be able to meet expected demand in the future, as measured by the load carrying capability of the system. Each electricity supply resource contributes some fraction of its name-plate capacity to the overall capability of the system, as indicated by the capacity credit assigned to the resource; the capacity credit is greater when power output is well-correlated with periods of time when there is a high risk of generation shortage. The capacity credit of a generator is therefore a “system” characteristic in that it is determined not only by the generator’s characteristics but also by the characteristics of the system to which that generator is connected.

The contribution of wind energy towards long-term reliability can be evaluated using standard approaches, and wind power plants are typically found to have a capacity credit of 5-40% of name-plate capacity (Holttinen *et al.*, 2009). The correlation between wind power output and electrical demand is an important determinant of the capacity credit of an individual wind power plant. In many cases, wind power output is uncorrelated or is weakly negatively correlated with periods of high electricity demand, reducing the capacity credit of wind power plants; this is not always the case, however, and wind power output in the UK has been found to be weakly positively correlated with periods of high demand (Sinden, 2007). These correlations are case specific as they depend on the diurnal, seasonal, and yearly characteristics of both wind power output and electricity demand. A second important characteristic of the capacity credit for wind energy is that its value decreases as wind electricity penetration levels rise because increased deployment of wind energy shifts the periods of greatest electric system risk to times with lower average levels of wind power output (Hasche *et al.*, 2010). Aggregating wind power plants over larger areas reduces the correlation between wind power outputs, as described earlier, and can therefore slow the decline in capacity credit as wind electricity penetration increases, though adequate transmission capacity is required to aggregate wind power plants over larger areas (Tradewind, 2009; EnerNex Corp, 2010).[18]

The relatively low average capacity credit of wind power plants (compared to conventional fossil units, for example) suggests that systems with large amounts of wind energy will also tend to have significantly more total nameplate generation capacity to meet the same peak load than will an electric system without large amounts of wind energy. Some of this generation capacity will operate infrequently, however, and the mix of conventional generation in an electric system with large amounts of wind energy will therefore increasingly shift towards “peaking” resources and away from “baseload” resources (e.g., Lamont, 2008; Milborrow, 2009; Boccard, 2010).

7.5.4 Operating electric systems with wind energy

The unique characteristics of wind energy, and especially power output variability and uncertainty, also hold important implications for electric system operations. Here we summarize those implications in general (Section 7.5.4.1), and then briefly discuss three specific case studies of the integration of wind energy into real electricity systems (Section 7.5.4.2).

7.5.4.1 Integration, flexibility, and variability

Because wind electricity is generated with a near-zero marginal operating cost, it is typically used to meet demand when it is available, thereby displacing the use of conventional generators that have higher marginal costs. This results in electric system operators and markets primarily dispatching conventional generators to meet demand minus any available wind energy (i.e., “net demand”[19]).

As wind electricity penetration grows, the variability of wind energy results in an overall increase in the magnitude of changes in net demand, and also a decrease in the minimum net demand. Figure 7.14 shows that, at relatively low levels of wind electricity penetration (7.5% of total electricity demand from wind energy), the magnitude of changes in net demand, as shown in the 15-minute ramp duration curve, is similar to the magnitude of changes in total demand (Figure 7.14(c)). At higher levels of wind electricity penetration (40% of total electricity demand from wind energy), however, the changes in net demand are greater than changes in total demand (Figure 7.14(d)). The figure also shows that, at high levels of wind electricity penetration, the magnitude of net demand

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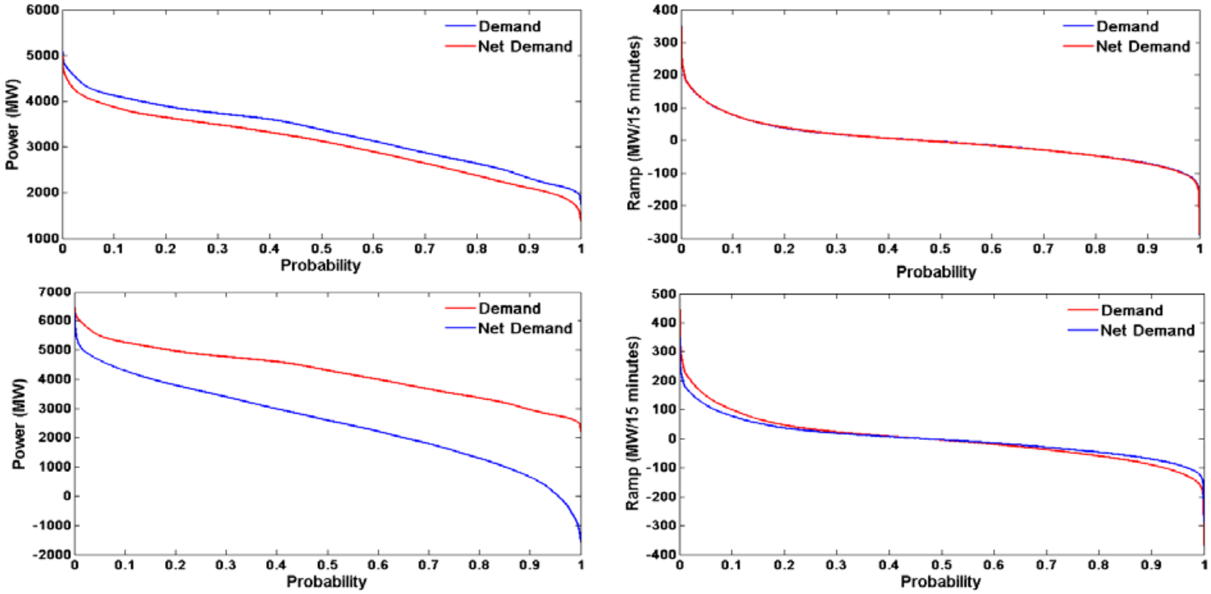
[18] Generation resource adequacy evaluations are also beginning to include the capability of the system to provide adequate flexibility and operating reserves to accommodate more wind energy (NERC, 2009). The increased demand from wind energy for operating reserves and flexibility is addressed in Section 7.5.4.

[19] Net demand is defined as total electrical demand minus wind electricity supply.

across all hours of the year is lower than total demand, and that in some hours the net demand is near or even below zero (Figure 7.14(b)).



(a) Demand duration curve

(c) Ramp duration curve

(b) Demand duration curve (projected)

(d) Ramp duration curve (projected)

Figure 7.14. Demand duration and 15-minute ramp duration curves for Ireland in (a,c) 2008 (7.5% wind electricity penetration), and (b,d) projected for high wind electricity penetration levels (40%).[20] Source: Data from www.eirgrid.com

As a result of these trends and the underlying variability and uncertainty in wind power output, wholesale electricity prices will tend to decline when wind power output is high, with a greater frequency of low or even negative prices (e.g., Jonsson *et al.*, 2010 [TSU: reference missing]). Increased wind electricity penetrations will therefore tend to reduce average wholesale prices in the short-term, though in the long-run the average effect of wind energy on wholesale prices is not as clear as pricing signals begin to influence decisions about the type of new generation that is built (Lamont, 2008; Sensfuß *et al.*, 2008; Sáenz de Miera *et al.*, 2008; MacCormack *et al.*, 2010).

These price impacts are a reflection of the fact that increased wind energy deployment will require conventional generating units to operate in a more flexible manner than required without wind energy. At low to medium levels of wind electricity penetration, the increase in *minute-to-minute* variability is expected to [TSU: be] relatively small and therefore inexpensive to manage in large electric systems (Smith *et al.*, 2007). The more significant operational challenges relate to the variability and commensurate increased need for flexibility to manage changes in wind power output over *1 to 6 hours* (Doherty and O'Malley, 2005). Incorporating state-of-the-art forecasting of wind energy over multiple time horizons into electric system operations can reduce the need for flexibility and operating reserves, and has been found to be especially important with high levels of wind electricity penetration (e.g., Doherty *et al.*, 2004; Tuohy *et al.*, 2009; GE Energy, 2010). Even with high-quality forecasts and geographically dispersed wind power plants, however, additional start-ups and shut-downs, part-load operation, and ramping will be required from conventional units to maintain the supply/demand balance (e.g., Göransson and Johnsson, 2009; Troy *et al.*, 2010).

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[20] Projected demand and ramp duration curves are based on scaling 2008 data (demand is scaled by 1.27 and wind power is scaled on average by 7). Ramp duration curves show the cumulative probability distributions of 15-minute changes in demand and net demand.

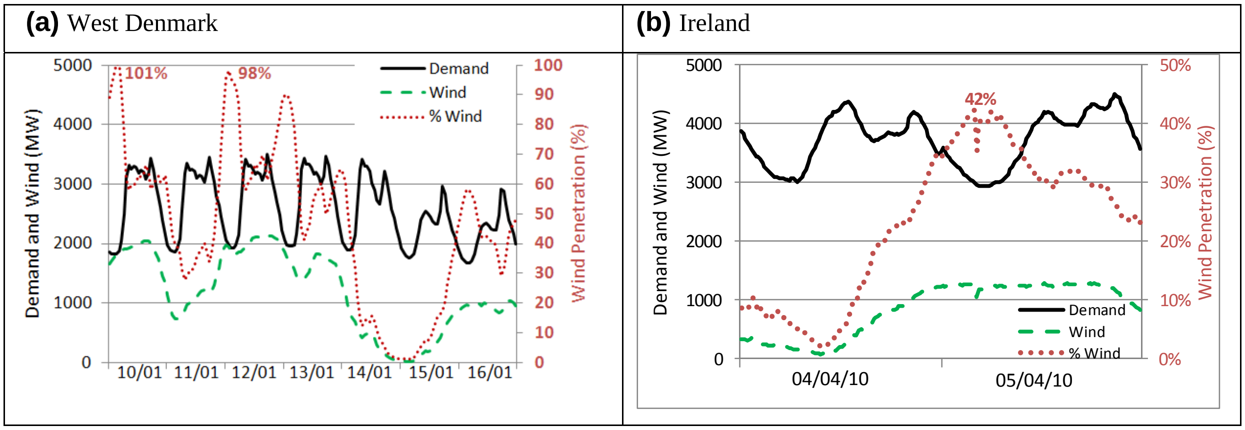
This additional flexibility is not free, as it increases wear and tear on boilers and other equipment, increases maintenance costs, and reduces power plant life (Denny and O'Malley, 2009). Various kinds of economic incentives can be used to ensure that the operational flexibility of conventional generators is made available to system operators. Some electricity systems, for example, have day-ahead, intra-day, and/or hour-ahead markets for electricity, as well as markets for reserves, balancing energy, and other ancillary services. These markets can provide pricing signals for increased (or decreased) flexibility when needed as a result of rapid changes in or poorly predicted wind power output, and can therefore reduce the cost of integrating wind energy (Smith *et al.*, 2007). Markets with shorter scheduling periods have also been found to be more responsive to variability and uncertainty in net load, and thereby facilitate wind energy integration (Kirby and Milligan, 2008), as have coordinated system operations across larger areas (Milligan and Kirby, 2008). Where wholesale electricity markets do not exist, other planning methods or incentives would be needed to ensure that existing conventional plants are flexible enough to accommodate increased deployment of wind energy. Planning systems and incentives may also need to be adopted to ensure that new conventional plants are sufficiently flexible to accommodate expected wind energy deployment. Moreover, in addition to flexible fossil units, hydropower stations, electrical storage, and various forms of demand response can also be used to facilitate the integration of wind energy. Wind power plants, meanwhile, can provide some flexibility by curtailing output or by limiting or even (partially) controlling ramp rates. Though curtailing wind power output is a simple and often times readily available source of flexibility, it is expensive to curtail plants that have low operating costs before reducing the output from conventional plants that have high fuel costs; as a result, wind power curtailment is not likely to be used extensively for this purpose, at least at low levels of wind electricity penetration.

7.5.4.2 Practical experience with operating electric systems with wind energy

Actual operating experience in different parts of the world demonstrates that wind energy can be reliably integrated into electric systems (Söder *et al.*, 2007). In some countries, as discussed earlier, wind energy already supplies in excess of 10% of annual electricity demand. The three examples reported here demonstrate the challenges associated with this operational integration, and the methods used to manage the additional variability and uncertainty associated with wind energy. Naturally, these impacts and management methods vary across regions for reasons of geography, electric system design, and regulatory structure.

Denmark has the largest wind electricity penetration of any country in the world, with wind energy supply equating to approximately 20% of total annual electricity demand. Total wind power capacity installed by the end of 2009 equalled 3.4 GW on a system with a peak demand of 6.5 GW. Much of the wind power capacity (2.7 GW) is located in Western Denmark, resulting in instantaneous wind power output exceeding total demand in some instances (see Figure 7.15). The Danish example demonstrates the value of access to markets for flexible resources and strong transmission connections to neighbouring countries. The Danish system operates without serious reliability issues in part because Denmark is well interconnected to two different synchronous electric systems. In conjunction with wind power output forecasting, this allows wind electricity to be exported to other markets and helps the Danish operator manage wind power variability. The interconnection with the Nordic system, in particular, provides access to flexible hydropower resources. Balancing the Danish system is much more difficult during periods when one of the interconnections is down, however, and more flexibility is expected to be required if Denmark markedly increases its penetration of wind electricity (EA Energianalyse, 2007).

In contrast to the strong interconnections of the Danish system with other electric systems, the island of Ireland has a single synchronous system; it is of similar size system to the Danish system but interconnection capacity is limited to a single 500 MW link. The wind power capacity installed by the end of 2009 was capable of supplying roughly 11% of Ireland's annual electricity demand, and the Irish system operators have successfully managed that level of wind electricity penetration. The large daily variation in electricity demand in Ireland, combined with the isolated nature of the Irish system, has resulted in a very flexible electric system that is particularly well suited to integrating wind energy. As a result, despite the lack of significant interconnection capacity, the Irish system has successfully operated with instantaneous levels of wind electricity penetration of over 40% (see Figure 15). Nonetheless, it is recognized that as wind electricity penetration levels increase further, new challenges will arise. Of particular concern is the possible lack of inertial response of wind turbines without additional turbine controls (Lalor *et al.*, 2005), the need for greater flexibility to maintain supply-demand balance, and the need to build substantial amounts of additional high-voltage transmission (AIGS, 2008). Moreover, in common with the Danish experience, much of the wind energy is and will be connected to the distribution system, requiring attention to reactive power control issues (Vittal *et al.*, 2010). Figure 7.15 illustrates the high levels of wind electricity penetration that exist in Ireland and West Denmark.


(a) West Denmark

(b) Ireland

Figure 7.15. Wind energy, electricity demand, and instantaneous penetration levels in (a) West Denmark for a week in January 2005, and (b) the island of Ireland for two days in April 2010. Source: Data from (a) www.energinet.dk; (b) www.eirgrid.com and SONI.

The Electric Reliability Council of Texas (ERCOT) operates a synchronous system with a peak demand of 63 GW and 8.5 GW of wind power capacity, and with a wind electricity penetration level of 6% of annual electricity demand by the end of 2009. ERCOT's experience demonstrates the importance of incorporating wind energy forecasts into system operations, and the need to schedule adequate reserves to accommodate system uncertainty. During February 26, 2008 a combination of factors led ERCOT to implement its emergency curtailment plan. On that day, ERCOT experienced a decline in wind power output of 1,500 MW over a three hour period, roughly 30% of the installed nameplate wind power capacity (Ela and Kirby, 2008; ERCOT, 2008). The event was exacerbated by the fact that scheduling entities – which submit updated resource schedules to ERCOT one hour prior to the operating hour – consistently reported an expectation of more wind power output than actually occurred. A state-of-the-art forecast was available, but was not yet integrated into ERCOT system operations, and that forecast predicted the wind energy event much more accurately. As a result of this experience, ERCOT accelerated its schedule for incorporating the advanced wind energy forecasting system into its operations.

7.5.5 Results from integration studies

In addition to actual operating experience, a number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed, covering many different regions of the world. These studies employ a wide variety of methodologies and have diverse objectives, but typically seek to quantify the costs and benefits of integrating wind energy into electric systems. The costs considered by these studies often include the need for additional transmission, the requirement to maintain sufficient resource adequacy, and the operating reserves required to accommodate the increased variability and uncertainty caused by wind energy. Benefits might include reduced fossil fuel usage and the CO_2 emissions savings from displaced conventional plants.

The results of these studies, as described in more detail below, demonstrate that the cost of integrating up to 20% wind electricity into electric systems is, in most cases, modest but not insignificant. Specifically, at low to medium levels of wind electricity penetration, the available literature suggests that the additional costs of managing electric system variability and uncertainty, ensuring resource adequacy, and adding new transmission to accommodate wind energy will generally not exceed 30% of the generation cost of wind energy.[21] That said, concerns about (and the costs of) wind energy integration will grow with wind energy deployment and, even at medium penetration levels, integration issues must be actively managed.

Addressing all integration impacts requires several different simulation models that operate over different time scales, and most studies therefore focus on a subset of the potential issues. The results of wind energy integration studies are also dependent on pre-existing differences in electric system designs and regulatory environments: important differences include generation capacity mix and the flexibility of that generation, the variability of demand, and the strength and breadth of the transmission system. Finally, study results differ because a standard methodology has not been developed for these studies, though significant progress has been made in developing agreement on many high-level study design principles (Holttinen *et al.*, 2009).

One of the most significant challenges in executing these studies is simulating wind power output data at high-time-resolutions for a chosen future wind electricity penetration level and for a sufficient duration for the results of the analysis to be statistically reliable. The data are then used in electric system simulations to mimic system planning and operations, thereby quantifying the costs, emissions savings, and transmission needs of high wind electricity penetrations. The first-generation integration studies used models that were not designed to fully reflect the variability and uncertainty of wind energy, resulting in studies that addressed only parts of the larger system. More recent studies have used models that can incorporate the uncertainty of wind power output from the day-ahead time scale to some hours ahead of delivery (e.g., Meibom *et al.*, 2009; Tuohy *et al.*, 2009). In additional, integration studies are increasingly simulating high wind electricity penetration scenarios over entire synchronized systems (not just individual, smaller balancing areas) (e.g., Tradewind, 2009; EnerNex Corp, 2010; GE Energy, 2010).

Regardless of the challenges to executing such studies, a number of significant wind energy integration studies in Europe and the U.S. have concluded that accommodating wind electricity penetrations of up to (and in a limited number of cases, exceeding) 20% is technically feasible, but not without challenges (Gross *et al.*, 2007; Smith *et al.*, 2007; Holttinen *et al.*, 2009; Milligan *et al.*, 2009). The estimated increase in short-term reserve requirements in eight studies summarized by Holttinen *et al.* (2009) has a range of 1-15% of installed wind power capacity at 10% wind electricity penetration, and 4-18% of installed wind power capacity at 20% wind electricity penetration. Those studies that predict a need for higher levels of reserves generally assume that day-ahead uncertainty and/or multi-hour variability of wind power output is handled with short-term reserves. In contrast, markets that are optimized for wind energy will generally be designed so

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[21] Section 8 estimates that the levelized cost of on-shore wind energy in 2009 ranged from US$50-150/MWh. As reported below, the high-end of the cost range for managing wind energy's variability and uncertainty ($5/MWh), ensuring resource adequacy (US$10/MWh), and adding new transmission (US$15/MWh) sums to $30/MWh, or roughly 30% of the mid-point of the 2009 levelized cost of on-shore wind energy (US$100/MWh).

that additional opportunities to balance supply and demand exist, reducing the reliance on more-expensive short-term reserves (e.g., Weber, 2010). Notwithstanding these differences in results and methods, however, the studies reviewed by Holttinen *et al.* (2009) find that, in general, wind electricity penetrations of up to 20% can be accommodated with increased system operating costs of roughly US$1.4–5.6/MWh of wind energy generated. Similar results are found by Gross *et al.* (2007), Smith *et al.* (2007), and Milligan *et al.* (2009). State-of-the-art wind power forecasts are often found to be a key factor in minimizing the impact of wind energy on market operations.

The benefits of adding a wind power plant to an electric system are often compared to the benefits of a baseload, or fully utilized, plant that generates an equivalent amount of energy on an annual basis. Using this framework, Gross *et al.* (2007) and Boccard (2010) estimate that the difference between the contribution to resource adequacy of a wind power plant and an energy-equivalent baseload plant can result in a US$5-10/MWh resource adequacy cost for wind energy at electricity penetration levels up to 20%. As discussed earlier, the correlation of wind power output to electricity demand, the geographic distribution of wind power plant siting, and the level of wind electricity penetration will all impact the capacity value of wind energy, and therefore this relative cost of resource adequacy.

Finally, several broad assessments of the need for and cost of transmission for wind energy have similarly found modest, but not insignificant, costs. The transmission cost for 300 GW of wind power capacity in the United States was estimated to add about $150-$300/kW to the installed cost of wind power plants (US DOE, 2008). More-detailed assessments of the transmission needed to accommodate increased wind energy deployment in the U.S. have found a wider range of results, with estimated costs sometimes reaching (or even exceeding) $400/kW (JCSP, 2009; Mills *et al.*, 2009; EnerNex Corp, 2010). Large-scale transmission for wind energy has also been considered in Europe (Czisch and Giebel, 2000) and China (Lew *et al.*, 1998). Results from country specific transmission assessments in Europe have resulted in varied estimates of the cost of transmission; Auer *et al.* (2004) and EWEA (2005) identified transmission costs for a number of European studies, with cost estimates that are somewhat lower than those found in the U.S. Holttinen *et al.* (2009) review wind energy transmission costs from several European national case studies, and find costs as high as $350/kW. At the high end of the range from the available literature ($400/kW), these costs would add roughly $15/MWh to the levelized cost of wind energy. Transmission expansion for wind energy can be justified by the reduction in congestion costs that would occur for the same level of wind energy deployment without transmission expansion. A European-wide study, for example, identified several transmission upgrades between nations and between high quality off-shore wind resource areas that would reduce transmission congestion and ease wind energy integration for a 2030 scenario (Tradewind, 2009). The avoided congestion costs associated with transmission expansion are similarly found to justify transmission investments in two U.S.-based detailed integration studies of high wind electricity penetrations (Milligan *et al.,* 2009).

7.6 Environmental and social impacts

Wind energy has significant potential to reduce (and already is reducing) GHG emissions, together with the emissions of other air pollutants, by displacing fossil fuel-based electricity generation. Because of the commercial readiness (Section 7.3) and cost (Section 7.8) of the technology, wind energy can be immediately deployed on a large scale (Section 7.9). As with other industrial activities, however, wind energy also has the potential to produce some detrimental impacts on the environment and on human beings, and many local and national governments have established planning, permitting, and siting requirements to minimize those impacts. These potential concerns need to be taken into account to ensure a balanced view of the advantages and disadvantages of wind energy. This section summarizes the best available knowledge on the most relevant environmental net benefits of wind energy (7.6.1), while also addressing ecological (7.6.2) and human impacts (7.6.3), public attitudes and acceptance (7.6.4), and processes for minimizing social and environmental concerns (7.6.5).

7.6.1 Environmental net benefits of wind energy

The environmental benefits of wind energy come primarily from a reduction of emissions from fossil fuel-based electricity generation. However, the manufacturing, transport, and installation of wind turbines induces some indirect negative effects, and the variability of wind power output also impacts the operations and emissions of conventional plants; such effects need to be subtracted from the gross benefits to begin to estimate the net benefits of wind energy. As shown below, these latter effects are modest compared to the net GHG reduction benefits of wind energy.

7.6.1.1 Direct impacts

The major environmental benefits of wind energy (as well as other forms of RE) result from displacing electricity generation from fossil-fuel based power plants, as the operation of wind turbines does not directly emit greenhouse gases or other air pollutants. In addition, by lowering the need for other forms of electricity supply, wind energy can reduce the need for cooling water for steam generators, the waste ash produced by coal generation, and the adverse impacts of coal mining and natural gas drilling.

Estimating the environmental benefits of wind energy is somewhat complicated by the operational characteristics of the electric system and the investment decisions that are made in new power plants to economically meet electricity load (Deutsche Energie-Agentur, 2005; NRC, 2007). In the short-run, increased wind energy will typically displace the operations of existing fossil plants that are otherwise on the margin. In the longer-term, however, new generating plants may be needed, and the presence of wind energy will influence what types of power plants are built in the future; specifically, increased wind energy will tend to favour peaking plants over baseload units (Kahn, 1979; Lamont, 2008). Because the impact of these factors are both complicated and system specific, the benefits of wind energy will also be system specific and are difficult to forecast with precision.

Despite these complications, it is clear that the direct impact of wind energy is to reduce air pollutants and GHG emissions. Depending on the characteristics of the electric system into which wind energy is integrated and the amount of wind energy supply, the reduction of air pollution and GHG emissions may be substantial. Globally, it has been estimated that the roughly 160 GW of wind power capacity already installed by the end of 2009 could generate 340 TWh/y of electricity and save more than 200 MMT CO_2/y (GWEC, 2010b).

7.6.1.2 Indirect lifecycle impacts

One indirect impact of wind energy arises from the release of GHGs and air pollutants during the manufacturing, transport, and installation of wind turbines, and their subsequent decommissioning. Life-cycle assessment (LCA) procedures based on ISO 14040 and ISO 14044 standards (ISO, 2006) have been used to analyze these impacts. Though these studies may include a range of impact categories, LCA studies for wind energy have often been used to determine the life-cycle GHG emissions per unit of wind-electricity generated (allowing for full fuel-cycle comparisons with other forms of electricity production) and the energy payback time of wind power plants (i.e., the time it takes a wind turbine to generate an amount of electricity equivalent to that used in its manufacture and installation). The results of a number of these recent LCA studies are summarized in Table 7.3.

Table 7.3. Wind energy carbon intensity and energy payback from various LCA studies

Article	Wind Turbine Size	Location	Capacity Factor	Energy Payback (years)	Carbon Intensity (gCO_2/kWh)
Schleisner (2000)	0.5 MW	on-shore	43.5%	0.26	9.7
Krohn (1997)	0.6 MW	on-shore	n/a	0.25	n/a
Voorspools (2000)	0.6 MW	on-shore*	n/a	n/a	27
Jungbluth *et al.* (2005)	0.8 MW	on-shore	20%	n/a	11
Pehnt (2006)	1.5 MW	on-shore	n/a	n/a	10.2
Elsam Engineering (2004)	2.0 MW	on-shore	n/a	0.65	7.6
Martínez *et al.* (2009)	2.0 MW	on-shore	23%	0.40	n/a
Vestas (2006)	3.0 MW	on-shore	30%	0.55	4.6
Tremeac and Meunier (2009)	4.5 MW	n/a	30%	0.58	15.8
Schleisner (2000)	0.5 MW	off-shore	40%	0.39	16.5
Voorspools (2000)	0.6 MW	off-shore*	n/a	n/a	9.2
Elsam Engineering (2004)	2.0 MW	off-shore	n/a	0.75	7.6
Jungbluth *et al.* (2005)	2.0 MW	off-shore	30%	n/a	13
Pehnt (2006)	2.5 MW	off-shore	n/a	n/a	8.9
Vestas (2006)	3.0 MW	off-shore	54%	0.57	5.2
Vattenfall (2003)	Not stated	n/a	n/a	n/a	14

* In Voorspools (2000), on-shore is described as “inland” and off-shore is described as “coastal”

The reported carbon intensity (in gCO_2/kWh) and energy payback (in years) of wind energy are low, but vary somewhat among published LCA studies, reflecting both methodological differences and differing assumptions about the life cycle of wind turbines. The carbon intensity of wind energy estimated by the studies included in Table 7.3 ranges from 4.6 to 27 gCO_2/kWh. Where studies have identified the significance of different stages of the life cycle of a wind power plant, it is clear that emissions from the manufacturing stage dominate overall life-cycle GHG emissions (e.g., Jungbluth *et al.*, 2005). Energy payback times for the studies presented in Table 7.3 suggest that the embodied energy of modern wind turbines is repaid in 3 to 9 months of operation.

7.6.1.3 Indirect variability impacts

Another concern that is sometimes raised is that the temporal variability and limited predictability of wind energy will limit the GHG emissions benefits of wind energy by increasing the short-term balancing reserves required for an electric system operator to maintain reliability (relative to the balancing reserve requirement without wind energy). Short-term reserves are generally provided by generating plants that are online and synchronized with the grid, and plants providing these reserves may be part-loaded to maintain flexibility to respond to short-term fluctuations. Part-loading fossil fuel-based generators decreases the efficiency of the plants and therefore creates a fuel efficiency and GHG emissions penalty relative to a fully-loaded plant. Analyses of the emissions benefits of wind energy do not always account for this effect.

The UK Energy Research Centre performed an extensive literature review of the costs and impacts of variable electricity supply; over 200 reports and articles were reviewed (Gross *et al.*, 2007). The review included a number of analyses of the fuel savings and GHG emissions benefits[22] of wind energy that accounted for the increase in necessary balancing reserves and the reduction in part-load efficiency of conventional plants. The efficiency penalty due to the variability of wind power output in four studies that explicitly addressed the issue ranged from near 0% to as much as 7%, for up to 20% wind electricity penetration (Gross *et al.*, 2006). In short, for moderate levels of wind electricity penetration, "there is no evidence available to date to suggest that in aggregate efficiency reductions due to load following amount to more than a few percentage points" (Gross and Heptonstall, 2008).[23]

7.6.1.4 Net environmental benefits

The precise balance of positive and negative environmental and health effects of wind energy is system specific, but can in general be documented by the difference in estimated external costs for wind energy and other electricity supply options, as shown in Chapter 10. Monetized figures for climate change damages, human health impacts, material damages, and agricultural losses show significant benefits from wind energy (e,g., Krewitt and Schlomann, 2006). Krewitt and Schlomann (2006) also qualitatively assess the direction of possible impacts associated with other damage categories (ecosystem effects, large accidents, security of supply, and geopolitical effects), finding that the net benefits of RE sources tend to be underestimated by not including these impacts in the monetized results. The environmental damages associated with conventional generation and benefits associated with wind energy have been summarized many times in the broader externalities literature (e.g., EC, 2003; Owen, 2004; Sundqvist, 2004; NRC, 2009).

7.6.2 Ecological impacts

There are, nonetheless, ecological impacts that need to be taken into account when assessing wind energy. Potential ecological impacts of concern for on-shore wind power plants include the population-level consequences of bird and bat collision fatalities and more-indirect habitat and ecosystem modifications. For off-shore wind energy, the aforementioned impacts as well as implications for benthic resources, fisheries, and marine life more generally must be considered. Finally, the possible consequences of wind energy on the local climate have received attention. The focus here is on impacts associated with wind power plants themselves, but associated infrastructures also have impacts to consider (e.g., transmission lines, transportation to site, etc.). Moreover, wind energy is not unique among energy sources in have ecological consequences; more-systematic assessments are needed to evaluate the *relative* impacts of different forms of energy supply, especially within the context of the varying contributions of these energy sources towards global climate change (see Chapter 9).

7.6.2.1 Bird and bat collision fatalities

Bird and bat fatalities through collisions with wind turbines are among the most publicized environmental concerns associated with wind power plants. Populations of many species of birds and bats are in decline, leading to concerns about the effects of wind energy on vulnerable species.

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[22] Because CO_2 emissions are generally proportional to fuel consumption for a single fossil-fuel plant, the CO_2 emissions penalty is similar to the fuel efficiency penalty.

[23] Katzenstein and Apt (2009) conclude that the efficiency penalty could be as high as 20%, but inaccurately assume that every wind power plant requires spinning reserves equivalent to the nameplate capacity of the wind plant. Accounting for the smoothing benefits of geographic diversity (see section 7.5) and the ability to commit and de-commit conventional thermal plants lowers the estimated efficiency penalty substantially (Mills *et al.*, 2009).

Though much remains unknown about the nature and population-level implications of these impacts, avian fatality rates are power plant- and species-specific, and can vary with region, site characteristics, season, weather, turbine size and design, and other factors. Focusing on all bird species combined, the U.S. National Research Council surveyed the available (limited) literature through early 2007 and found bird mortality estimates that range from 0.95 to 11.67 per MW per year (NRC, 2007); other results, including those from Europe, provide a reasonably similar range of estimates (e.g., (De Lucas *et al.*, 2004; Drewitt and Langston, 2006; Everaert and Stienen, 2007; Kuvlesky *et al.*, 2007). Though most of the bird fatalities reported in the literature are of songbirds (Passeriformes), which are the most abundant bird group in terrestrial ecosystems (e.g., Erickson *et al.*, 2005; NRC, 2007), raptor fatalities are considered to be of greater concern as their populations tend to be relatively small. Compared to songbird fatalities, raptor fatalities have been found to be relatively low; nonetheless, these impacts are site specific, and there are cases in which raptor fatalities (and the potential for population-level effects) have raised concerns (e.g., Barrios and Rodriquez, 2004; Kuvlesky Jr. *et al.*, 2007; NRC, 2007; Smallwood and Thelander, 2008). As off-shore wind energy has increased, concerns have also been raised about seabirds. The limited research to date does not suggest that off-shore wind power plants pose a disproportionately large risk to birds, relative to on-shore wind energy (e.g., Dong Energy *et al.*, 2006); Desholm and Kahlert (2005), for example, find that seabirds tend to detect and avoid large off-shore wind power plants.

Bat fatalities have not been researched as extensively as bird fatalities at wind power plants, and data allowing reliable assessments of bat fatalities are somewhat limited (Dürr and Bach, 2004; Kunz *et al.*, 2007b; NRC, 2007). Several wind power plants have reported sizable numbers of bat fatalities, but other studies have shown low fatality rates. Surveying the available literature through early 2007, the U.S. National Research Council reported observed bat fatalities ranging from 0.8 to 41.1 bats per MW per year (NRC, 2007); a later review of 21 studies by Arnett *et al.* (2008) found fatality rates of 0.2 to 53.3 bats per MW per year. The specific role of different influences such as site characteristics, weather conditions, and turbine size, placement, and operation remain somewhat uncertain due to the lack of extensive and comparable studies (e.g., Kunz *et al.*, 2007b; Arnett *et al.*, 2008). Because bats are long-lived and have low reproduction rates, because of the patterns of bat mortality at wind power plants (e.g., research has shown that bats may be attracted to wind turbine rotors), and because of uncertainty about the current size of bat populations, the impact of wind power plants on bat populations is of particular contemporary concern (e.g., Barclay *et al.*, 2007; Horn *et al.*, 2008).

Significant uncertainty remains on the causal mechanisms underlying fatality rates and the effectiveness of mitigation measures, leading to limited ability to predict bird and bat fatality rates. Nonetheless, *possible* approaches to reducing fatalities that have been reported include siting power plants in areas with lower bird and bat population densities, placing turbines in areas with low prey density, avoiding lattice support towers, and using different numbers and sizes of turbines. Recent research also suggests that curtailing the operation of wind turbines during low wind situations may result in considerable reductions in bat fatalities (Arnett *et al.*, 2009; Baerwald *et al.*, 2009).

The magnitude and population-level consequences of bird and bat collision fatalities can also be viewed in the context of other fatalities caused by human activities. The number of bird fatalities at wind power plants is orders of magnitude lower than other anthropogenic causes of bird deaths (e.g., vehicles, buildings and windows, transmission lines, communications towers, house cats, pollution and other contaminants) (Erickson *et al.*, 2005; NRC, 2007). Moreover, it has been suggested that wind power plants are not currently causing meaningful declines in bird population levels (NRC, 2007), and that other energy supply options also impact birds and bats through collisions, habitat modifications, and contributions to global climate change (Lilley and Firestone, 2008; Sovacool, 2009). These assessments are based on aggregate comparisons, however, and the cumulative population-level impacts of wind energy development on some species where biologically significant impacts are possible remain uncertain (especially vis-à-vis bats). Improved methods to assess these population-level impacts and their possible mitigation are needed (Kunz *et al.*, 2007a), especially as wind energy increases and in comparison to the impacts associated with other electricity supply options.

7.6.2.2 Habit and ecosystem modifications

The habitat and ecosystem modification impacts of wind power plants on flora and fauna include, but are not limited to, avoidance of or displacement from an area, habitat destruction, and reduced reproduction (e.g., Drewitt and Langston, 2006; NRC, 2007; Stewart *et al.*, 2007). The relative biological significance of these impacts, compared to bird and bat collision fatalities, remains unclear. Moreover, the nature of these impacts will depend in part on the ecosystem into which wind power plants are integrated. Wind power plants are often installed in agricultural landscapes or on brown-field sites. In such cases, very different habitat and ecosystem impacts might be expected compared to wind power plants that are sited on previously undisturbed forested ridges or native grasslands. The development of wind power plants in largely undisturbed forests may, for example, lead to additional habitat destruction and fragmentation for intact forest-dependent species due to forest clearing for access roads, turbine foundations, and power lines (e.g., Kuvlesky Jr. *et al.*, 2007; NRC, 2007). Because habitat modification impacts are highly site and species specific, they are ideally addressed (with mitigation measures) in the wind power plant siting process; concerns for these impacts have also led to broader planning ordinances in some countries prohibiting the construction of wind power plants in ecologically sensitive areas.

The impacts of wind power plants on marine life have moved into focus as wind energy developments start to go off-shore and, as part of the licensing procedures for off-shore wind power plants, numerous studies on the possible impacts of wind power plants on marine life and ecosystems have been conducted. As Michel *et al.* (2007) point out, there are ‘several excellent reviews... on the potential impacts of offshore wind parks on marine resources; most are based on environmental impact assessments and monitoring programs of existing offshore wind parks in Europe…’. The localized impacts of off-shore wind energy development on marine life depend greatly on site-specific conditions, and can be both negative and positive (e.g., Dong Energy *et al.*, 2006; Köller *et al.*, 2006; Michel *et al.*, 2007; Wilhelmsson and Malm, 2008; Punt *et al.*, 2009; Wilson and Elliott, 2009). Potential negative impacts include underwater sounds, electromagnetic fields, physical disruption, and the establishment of invasive species. The physical structures may, however, create new breeding grounds or shelters and act as artificial reefs or fish aggregation devices (e.g., Wilhelmsson *et al.*, 2006). Additional research is warranted on these impacts, especially in comparison to other sources of energy supply, but the impacts do not appear to be disproportionately large. In advance of conclusive findings, however, concerns about the impacts of off-shore wind energy on marine life and migrating bird populations have led to national zoning efforts in some countries that exclude the most-sensitive areas from development.

7.6.2.3 Impact of wind power plants on the local climate

The possible impact of wind power plants on the local climate has also been the focus of some research. Wind power plants extract momentum from the air flow and thus reduce the wind speed behind the turbines, and also increase vertical mixing by introducing turbulence across a range of length scales (Petersen *et al.*, 1998). These two processes are described by the term “wind turbine wake” (Barthelmie *et al.*, 2004). Though intuitively turbine wakes must increase vertical mixing of the near-surface layer, and thus may increase atmosphere-surface exchange of heat, water vapour, and other parameters, the magnitude of the effect remains uncertain. One study using blade element momentum theory suggests that even very large scale wind energy deployment, sufficient to supply global energy needs, would remove less than 1/10,000th of the total energy within the lowest 1 km of the atmosphere (Sta. Maria and Jacobson, 2009). Other studies have sought to quantify more-local effects by treating large wind power plants as a block of enhanced surface roughness length or an elevated momentum sink in regional and global models. These studies have typically analyzed scenarios of substantial wind energy deployment, and have found changes in local surface temperature of up to or even exceeding 1°C, and in surface winds of several meters per second (Keith *et al.*, 2004; Kirk-Davidoff and Keith, 2008; Wang and Prinn, 2010); these local effects could have secondary impacts on rainfall, clouds, and other climate variables. Though the global average impact of these more-local changes is much less pronounced, the local changes could have implications for ecosystems and humans.

The assumptions and methods used by these studies may not, however, accurately represent the mechanisms by which wind turbines interact with the atmosphere. Studies often incorrectly assume that wind turbines act as invariant momentum sinks; that turbine densities are above what is the norm; and that wind energy development occurs at a more substantial and geographically concentrated scale than is likely. Observed data and models from large off-shore wind power plants, for example, indicate that they may be of sufficient scale to perceptibly interact with the entire (relatively shallow) atmospheric boundary layer (Frandsen *et al.*, 2006), but on-site measurements and remotely sensed near-surface wind speeds suggest that wake effects from large developments may no longer be discernible in near-surface wind speeds and turbulence intensity at approximately 20 km downwind (Christiansen and Hasager, 2005, 2006; Frandsen *et al.*, 2009). As a result, the impact of wind energy on local climates remains uncertain. More generally, it should also be recognized that wind turbines are not the only structures to potentially impact local climate variables, and that any impacts caused by increased wind energy development should be placed in the context of other anthropogenic climate influences (Sta. Maria and Jacobson, 2009).

7.6.3 Impacts on humans

In addition to ecological consequences, wind energy development impacts humans in various ways. The primary impacts addressed here include land and marine usage, visual impacts, proximal impacts such as noise, flicker, health, and safety, and property value impacts.

7.6.3.1 Land and marine usage

Wind turbines are sizable structures, and wind power plants can encompass a large area (5-10 MW per km^2 is often assumed), thereby using space that might otherwise be used for other purposes. The land footprint specifically disturbed by on-shore wind turbines and their supporting roads and infrastructure, however, typically ranges from 2% to 5% of the total area encompassed by a wind power plant, allowing agriculture, ranching, and certain other activities to continue within the area. Some forms of land use may be precluded from the area, such as housing developments, airport approaches, and some radar installations. Nature reserves and historical and/or sacred sites are also often particularly sensitive. Somewhat similar issues apply for off-shore wind power plants.

The impacts of wind power plants on aviation, shipping, communications, and radar must also be considered, and depend on the placement of wind turbines and power plants. By avoiding airplane landing corridors and shipping routes, interference of wind power plants with shipping and aviation can be kept to a minimum (Hohmeyer *et al.*, 2005). Integrated marine spatial planning and integrated coastal zone management approaches are also starting to include off-shore wind energy, thereby helping to assess the ecological impacts and economic and social benefits for coastal regions of alternative marine and coastal uses, and to minimize conflict among those uses (e.g., Murawski, 2007; Ehler and Douvere, 2009; Kannen and Burkhard, 2009).

Electromagnetic interference (EMI) associated with wind turbines can come in various forms (e.g., Krug and Lewke, 2009). In general, wind turbines can interfere with detection of signals through reflection and blockage of electromagnetic waves and creation of large reflected radar returns, including Doppler produced by the rotation of turbine blades. Many EMI effects can be avoided by appropriate siting, for example, not locating wind turbines in close proximity to transmitters or receivers (Summers, 2000; Hohmeyer *et al.*, 2005). Moreover, there are no fundamental physical constraints preventing mitigation of EMI (Brenner, 2008). In the case of military (or civilian) radar, reports have concluded that radar systems can sometimes be modified to ensure that aircraft safety and national defence are maintained (Butler and Johnson, 2003; Brenner 2008). In particular, radar system may have to be replaced, upgraded, or gap filling and signal fusion systems installed, at some cost. In addition, research is underway to investigate wind turbine design changes that may mitigate adverse impacts by making turbines less reflective to radar systems. EMI impacts can also extend to TV, GPS, and communications systems and, where they exist, these impacts can generally be managed by appropriate siting of wind power plants and through technical solutions.

7.6.3.2 Visual impacts

Visual impacts, and specifically how wind turbines and related infrastructures fit into the surrounding landscape, are often among the top concerns of communities considering wind power plants (NRC, 2007; Wolsink, 2007; Wustenhagen *et al.*, 2007; Firestone and Kempton, 2007; Firestone *et al.*, 2009; Jones and Eiser, 2009), of those living near existing wind power plants (Thayer and Hansen, 1988; Krohn and Damborg, 1999; Warren *et al.*, 2005), and of institutions responsible for overseeing wind energy development (Nadaï and Labussière, 2009). To capture the strongest and most consistent winds, wind turbines are often sited at high elevations and where there are few obstructions relative to the surrounding area. Moreover, wind turbines and power plants have grown in size, making the turbines and related transmission infrastructure more visible. Finally, as wind power plants increase in number and geographic spread, plants are being located in a wider diversity of landscapes (and, with off-shore wind energy, unique seascapes as well), including more highly valued areas.

Though concerns about visibility cannot be fully mitigated, many jurisdictions require an assessment of visual impacts as part of the siting process, including defining the geographic scope of impact and preparing photo and video montages depicting the area before and after wind energy development. Other recommendations that have emerged to minimize visual intrusion include: using similar size and shaped wind turbines, using light coloured paints, choosing a smaller number of larger turbines over a larger number of smaller ones, undergrounding interconnection cabling, and ensuring that blades rotate in the same direction (e.g., Hohmeyer *et al.*, 2005). More generally, a rethinking of traditional concepts of "landscape" to include wind turbines has sometimes been recommended (Pasqualetti *et al.*, 2002) including, for example, setting aside areas where development can occur and others where it is precluded, especially when such planning allows for public involvement (Nadaï and Labussière, 2009).

7.6.3.3 Noise, flicker, health, and safety

A variety of proximal “nuisance” effects are also sometimes raised with respect to wind energy development, the most prominent of which is noise. Noise from wind turbines can be a problem especially for those living within close range. Although environmental noise guidelines (US EPA, 1974, 1978; WHO, 1999, 2009) are sufficient to ensure that direct health effects are avoided (e.g., hearing loss) (McCunney and Meyer, 2007), some nearby residents experience annoyance from wind turbine sound (Pedersen and Waye, 2007, 2008; Pedersen *et al.*, 2010). This annoyance is correlated with acoustic factors (e.g., sound levels and characteristics) and also with non-acoustic factors (e.g., visibility of, or attitudes towards, the turbines) (Pedersen and Waye, 2007, 2008;

Pedersen *et al.*, 2010). Concerns about noise emissions may be especially great when hub-height wind speeds are high, but ground-level speeds are low (i.e., conditions of high wind shear). Under such conditions, the lack of wind-induced background noise at ground level coupled with higher sound levels from the turbines has been linked to increased audibility and in some cases annoyance (Van den Berg, 2004, 2005, 2008; Prospathopoulos and Voutsinas, 2005).

Significant efforts have been made to reduce the sound levels emitted by wind turbines. As a result, mechanical sounds from modern wind turbines (e.g., gearboxes and generators) have been significantly reduced. Aero-acoustic noise is now the dominant concern (Wagner *et al.*, 1996), and some of the specific aero-acoustic characteristics of wind turbines (e.g., Van den Berg, 2005) have been found to be particularly detectable (Fastl and Zwicker, 2007) and annoying (Bradley, 1994; Bengtsson *et al.*, 2004 [TSU: references missing]). Reducing aero-acoustic noise can be most easily accomplished by reducing blade speed, but different tip shapes and airfoil designs have also been explored (Migliore and Oerlemans, 2004; Lutz *et al.*, 2007). Regardless of these efforts, wind turbines create noise, and predictive models and environmental regulations to manage these impacts have improved. Specifically, in some jurisdictions, both the wind shear and maximum sound power levels under all operating conditions are taken into account when establishing regulations (Bastasch *et al.*, 2006). Absolute maximum sound levels during the day (e.g., 55 dBA) and night (e.g., 45 dBA) can also be coupled with maximum levels that are set relative to pre-existing background sound levels (Bastasch *et al.*, 2006). In other jurisdictions, simpler and cruder set-backs mandate a minimum distance between turbines and other structures (MOE, 2009).

In addition to sound impacts, rotating turbine blades can also cast moving shadows (i.e., shadow flicker), which may be annoying to residents living close to wind turbines. Turbines can be sited to minimize these concerns, or the operation of wind turbines can be stopped during acute periods (Hohmeyer *et al.*, 2005). In some countries, the use of such operation control systems is mandated by licensing authorities. Finally, wind turbines can shed parts of or whole blades as a result of an accident or icing (or more broadly, shed ice that has built up on the blades, or collapse entirely). Wind energy technology certification standards are aimed at reducing such accidents, and injuries are rare or non-existent (see Section 7.3.3).

7.6.3.4 Property values

The visibility of wind power plants may translate into negative impacts on residential property values at the local level. Further, if various proximal nuisance effects are prominent, such as turbine noise, shadow flicker, health, or safety concerns, additional impacts to local property values may occur. Although these concerns may be reasonable given effects found for other environmental disamenities (e.g., high voltage transmission lines, fossil fuel power plants, and landfills; see Simons, 2006), published research has not found strong evidence of an effect for wind power plants (e.g., Sims and Dent, 2007; Sims *et al.*, 2008; Hoen *et al.*, 2009). This might be explained by the setbacks normally employed between homes and wind turbines; studies on the impacts of transmission lines on property values, for example, sometimes find that effects can fade at distances of 100m (e.g., Des Rosiers, 2002). Alternatively, any effects may be too infrequent and/or small to distinguish statistically. More research is needed on the subject, but based on other disamenity research (e.g., Boyle and Kiel, 2001; Jackson, 2001; Simons and Saginor, 2006), if any impacts do exist, it is likely that those effects are most pronounced within short distances of wind turbines, in the period immediately following wind power plant announcement, but fade over distance and time after a wind power plant is constructed (Wolsink, 2007).

7.6.4 Public attitudes and acceptance

Despite the possible impacts described above, surveys have consistently found wind energy to be widely accepted by the general public (e.g., Warren *et al.*, 2005; Jones and Eiser, 2009; Klick and Smith, 2010; Swofford and Slattery, 2010). Translating this broad support into increased deployment (closing the "social gap" – see e.g., Bell *et al.,* 2005), however, often requires the support of local host communities and/or decision makers (Toke, 2006; Toke *et al.*, 2008). To that end, a number of concerns exist that might temper the enthusiasm of these stakeholders towards wind energy, such as land and marine use, and the visual, proximal, and property value impacts discussed above. In general, research has found that public concern towards wind energy development is greatest directly after the announcement of a wind power plant, but that acceptance increases after construction when actual impacts can be assessed (Wolsink, 1989; Warren *et al.*, 2005; Eltham *et al.*, 2008). Some studies have found that those most familiar with existing wind power plants, including those who live closest to them, are more accepting (or less concerned) than those less familiar and further away (Krohn and Damborg, 1999; Warren *et al.*, 2005), but other research has found the opposite to be true (van der Horst, 2007; Swofford and Slattery, 2010). Possible explanations for this apparent discrepancy include differences in attitudes towards *proposed* versus *existing* wind power plants (Swofford and Slattery, 2010), the pre-existing characteristics and values of the local community (van der Horst, 2007), and the degree of trust that the local community has towards the development process and its outcome (Thayer and Freeman, 1987; Jones and Eiser, 2009). Research has also found that pre-construction attitudes can linger after the turbines are erected: for example, those opposed to a wind power plant's development have been found to consider the eventual plant to be noisier and more visually intrusive that those who favoured the same plant in the pre-construction time period (Krohn and Damborg, 1999; Jones and Eiser, 2009). Finally, some research has found that concerns can be compounding. For instance, those who found turbines to be visually intrusive also found the noise from those turbines to be more annoying (Pedersen and Persson Waye, 2004).

7.6.5 Minimizing social and environmental concerns

Regardless of the type and degree of social and environmental concerns, addressing them directly is an essential part of any successful wind power planning and plant siting process. To that end, involving the local community in the planning and siting process has sometimes been shown to improve outcomes (Loring, 2007; Toke *et al.*, 2008; Nadaï and Labussière, 2009; Jones and Eiser, 2009). This might include, for example, allowing the community to weigh in on alternative wind power plant and turbine locations, and improving education by hosting visits to existing wind power plants. Public attitudes have been found to improve when the development process is perceived as being transparent (Wolsink, 2000; Loring, 2007; Gross, 2007). Further, experience suggests that ownership of local wind power plants can improve public attitudes towards wind energy development (Wolsink, 2007; Gross, 2007; Jones and Eiser, 2009).

Proper planning for both on- and off-shore wind energy can also help to minimize social and environmental impacts, and a number of siting guideline documents have been developed (e.g., Nielsen, 1996; NRC, 2007; AWEA, 2008). Appropriate planning and siting will generally avoid placing wind turbines too close to dwellings, streets, railroad lines, airports, and shipping routes, and will avoid areas of heavy bird and bat activity; a variety of pre-construction studies are often conducted to define these impacts and their mitigation. Habitat fragmentation can often be minimized by careful placement of wind turbines and wind power plants and by proactive governmental planning for wind energy deployment. Examples of such planning can be found in many jurisdictions across the world.

Although an all-encompassing numerical comparison of the full external costs and benefits of wind energy is impossible, as some impacts are very difficult to monetize, available evidence suggests that the positive environmental and social effects of wind energy generally outweigh any negative impacts that remain after careful planning and siting procedures are followed (see, e.g., Jacobson, 2009). In practice, however, complicated and time-consuming planning and siting processes are key obstacles to wind energy development in some countries and contexts (e.g., Bergek, 2010; Gibson and Howsam, 2010). In part, this is because even if the environmental and social impacts of wind energy are minimized through proper planning and siting procedures and community involvement, some impacts will remain. Efforts to better understand the nature and magnitude of these remaining impacts, together with efforts to minimize and mitigate those impacts, will therefore need to be pursued in concert with increasing wind energy deployment.

7.7 Prospects for technology improvement and innovation

Over the past three decades, innovation in the design of grid-connected wind turbines has led to significant cost reductions, while the capacity of individual turbines has grown markedly. The "square-cube law" is a rule of thumb that states that as a wind turbine increases in size, its theoretical energy output tends to increase by the square of the rotor diameter (i.e., the rotor-swept area), while the volume of material (and therefore its mass and cost) required to scale at the same rate increases as the cube of the rotor diameter, all else being equal. As a result, at some size, the cost of a larger turbine will grow faster than the resulting energy output and revenue, making further upscaling uneconomic. To date, engineers have successfully engineered around this relationship, preventing significant increases in the cost of wind energy as turbines have grown larger, by changing design rules with increasing turbine size and by removing material or using it more efficiently to trim weight and cost. Engineering around the "square-cube law" remains a fundamental objective of research efforts aimed at further reducing the delivered cost of energy from wind turbines, especially for off-shore installations.

This section describes research and development programs in wind energy (7.7.1), system-level design and optimization approaches that may yield further reductions in the levelized cost of wind energy (7.7.2), component-level opportunities for innovation in wind energy technology (7.7.3), and the need to improve the scientific underpinnings of wind energy technology (7.7.4). Significant opportunities remain for design optimization of on-shore and off-shore wind turbines, and sizable cost reductions remain possible in the years ahead, though improvements are likely to be more-incremental in nature than radical changes in fundamental design.[24]

7.7.1 Research and development programs

Public and private research and development (R&D) programmes have played a major role in the technical advances seen in wind energy over the last decades (Klaassen *et al.*, 2005; Lemming *et al.*, 2009). Government support for R&D, in collaboration with industry, has led to system and component-level technology advancements, as well as improvements in resource assessment, technical standards, grid integration, wind energy forecasting, and other areas. From 1974 to 2006, government R&D budgets for wind energy in IEA countries totalled $3.8 billion (2005$): this represents an estimated 10% share of RE R&D budgets, and just 1% of total energy R&D expenditures (IEA, 2008; EWEA, 2009). In 2008, OECD research funding for wind energy totalled $180 million (2005$), or 1.5% of all energy R&D funding; additional funding was provided by non-

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[24] This section focuses on scientific and engineering challenges directly associated with reducing the cost of wind energy, but additional research areas of importance include: research on the integration of wind energy into electricity systems and grid compatibility (e.g., forecasting, storage, power electronics); social science research on policy measures and social acceptance; and scientific research to understand the impacts of wind energy on the environment and on humans. These issues are addressed only peripherally in this section.

OECD countries. Government-sponsored R&D programs have often emphasized longer-term innovation, while industry-funded R&D has focusing on shorter-term production, operation, and installation issues. Though data are scarce on industry R&D funding, EWEA (2009), Carbon Trust (2008a), and Wiesenthal *et al.* (2009) [TSU: reference missing] find that the ratio of turbine manufacturer R&D expenditures to net revenue typically ranges from 2% to 3%, while Wiesenthal *et al.* (2009) finds that corporate wind energy R&D in the EU is three times as large as government R&D investments.

Wind energy research strategies have been developed through government and industry collaborations, historically centred on Europe and the United States, though growing public R&D efforts in other countries and regions bear note (e.g., Tan, 2010). In a study to explore the technical and economic feasibility of meeting 20% of electricity demand in the U.S. with wind energy, the U.S. Department of Energy found that key areas of further research included continued development of turbine technology, improved and expanded manufacturing processes, grid integration of wind energy, and siting and environmental concerns (US DOE, 2008). The European Wind Energy Technology Platform (TPWind), meanwhile, has developed a roadmap through 2020 that is expected to form the basis for future European wind energy R&D strategies, with the following areas of focus: new turbines and components; off-shore structures; grid integration; and wind resource assessment and spatial planning (EU, 2008; EC, 2009). One notable feature of both of these planning efforts is that neither envisions a sizable technology breakthrough for wind energy in the years ahead: instead, the path forward is seen as many evolutionary steps, executed through incremental technology advances, that may nonetheless result in significant improvements in the delivered cost of wind energy.

7.7.2 System-level design and optimization

Modern wind turbine design and operation requires advanced, integrated design approaches to optimize system cost and performance. Wind turbines are complex systems that span multiple disciplines. Optimization therefore requires a whole-system perspective that evaluates the wind turbine as an aerodynamic device, as a mechanical structure, as a control system, and finally as an electrical plant (EU, 2008). Studies have identified a number of areas where technology advancements could result in changes to the capital cost, annual energy production, reliability, O&M, and grid integration of wind energy. Examples of scaling studies that have explored the system-level impacts of advanced concepts include those conducted by the U.S. DOE under the Wind Partnership for Advanced Component Technologies (WindPACT) project (GEC, 2001; Griffin, 2001; Shafer *et al.*, 2001; Smith, 2001; Malcolm and Hansen, 2006). Ultimately, component-level advances must be evaluated based on system-level cost and performance impacts; to be viable, increased energy capture associated with larger rotors, for example, must increase expected electricity sales revenue to a greater extent than the additional materials and installation costs. Sophisticated design approaches are therefore required to systematically evaluate and optimize advanced wind turbine concepts.

One assessment of the possible impacts of technical advancements on wind energy production and capital costs is summarized in Table 7.4 (US DOE, 2008). Though not all of these improvements may be achieved, there is sufficient potential to warrant continued R&D. The most likely scenario, as shown in Table 7.4, is a sizeable increase in energy production with a modest drop in capital cost (compared to 2002 levels, which is the baseline for the estimates in Table 7.4).

Table 7.4. Areas of potential technology improvement from a 2002 baseline wind turbine (US DOE, 2008)*

Technical Area	Potential Advances	Increments from Baseline (Best/Expected/Least, Percent)	
		Annual Energy Production (%)	**Turbine Capital Cost (%)**
Advanced Tower Concepts	* Taller towers in difficult locations * New materials and/or processes * Advanced structures/foundations * Self-erecting, initial or for service	+11/+11/+11	+8/+12/+20
Advanced (Enlarged) Rotors	* Advanced materials * Improved structural-aero design * Active controls * Passive controls * Higher tip speed/lower acoustics	+35/+25/+10	-6/-3/+3
Reduced Energy Losses and Improved Availability	* Reduced blade soiling losses * Damage tolerant sensors * Robust control systems * Prognostic maintenance	+7/+5/0	0/0/0
Advanced Drive Trains (Gearboxes and Generators and Power Electronics)	* Fewer gear stages or direct drive * Medium/low-speed generators * Distributed gearbox topologies * Permanent-magnet generators * Medium-voltage equipment * Advanced gear tooth profiles * New circuit topologies * New semiconductor devices * New materials (GaAs, SiC)	+8/+4/0	-11/-6/+1
Manufacturing Learning	* Sustained, incremental design and process improvements * Large-scale manufacturing * Reduced design loads	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21

* The baseline for these estimates was a 2002 turbine system in the U.S. There have already been sizeable improvements in capacity factor since 2002, from just over 30% to almost 35%, while capital costs have increased due to large increases in commodity costs in conjunction with a drop in the value of the U.S. dollar. Therefore, working from a 2008 baseline, one might expect a more-modest increase in capacity factor, but the 10% capital cost reduction is still quite possible (if not conservative), particularly from the higher 2008 starting point. Finally, the table does not consider any changes in the overall wind turbine design concept (e.g., 2-bladed turbines).

7.7.3 Component-level innovation opportunities

The potential areas of innovation outlined in Table 7.4 are further described in Sections 7.7.3.1-7.7.3.5. These component-level innovations will impact both on-shore and off-shore wind energy, but some will be more important for off-shore wind energy technology due to the earlier state of and greater operational challenges facing that technology. Additional advancements that are more-specific to off-shore wind energy are described in Section 7.7.3.6.

7.7.3.1 Advanced tower concepts

Taller towers allow the rotor to access higher wind speeds in a given location, increasing annual energy capture. The cost of large cranes and transportation, however, acts as a limit to tower height.

As a result, research is being conducted into several novel tower designs that would eliminate the need for cranes for very high, heavy lifts. One concept is the telescoping or self-erecting tower, while other designs include lifting dollies or tower-climbing cranes that use tower-mounted tracks to lift the nacelle and rotor to the top of the tower. Still other developments aim to increase the height of the tower without unduly sacrificing material demands through the use of different materials, such as concrete and fibreglass, or different designs, such as space-frame construction or panel sections (see, e.g., GEC, 2001; Malcolm, 2004; Lanier, 2005).

7.7.3.2 Advanced rotors and blades

Due to technology advancements in recent years, blade mass has been scaling at roughly an exponent of 2.4 to rotor diameter, compared to the expected exponent of 3.0 based on the “square-cube” law (Griffin, 2001). The significance of this development is that wind turbine blades have become lighter for a given length over time.

If advanced R&D can provide even better blade design methods, coupled with better materials (such as carbon fibre composites) and advanced manufacturing methods, then it will be possible to continue to innovate around the square-cube law in blade design. A simple approach to reducing cost involves developing new blade airfoil shapes that are much thicker where strength is most required, near the blade root, allowing inherently better structural properties and reducing overall mass. These airfoil shapes potentially offer equivalent aerodynamic performance, but have yet to be proven in the field. Another approach to increasing blade length while limiting increased material demand is to reduce the fatigue loading on the blade. The benefit of this approach is that the approximate rule of thumb for fibreglass blades is that a 10% reduction in cyclic stress can more than double the fatigue lifetime. Blade fatigue loads can be reduced by controlling the blade’s aerodynamic response to turbulent wind by using mechanisms that vary the angle of attack of the blade airfoil relative to the wind inflow. This is primarily accomplished with full-span blade pitch control. An elegant concept, however, is to build passive means of reducing loads directly into the blade structure (Ashwill, 2009). By carefully tailoring the structural properties of the blade using the unique attributes of composite materials, the blade can be built in a way that couples the bending deformation of the blade resulting from the wind with twisting deformation that passively mimics the motion of blade pitch control. Another approach is to build the blade in a curved shape so that the aerodynamic load fluctuations apply a twisting movement to the blade, which will vary the angle of attack (Ashwill, 2009). Because wind inflow displays a complex variation of speed and character across the rotor disk, partial blade span actuation and sensing strategies to maximize load reduction are also promising (Buhl *et al.*, 2005; Lackner and van Kuik, 2009). Devices such as trailing edge flaps and micro-tabs, for example, are being investigated, but new sensors may need to be developed for this purpose, with a goal of creating “smart” blades with embedded sensors and actuators to control local aerodynamic effects (Andersen *et al.*, 2006; Berg *et al.*, 2009). To achieve these new designs, better understanding of wind turbine aeroelastic, aerodynamic, and aeroacoustic responses associated with complicated blade motion will be needed, as will control algorithms to incorporate these sensors and actuators in wind turbine operation schemes.

7.7.3.3 Reduced energy losses and improved availability

Advanced turbine control and condition monitoring are expected to provide a primary means to improve turbine reliability and availability, reduce O&M costs, and ultimately increase energy capture, both for individual turbines and wind power plants, and both on-shore and off-shore. Advanced controllers are envisioned that can better control the turbine during turbulent winds and thereby reduce fatigue loading and extend blade life (Bossanyi, 2003; Stol and Balas, 2003; Wright, 2004), monitor and adapt to wind conditions to increase energy capture and reduce the impact of blade soiling or erosion (Johnson *et al.*, 2004; Johnson and Fingersh, 2008; Frost *et al.*, 2009), and anticipate and protect against damaging wind gusts by using new sensors to detect wind speeds immediately ahead of the blade (Larsen *et al.*, 2004; Hand and Balas, 2007). Condition-monitoring systems of the future are expected to track and monitor ongoing conditions at critical locations in the turbine and report incipient failure possibilities and damage evolution, so that improved maintenance procedures can minimize outages and downtimes (Hameed *et al.*, 2010). The full development of advanced control and monitoring systems of this nature will require considerable operational experience, and optimization algorithms will likely be turbine-specific; the general approach, however, should be transferrable between turbine designs and configurations.

7.7.3.4 Advanced drive trains, generators, and power electronics

Several unique turbine designs are under development or in early commercial deployment to reduce drive train weight and cost while improving reliability (Poore and Lettenmaier, 2003; Bywaters *et al.*, 2004; EWEA, 2009). One option, already in commercial use, is a direct-drive generator (removing the need for a gearbox); more than 10% of the wind power capacity installed in 2009 used direct drive turbines (BTM, 2010). The trade-off is that the slowly rotating generator must have a high pole count and be large in diameter, imposing a weight penalty. The decreased cost and increased availability of rare-earth permanent magnets is expected to significantly affect the size and cost of future direct-drive generator designs, however, as permanent-magnet designs tend to be more compact and potentially lightweight, as well as reducing electrical losses in the windings.

A hybrid of the current geared and direct-drive approaches is the use of a single-stage drive using a low- or medium-speed generator. This allows the use of a generator that is significantly smaller and lighter than a comparable direct-drive design, and reduces (but does not eliminate) reliance on a gearbox. Another approach is the distributed drive train, where rotor torque is distributed to multiple smaller generators (rather than a single, larger one), reducing overall size and weight.

Power electronics that provide full power conversion from variable frequency AC electricity to constant frequency 50 or 60 Hz are also capable of providing ancillary grid services. The growth in turbine size is driving larger power electronic components as well as innovative higher-voltage circuit topologies. In the future, it is expected that wind turbines will use higher-voltage generators and converters than are used today (Erdman and Behnke, 2005), and therefore also make use of higher-voltage and higher-capacity circuits and transistors. New power conversion devices will need to be fully compliant with emerging grid codes to ensure that wind power plants do not degrade the reliability of the electric system.

7.7.3.5 Manufacturing learning

Manufacturing learning refers to the learning by doing achieved in serial production lines with repetitive manufacturing (see Section 7.8.4 for a broader discussion of learning in wind energy technology). Though turbine manufacturers already are beginning to operate at significant scale, as the industry expands further, additional cost savings can be expected. For example, especially as turbines have increased in size, concepts such manufacturing at wind power plant sites and segmented blades are being explored to reduce transportation costs. Further increases in manufacturing automation and optimized processes will also contribute to cost reductions in the manufacturing of wind turbines and components.

7.7.3.6 Off-shore research and development opportunities

The cost of off-shore wind energy exceeds that of on-shore wind energy due, in part, to higher operating costs as well as more-expensive installation and support structures. The potential component-level technology advancements described above will contribute to lower off-shore wind energy costs, and some of these advances may be driven by off-shore wind energy applications. In addition, however, there are several areas of possible advancement that are more-specific to off-shore wind energy, including O&M strategies, installation and assembly schemes, support structure design, and the development of larger turbines, possibly including new turbine concepts.

Off-shore wind turbines operate in harsh environments driven by both wind and wave conditions that can make access to turbines challenging or even impossible for extended periods. A variety of methods to provide greater access during a range of conditions, including inflatable boats or helicopters, are being evaluated (van Bussel and Bierbooms, 2003). Sophisticated O&M approaches that include remote assessments of turbine operability and the scheduling of preventative maintenance to maximize access during favourable conditions are also being investigated, and employed (Wiggelinkhuizen *et al.*, 2008). The development of more-reliable turbine components, even if more expensive on a first-cost basis, is also expected to play a major role in reducing the overall levelized cost of off-shore wind energy. Efforts are underway to more-thoroughly analyze gearbox dynamics, for example, to contribute to more reliable designs (Peeters *et al.*, 2006; Heege *et al.*, 2007). The component level innovations described earlier, such as advanced direct-drive generators and passive blade controls, may also improve overall technology reliability.

Off-shore wind turbine size is not restricted by road or other land-based infrastructure limits. As a result, though off-shore wind turbines are currently installed as individual components, concepts are being considered where fully-assembled turbines are transported on special-purpose vessels and mounted on previously installed support structures. In addition to creating the vessels needed for such installation practices, ports and staging areas would need to be designed to efficiently perform the assembly processes.

Additional off-shore wind energy R&D is required to improve support structure design. Foundation structure innovation offers the potential to access deeper waters, thereby increasing the potential wind resource available. Off-shore turbines have historically been installed in relatively shallow water, up to 30 m, on a mono-pile structure that is essentially an extension of the tower, but gravity-based structures have become more common. Other concepts that are more appropriate for deeper water depths include fixed-bottom space-frame structures, such as jackets and tripods, and floating platforms, such as spar-buoys, tension-leg platforms, semi-submersibles, or hybrids of these concepts. Offshore wind turbine support structures may undergo dynamic responses associated with wind and wave loads, requiring an integrated analysis of the rotor, tower, and support structure supplemented with improved estimates of soil stiffness and scour conditions specific to off-shore support structures (Nielsen *et al.*, 2009). Floating wind turbines further increase the complexity of turbine design due to the additional motion of the base but, if cost effective, can offer access to significant additional wind resource areas; encourage standard technology development that is independent of water depth and seabed condition; and lead to simplified installation and decommissioning practices (EWEA, 2009). In 2009, the first full-scale floating wind turbine pilot plant was deployed off the coast of Norway at a 220 m depth. Figure 7.16(a,b) depicts some of the foundation concepts (a) being employed or considered in the near term, while also (b) illustrating the concept of floating wind turbines, which are being considered for the longer term.

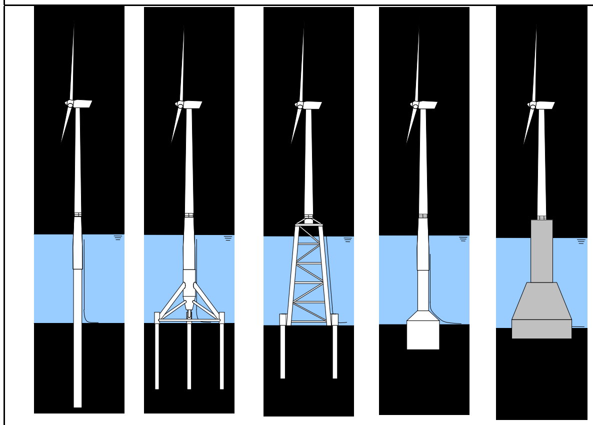
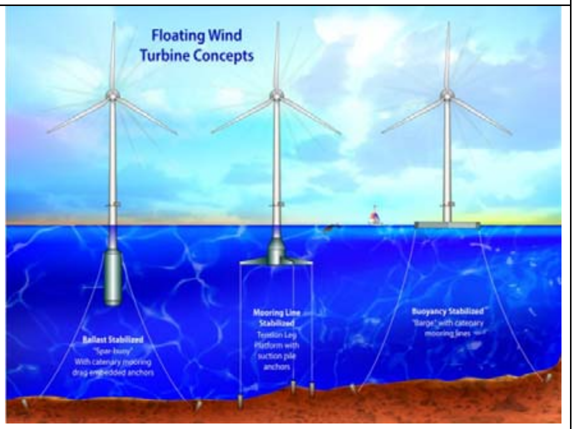
(a) Near-term off-shore foundation concepts	**(b)** Floating off-shore turbine concept
	
Source: UpWind.eu	Source: NREL

Figure 7.16(a,b). Off-shore wind turbine foundation designs

Future off-shore wind turbines may be larger, lighter, and more-flexible. Off-shore wind turbine size is not restricted in the same way as on-shore wind energy technology, and turbines of 10 MW or larger are under consideration. Future off-shore turbine designs can benefit from many of the possible component-level advances described previously. Nonetheless, the development of large turbines for off-shore applications remains a significant research challenge, requiring continued advancement in component design and system-level analysis. Concepts that reduce the weight of the blades, tower, and nacelle become more important as size increases, providing opportunities for greater advancement than may be incorporated in on-shore wind energy technology. In addition to larger turbines, design criteria for off-shore applications may be relaxed in cases where noise and visual impacts are of lesser concern. As a result, other advanced turbine concepts are under investigation, including 2-bladed, downwind turbines. Downwind turbine designs may allow less-costly yaw mechanisms, and the use of softer more flexible blades (Breton and Moe, 2009). Finally, innovative turbine concepts and significant upscaling of existing designs will require improved turbine modelling to better capture the operating environment in which off-shore turbines are installed, including the dynamic response of turbines to wind and wave loading (see Section 7.7.4).

7.7.4 The importance of underpinning science

Although wind energy technology is being deployed at a rapid scale today, there remains significant potential for continued innovation to further reduce cost and improve performance. International wind turbine design and safety standards dictate the level of analysis and testing required prior to commercializing new concepts. At the same time, technical innovation will push the design criteria and analysis tools to the limits of physical understanding. A significant effort is therefore needed to further advance the fundamental knowledge of the wind turbine operating environment in order to assure a new generation of reliable, safe, cost-effective wind turbines, and to further optimize wind power plant siting and design.

Wind turbines operate in a challenging environment, and are designed to withstand a wide range of conditions with minimal attention. Wind turbines are complex, nonlinear, dynamic systems forced by gravity, centrifugal, inertia, and gyroscopic loads as well as unsteady aerodynamic, hydrodynamic (for off-shore), and corrosion impacts. Modern wind turbines also operate in a layer of the atmosphere (from 50 m to 200 m) that is complex, and are impacted by phenomena that occur over scales ranging from microns to thousands of kilometres. Accurate, reliable wind measurements and computations across these scales are important (Schreck *et al.*, 2008). In addition, fundamental scientific research in a number of areas will improve the physical understanding of this operating environment, which in turn can lead to more-precise design requirements that can facilitate the development of the innovative concepts described in Section 7.7.3. Research in areas of aeroelastics, unsteady aerodynamics, aeroacoustics, advanced control systems, and atmospheric science has yielded improved design capabilities in the past (Schreck *et al.*, 2010), and can continue to improve mathematical models and experimental data that reduce the risk of unanticipated failures, increase the reliability of the technology, and encourage further design innovation.

Although the physics are strongly coupled, there are four primary spatio-temporal levels requiring additional research: (1) wind conditions that affect individual turbines, (2) wind power plant siting and array effects, (3) mesoscale atmospheric processes, and (4) global and local climate effects.

Wind conditions that affect individual wind turbines encompass detailed characterizations of wind flow fields and the interaction of those flows with wind turbines. Wind turbine aerodynamics are complicated by three-dimensional effects in rotating blade flow fields that are unsteady and create load oscillations linked to dynamic stall. Understanding these aerodynamic effects, however, is critical for making load predictions that are accurate enough for use in turbine designs. To this point, these effects have been identified and quantified based on wind tunnel and field experiments (Schreck *et al.*, 2000, 2001; Schreck and Robinson, 2003; Madsen *et al.*, 2010), and empirical models of these effects have been developed (Bierbooms, 1992; Du and Selig, 1998; Snel, 2003; Leishman, 2006). Currently, these aerodynamic models rely on Blade-Element Moment methods (Spera, 2009) augmented with analytically and empirically based models to calculate the aerodynamic forces along the span of the blade. The availability of effective Computational Fluid Dynamics codes and their potential to deliver improved predictive accuracy, however, is prompting broader application (Hansen *et al.*, 2006). Aeroelastic models, meanwhile, are used to translate aerodynamic forces into structural responses throughout the turbine system. As turbines grow in size and are optimized, the structural flexibility of the components will necessarily increase, causing more of the turbine’s vibration frequencies to play a prominent role. To account for these effects, future aeroelastic tools will have to better model large variations in the wind inflow across the rotor, higher-order vibration modes, nonlinear blade deflection, and aeroelastic damping and instability (Quarton, 1998; Rasmussen *et al.*, 2003; Riziotis *et al.*, 2004; Hansen, 2007). The application of novel load-mitigation control technologies to blades (e.g., deformable trailing edges) (Buhl *et al.*, 2005) will require analysis based on aeroelastic tools that are adapted for these architectures. Similarly, exploration of control systems that utilize wind-speed measurements in advance of the blade, such as Light Detection and Ranging (Harris *et al.*, 2006) or pressure probe measurements (Larsen *et al.* (2004), will also require improved aeroelastic tools. Off-shore wind energy will require that aeroelastic tools better model the coupled dynamic response of the wind turbine and the foundation/support platform, as subjected to combined wind and wave loads (Passon and Kühn, 2005; Jonkman, 2009). Finally, aeroacoustic noise (i.e., the noise of turbine blades) is an issue for wind turbines (Wagner *et al.*, 1996), and increasing sophisticated tools are under development to better understand and manage these effects (Wagner *et al.*, 1996; Moriarty and Migliore, 2003; Zhu *et al.*, 2005, 2007; Shen and Sörensen, 2007). As turbine aerodynamic, aeroelastic, and aeroacoustic modelling advances, the crucial role (e.g., Simms *et al.*, 2001) of research-grade turbine aerodynamics experiments (Hand *et al.*, 2001; Snel *et al.*, 2009) grows ever more evident, as does the need for future high-quality laboratory and field experiments. Even though wind turbines now extract energy from the wind at levels approaching the theoretical maximum, improved understanding of aerodynamic phenomena will allow more accurate calculation of loads and thus the development lighter, more reliable, and higher-performing turbines.

Wind power plant siting and array effects impact energy production and equipment reliability at the power plant level. Rotor wakes create aeroelastic responses on downwind turbines (Larsen *et al.*, 2008). Improved models of wind turbine wakes (Thomsen and Sørensen, 1999; Frandsen *et al.*, 2007) will therefore yield more reliable predictions of energy capture and better estimates of fatigue loading in large, multiple-row wind power plants, both on-shore and off-shore. This improved understanding may then lead to improved wind turbine and power plant designs intended to minimize energy capture degradations and manage wake-based load impacts.

Planetary boundary layer research is important for accurately determining wind flow and turbulence in the presence of various atmospheric stability effects and complex land surface characteristics. Research in mesoscale atmospheric processes aims at improved [TSU: improving] the fundamental understanding of mesoscale and local wind flows (Banta *et al.*, 2003; Kelley *et al.*, 2004). In addition to its contribution towards understanding turbine-level aerodynamic and array wake effects, a better understanding of mesoscale atmospheric processes will yield improved wind energy resource assessments and forecasting methods. Physical and statistical modelling to resolve spatial scales in the 100-m to 1000-m range, a notable gap in current capabilities (Wyngaard, 2004), could occupy a central role of this research.

Finally, additional research is warranted on the interaction between global and local climate effects, and wind energy. Specifically, work is needed to identify and understand historical trends in wind resource variability in order to increase the reliability of future wind energy performance predictions. As discussed earlier in this chapter, further work is also warranted on the possible impacts of climate change on wind energy resource conditions, and on the impact of wind energy development on local, regional, global climates.

Significant progress in many of the above areas requires interdisciplinary research. Also crucial is the need to use experiments and observations in a coordinated fashion to support and validate computation and theory. Models developed in this way will be essential for improving: (1) wind turbine design, (2) wind power plant performance estimates, (3) wind resource assessments, (4) short-term wind energy forecasting, and (5) estimates of the impact of large-scale wind energy deployment on the local climate, as well as the impact of potential climate change effects on wind resources.

7.8 Cost trends[25]

Though the cost of wind energy has declined significantly since the 1980s, in most regions of the world, policy measures are required to make wind energy economically attractive (e.g., NRC, 2010a). In areas with particularly good wind resources or particularly costly alternative forms of power supply, however, the cost of wind energy can be competitive with fossil generation (e.g., Berry, 2009; IEA, 2009a; IEA and OECD, 2010). Moreover, continued technology advancements in on- and off-shore wind energy are expected (Sections 7.7), supporting further cost reductions. Because the degree to which wind energy is utilized globally and regionally will depend largely on the economic performance of wind energy compared to alternative power sources, this section describes the factors that affect the cost of wind energy (7.8.1), highlights historical trends in the cost and performance of wind power plants (7.8.2), summarizes data and estimates the levelized cost of wind energy in 2009 (7.8.3), and forecasts the potential for further cost reductions (7.8.4). The relative economic competitiveness of wind energy, which includes other factors such as subsidies and environmental externalities, is not covered in this section. Similarly, the costs of integration and transmission are not covered here, but are instead discussed in Section 7.5.

7.8.1 Factors that affect the cost of wind energy

The cost of both on-shore and off-shore wind energy is affected by five fundamental factors: annual energy production, installation costs, operating and maintenance costs, financing costs, and the

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[25] All cost data are presented in real, 2005 U.S. dollars (US2005$)

assumed economic life of the plant. Available support policies can also influence the cost (and price) of wind energy, as well as the cost of other electricity supply options, but these factors are not addressed here.

The nature of the wind resource largely determines the annual energy production from a prospective wind power plant, and is among the most important economic factors. Precise micro-siting of wind power plants and even individual turbines is critical for maximizing energy production. The trend toward turbines with larger rotor diameters and taller towers has led to increases in annual energy production per unit of installed capacity, and has also allowed wind power plants in lower resource areas to become more economically competitive over time. Off-shore wind power plants will, generally, be exposed to better wind resources than will on-shore power plants.

Wind power plants are capital intensive and, over their lifetime, the initial capital investment ranges from 75-80% of total expenditure, with operating costs contributing the balance (Blanco, 2009; EWEA, 2009). The capital cost of wind power plant installation includes the cost of the turbines (turbines, transportation to site, and installation), grid connection (cables, sub-station, interconnection), civil works (foundations, roads, buildings), and other costs (engineering, licensing, permitting, environmental assessments, and monitoring equipment). Table 7.5 shows a rough breakdown of the capital cost components for modern wind power plants. Turbine costs comprise more than 70% of total installed costs for on-shore wind power plants. The remaining costs are highly site-specific. Off-shore wind power plants are dominated by these other costs, with the turbines often contributing less than 50% of the total. Site-dependent characteristics such as water depth and distance to shore significantly affect grid connection, civil works, and other costs. Off-shore turbine foundations and internal electric grids are also considerably more costly than those for on-shore power plants (see also, Junginger *et al.*, 2004).

Table 7.5. Installed cost distribution for on-shore and off-shore wind power plants (Blanco, 2009; EWEA, 2009)

Cost Component	On-shore	Off-shore*
Turbine	71% - 76%	37% - 49%
Grid connection	10% - 12%	21% - 23%
Civil works	7% - 9%	21% - 25%
Other capital costs	5% - 8%	9% - 15%

* Off-shore cost categories consolidated from original

The O&M costs of wind power plants include fixed costs such as land leases, insurance, taxes, management, and forecasting services, as well as variable costs related to the maintenance and repair of turbines, including spare parts. O&M comprises approximately 20% of total wind power plant expenditure over a plant's lifetime (Blanco, 2009), with roughly 50% of total O&M costs associated directly with maintenance, repair, and spare parts (EWEA, 2009). Costs for off-shore wind energy are higher than for on-shore due to harsher weather conditions that impede access, as well as the higher transportation costs incurred to access off-shore turbines (Blanco, 2009).

Financing arrangements, including the cost of debt and equity and the proportional use of each, can also influence the cost of wind energy, as can the expected operating life of the wind power plant. For example, ownership and financing structures have evolved in the U.S. that minimize the cost of capital while taking advantage of available tax incentives (Bolinger *et al.*, 2009). Other research has found that the predictability of the policy measures supporting wind energy can have a sizable impact on financing costs, and therefore the ultimate cost of wind energy (Wiser and Pickle, 1998; Dunlop, 2006; Dinica, 2006; Agnolucci, 2007). Because off-shore wind power plants are still relatively new, with greater performance risk, higher financing costs are experienced than for on-shore plants (Dunlop, 2006; Blanco, 2009), and larger firms tend to dominate off-shore wind energy development and ownership (Markard and Petersen, 2009).

7.8.2 Historical trends

7.8.2.1 Installed capital costs

From the beginnings of commercial wind energy deployment to roughly 2004, the installed capital cost of on-shore wind power plants dropped, while turbine size grew significantly. With each generation of wind turbine technology during this period, design improvements and turbine scaling led to decreased installed costs. Historical installed capital cost data from Denmark and the United States demonstrate this trend (Figure 7.17(a,b)). From 2004 to 2009, however, capital costs increased. Wind power plant costs in Denmark in 2009 averaged approximately US$1,400/kW, while costs in the U.S. in 2009 averaged US$1,900/kW, both up substantially from earlier lows. Some of the reasons behind these increased costs are described in Section 7.8.3.

(a) Wind power plant costs in Denmark (Nielson et al., 2010)

(b) Wind power plant costs in the United States (Wiser and Bolinger, 2010)

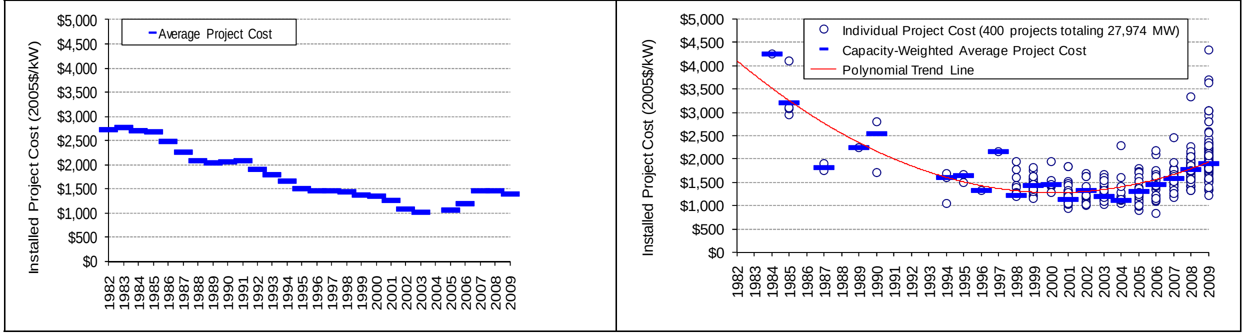

Figure 7.17. Installed cost of on-shore wind power plants in (a) Denmark and (b) the United States

The installed costs of off-shore wind power plants are highly site-specific, but have historically been 50% to more than 100% more expensive than on-shore plants (IEA, 2008; BWEA and Garrad Hassan, 2009; EWEA, 2009). Off-shore costs have also been influenced by the same factors that caused rising on-shore costs from 2004 through 2009, as described in Section 7.8.3, leading to a doubling of the average installed cost of off-shore plants from 2004 through 2009 (BWEA and Garrad Hassan, 2009).

7.8.2.2 Operation and maintenance

Modern turbines that meet IEC standards are designed for a 20-year life, and plant lifetimes may exceed 20 years if O&M costs remain at an acceptable level. Few wind power plants were constructed 20 or more years ago, however, and there is therefore limited experience in plant operations over this entire time period. Moreover, those wind power plants that have reached or exceeded their 20-year lifetime tend to have turbines that are much smaller and less sophisticated than their modern counterparts. Early turbines were also designed using more conservative criteria, though they followed less stringent standards than today's designs. As a result, these early plants only offer limited guidance for estimating O&M costs for more-recent turbine designs.

In general, O&M costs during the first couple of years of a wind power plant's life are covered, in part, by manufacturer warranties that are included in the turbine purchase, resulting in lower ongoing costs than in subsequent years. Newer turbine models also tend to have lower initial O&M costs than older models, with maintenance costs increasing as turbines age (Blanco, 2009; EWEA, 2009; Wiser and Bolinger, 2009). Off-shore wind power plants have historically incurred higher O&M costs than on-shore plants (Junginger *et al.*, 2004; EWEA, 2009; Lemming *et al.*, 2009).

7.8.2.3 Energy production

The performance of wind power plants is primarily governed by local wind conditions, but is also impacted by wind turbine design optimization, performance, and availability, and by the effectiveness of O&M procedures. Improved resource assessment and siting methodologies developed in the 1970s and 1980s played a major role in improved wind power plant productivity. Advancements in wind energy technology, including taller towers and larger rotors, have also contributed to increased energy capture (EWEA, 2009).

Data on average fleet-wide capacity factors[26] over time for a large sample of on-shore wind power plants in the U.S. show a trend toward higher average capacity factors over time, as wind power plants built more recently have higher average capacity factors than those built earlier (Figure 7.18). Higher hub heights and larger rotor sizes are primarily responsible for these improvements, as the more-recent wind power plants built in this time period and included in Figure 7.18 were, on average, sited in increasingly lower wind resource regimes.

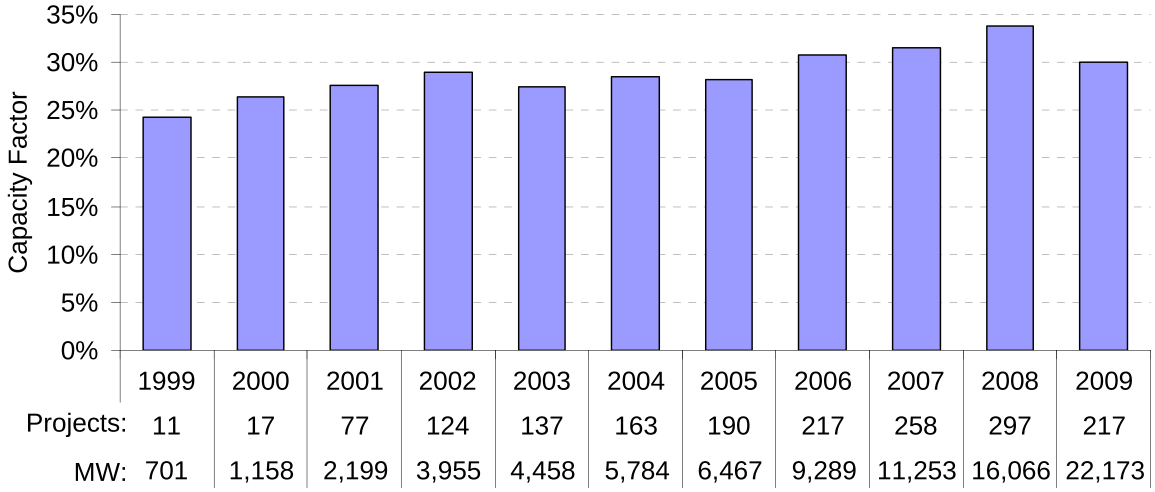

Figure 7.18. Fleet-wide average capacity factors for a large sample of wind power plants in the U.S. from 1999 - 2009 (Wiser and Bolinger, 2010)

Using a different metric for wind power plant performance, annual energy production per square meter of swept rotor area (kWh/m^2) for a given wind resource site, improvements of 2-3% per year over the last 15 years have been documented (IEA, 2008; EWEA, 2009).

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[26] A wind power plant's capacity factor is only a partial indicator of performance (EWEA, 2009). Most turbine manufacturers supply variations on a given generator capacity with multiple rotor diameters and hub heights. In general, for a given generator capacity, increasing the hub height, the rotor diameter, or the average wind speed will result in increased capacity factor. When comparing different wind turbines, however, it is possible to increase annual energy capture by using a larger generator, while at the same time decreasing the wind power plant's capacity factor.

7.8.3 Current conditions

7.8.3.1 Installed capital costs

The cost for on-shore wind power plants installed worldwide in 2009 averaged approximately US$1,750/kW, with the majority of plants falling in the range of US$1,400/kW to US$2,100/kW (Milborrow, 2010). Wind power plants installed in the United States in 2009 averaged US$1,900/kW (Wiser and Bolinger, 2010). Costs in some markets were lower: for example, average wind power plant costs in China in 2008-09 were around US$1,000-1,350/kW, driven in part by the dominance of several Chinese turbine manufacturers serving the market with lower-cost wind turbines (China Renewable Energy Association, 2009; Li and Ma, 2009; Li, 2010).

Wind power plant costs rose from 2004 to 2009 (Figure 7.17), an increase primarily caused by the rising price of wind turbines (Wiser and Bolinger, 2009). Those cost increases have been attributed to a number of factors, including: escalation (in real terms) in the cost of labour and materials inputs; increasing profit margins among turbine manufacturers and their component suppliers; the relative strength of the Euro currency; and the increased size of turbine rotors and hub heights (Bolinger *et al.*, 2010). Increased rotor diameters and hub heights have enhanced the energy capture of modern wind turbines, but those performance improvements have come with increased installed turbine costs, measured on a $/kW basis. The costs of raw materials, including steel, copper, cement, aluminium, and carbon fibre, also rose sharply from 2004 through mid-2008 as a result of strong global economic growth. In addition to higher raw materials costs, the strong demand for wind turbines over this period put upward pressure on labour costs, and enabled turbine manufacturers and their component suppliers to boost profit margins. Strong demand, in excess of available supply, also placed particular pressure on critical components such as gearboxes and bearings (Blanco 2009), which had traditionally been provided by only a small number of suppliers. Moreover, because many of the wind turbine manufacturers have historically been based in Europe, and many of the critical components like gearboxes and bearings have similarly been manufactured in Europe, the relative value of the Euro to other currencies such as the U.S. dollar also contributed to wind energy technology price increases in certain countries. Turbine manufacturers and component suppliers responded to the tight supply by expanding or adding new manufacturing facilities. Coupled with reductions in materials costs that began in late 2008 as a result of the global financial crisis, these trends began to moderate wind turbine costs at the beginning of 2009 (Wiser and Bolinger, 2009).

Due to the relatively small number of off-shore wind power installations, cost data are sparse. Nonetheless, the average cost of off-shore wind power plants is considerably higher than that for on-shore plants, and the factors that have increased the cost of on-shore plants have similarly affected the off-shore sector. The limited availability of turbine manufacturers supplying the off-shore market, and of vessels to install such plants, has exacerbated cost increases since 2004, as did the fierce competition among industry players for early-year (before 2005) off-shore demonstration plants (BWEA and Garrad Hassan, 2009). As a result, off-shore wind power plants over 50 MW in size, either built between 2006 and 2009 or planned for 2010, had installed costs that ranged from approximately US$2,000/kW to US$5,000/kW (IEA, 2008, 2009a; BWEA and Garrad Hassan, 2009; Snyder and Kaiser 2009a), with most estimates in a narrower range of US$3,200/kW to US$4,600/kW (Milborrow, 2010). These capital costs are roughly 100% higher than costs seen in the 2000-2004 timeframe (BWEA and Garrad Hassan, 2009).

7.8.3.2 Operation and maintenance

Though fixed O&M costs such as insurance, land payments, and routine maintenance are relatively easy to estimate, variable costs such as repairs and spare parts are more difficult to predict (Blanco, 2009). O&M costs can vary by wind power plant, turbine age, and the availability of a local servicing infrastructure, among other factors. Levelized O&M costs for on-shore wind energy are often estimated to range from US$12/MWh to US$23/MWh (Blanco, 2009): these figures are reasonably consistent with costs reported in IEA (2008), EWEA (2009), Wiser and Bolinger (2009), and Milborrow (2010).

Limited empirical data exist on O&M costs for off-shore wind energy, due in large measure to the limited number of operating plants and the limited duration of those plants' operation. Reported or estimated O&M costs for off-shore plants installed since 2002 range from US$20/MWh to US$40/MWh (EWEA, 2009; IEA, 2009a; Lemming *et al.*, 2009; Milborrow, 2010).

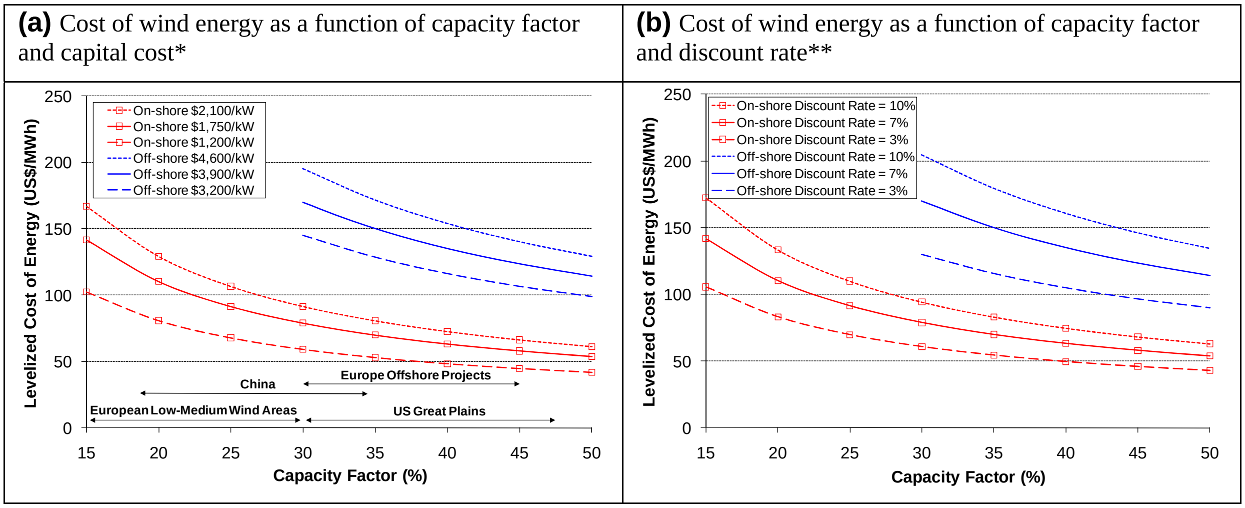
7.8.3.3 Energy production

On-shore wind power plant performance varies from site-to-site primarily as a function of the wind resource, with capacity factors ranging from below 20% to more than 50% depending on local resource conditions. Among countries, variations in average performance again reflect differing wind resource conditions: the average capacity factor for Germany's installed plants has been estimated at 20.5% (BTM, 2010); European country-level average capacity factors range from 20-30% (Boccard, 2009); average capacity factors in China are reported at roughly 23% (Li, 2010); average capacity factors in India are reported at around 20% (Goyal, 2010); and the average capacity factor for U.S. wind power plants is above 30% (Wiser and Bolinger, 2010). Off-shore wind power plants often experience a narrower range in capacity factors, with a typical range of 35% to 45% for the European plants installed to date (Lemming *et al.*, 2009).

Because of these variations among countries and individual plants, which are primarily driven by local wind resource conditions but are also affected by turbine design and operations, estimates of the levelized cost of wind energy must include a range of energy production estimates. Moreover, because the attractiveness of off-shore plants is enhanced by the potential for greater energy production than for on-shore plants, performance variations among on- and off-shore wind energy must also be considered.

7.8.3.4 Levelized cost of energy estimates

Using the methods summarized in Appendix II, the levelized cost of wind energy for power plants built in 2009 is presented in Figure 7.19(a, b). Estimated costs are presented over a range of energy production estimates to represent the cost variation associated with inherent differences in the wind resource. The x-axis for these charts roughly correlates to annual average wind speeds from 6 m/s to 10 m/s. On-shore capital costs are assumed to range from US$1,200/kW to US$2,100/kW (with a mid-level cost of US$1,750/kW); installed costs for off-shore wind energy range from US$3,200/kW to US$4,600/kW (mid-point of US$3,900/kW). Levelized O&M costs are assumed to average US$16/MWh and US$30/MWh over the life of the plant for on-shore and off-shore wind energy, respectively. A power plant design life of 20 years is assumed, and discount rates of 3% to 10% (mid-point estimate of 7%) are used to produce levelized cost estimates. Taxes and policy incentives are not included in these calculations.



(a) Cost of wind energy as a function of capacity factor and capital cost*

(b) Cost of wind energy as a function of capacity factor and discount rate**

* Discount rate assumed to equal 7%

** On-shore capital cost assumed at US$1,750/kW, and off-shore at US$3,900/KW

Figure 7.19. Estimated levelized cost of on-shore and off-shore wind energy, 2009

The levelized cost of on- and off-shore wind energy in 2009 varies substantially, depending on assumed capital costs, energy production, and discount rates. For on-shore wind energy, levelized costs in good to excellent wind resource regimes average US$50-100/MWh. Levelized costs can reach US$150/MWh in lower resource areas. The cost of wind energy in China and the U.S. tend toward the lower range of these estimates, due to lower average installed costs (China) and higher average capacity factors (U.S.); costs in much of Europe tend towards the higher end of the range due to relatively lower average capacity factors. Off-shore wind energy is generally more expensive than on-shore, with typical levelized costs that range from US$100/MWh to US$200/MWh; where the exploitable on-shore wind resource is limited, however, off-shore plants can sometimes compete with on-shore plants.

7.8.4 Potential for further reductions in the cost of wind energy

The wind energy industry has developed over a period of 30 years. Though the dramatic cost reductions seen in past decades will not continue indefinitely, the potential for further reductions remain given the many potential areas of technological advance described in Section 7.7. This potential spans both on- and off-shore wind energy technologies; given the relative immaturity of off-shore wind energy, however, greater cost reductions can be expected in that segment. Two approaches are commonly used to forecast the future cost of wind energy: (1) learning curve estimates that assume that future wind energy costs will follow a trajectory that is similar to an historical learning curve based on past costs; and (2) engineering-based estimates of the specific cost reduction possibilities associated with new or improved wind energy technologies or manufacturing capabilities.

7.8.4.1 Learning curve estimates

Learning curves have been used extensively to understand past cost trends and to forecast future cost reductions for a variety of energy technologies (e.g., McDonald and Schrattenholzer, 2001; Kahouli-Brahmi, 2009). Learning curves start with the premise that increases in the cumulative capacity of a given technology lead to a reduction in its costs. The principal parameter calculated by learning curve studies is the learning rate: for every doubling of cumulative installation or production, the learning rate specifies the associated percentage reduction in costs.

A number of studies have evaluated learning rates for on-shore wind energy. There is a wide range of calculated learning rates, from 4% to 32% (Table 7.6), suggesting that historical cost reductions have been significant, but that there is relatively little agreement on the magnitude of those reductions. This wide variation can be explained by differences in learning model specification (e.g., one factor or multi-factor learning curves), variable selection and assumed system boundaries (e.g., whether installed cost, turbine cost, or levelized energy costs are explained, and whether global or country-level cumulative installations are used), data quality, and the time period over which data are available. Because of these differences, the various learning rates for wind energy presented in Table 7.6 cannot easily be compared. Focusing only on those studies completed in 2004 and later, and that have prepared estimates of learning curves based on total wind power plant installed costs and global cumulative installations, the range of learning rates narrows to 10-17%.

Table 7.6. Summary of learning curve literature for wind energy

		Global or National		
Authors	**Learning By Doing Rate (%)**	**Independent Variable (cumulative installed capacity)**	**Dependent Variable**	**Data Years**
Neij (1997)	4%	Denmark	Denmark (turbine cost)	1982-1995
Mackay and Probert (1998)	14%	U.S.	U.S. (turbine cost)	1981-1996
Neij (1999)	8%	Denmark	Denmark (turbine cost)	1982-1997
Wene (2000)	32%	U.S. **	U.S. (production cost)	1985-1994
Wene (2000)	18%	EU **	EU (production cost)	1980-1995
Miketa and Schrattenholzer (2004)*	10%	Global	Global (installed cost)	1971-1997
Junginger *et al.* (2005)	19%	Global	UK (installed cost)	1992-2001
Junginger *et al.* (2005)	15%	Global	Spain (installed cost)	1990-2001
Klaassen *et al.* (2005) *	5%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Kobos *et al.* (2006) *	14%	Global	Global (installed cost)	1981-1997
Jamasb (2007) *	13%	Global	Global (installed cost)	1980-1998
Söderholm and Sundqvist (2007)	5%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Söderholm and Sundqvist (2007) *	4%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Neij (2008)	17%	Denmark	Denmark (production cost)	1980-2000
Kahouli-Brahmi (2009)	17%	Global	Global (installed cost)	1979-1997
Nemet (2009)	11%	Global	California (turbine cost)	1981-2004
Wiser and Bolinger (2009)	11%	Global	U.S. (installed cost)	1982-2008

* Two-factor learning curve that also includes R&D; all others are one-factor learning curves

** Independent variable is cumulative production of electricity

There are also a number of limitations to the use of such models to forecast future costs. First, learning curves typically (and simplistically) model how costs have decreased with increased installations in the past, and do not comprehensively explain the reasons behind the decrease. In reality, costs may decline in part due to traditional learning and in part due to other factors, such as

R&D expenditure and increases in turbine and power plant size. If learning curves are used to forecast future cost trends, one must not only assume that the factors that have driven costs in the past will be sustained into the future, but that those drivers operate based on cumulative installations. In reality, as technologies mature, diminishing returns in cost reduction can be expected (Arrow, 1962; Ferioli *et al.*, 2009). Second, the most appropriate cost measure for wind energy is arguably the levelized cost of energy, as wind energy production costs are affected by both installed costs and energy production (EWEA, 2009; Ferioli *et al.*, 2009). Unfortunately, only two of the published studies calculate the learning rate for wind energy using a levelized cost of energy metric (Wene, 2000; Neij, 2008); most studies have used the more-readily available metrics of total installed cost or turbine cost. Third, a number of the published studies have sought to explain cost trends based on cumulative wind power capacity installations or production in individual countries or regions of the world; because the wind energy industry is global in scope, however, it is likely that most learning is now occurring based on cumulative global installations. Finally, from 2004 through 2009, the installed cost of wind power plants increased substantially, countering the effects of learning, and questioning the sole reliance on cumulative installations as a predictor of future costs.

7.8.4.2 Engineering model estimates

Whereas learning curves examine aggregate historical data to forecast future trends, engineering-based models focus on the possible cost reductions associated with specific design changes and/or technical advancements. These models can lend support to learning curve predictions by defining the technology advances that can yield cost reductions and/or energy production increases.

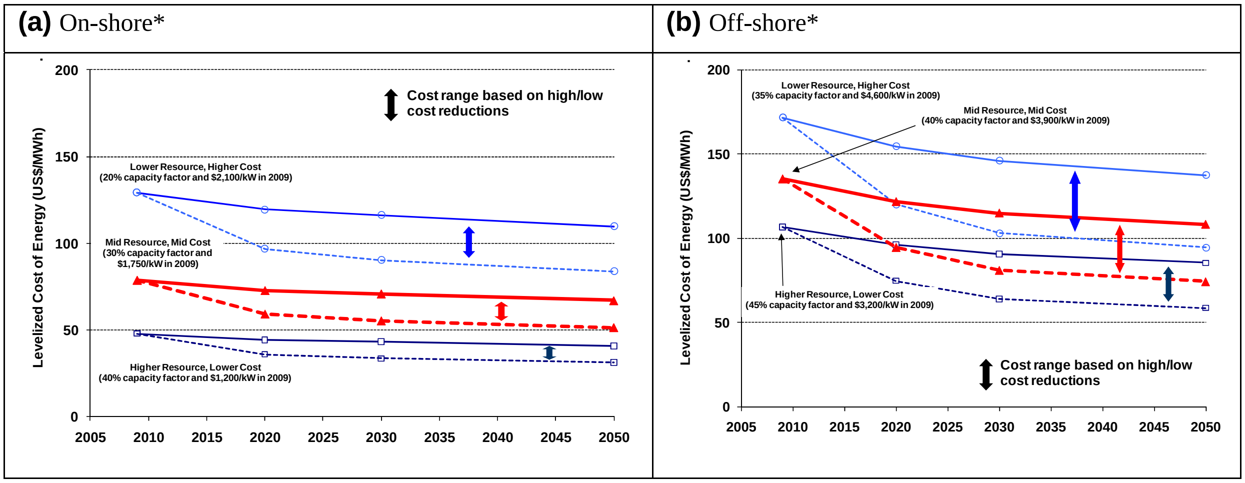
These models have been used to estimate the impact of potential technology improvements on wind power plant capital costs and energy production, as highlighted earlier in Section 7.3. Given these possible technology advancements (in combination with manufacturing learning), the U.S. DOE (2008) estimates that on-shore wind energy capital costs may decline by 10% by 2030, while energy production may increase by roughly 15%, relative to a 2008 starting point (see Table 7.4, and the note under that table). Combined, these two impacts correspond to a reduction in the levelized cost of energy from on-shore wind energy of 17% by 2030.

Given the relative immaturity of off-shore wind energy, there is arguably greater potential for technical advancements than in on-shore wind energy technology, particularly in foundation design, electrical system design, and O&M costs. Larger off-shore wind power plants are also expected to trigger more efficient installation procedures and dedicated vessels, enabling lower costs. Future energy cost reductions have been estimated by associating potential cost reductions with these technical improvements, resulting in cost reduction estimates ranging from 18-39% by 2020, and 17-66% by 2030 (Junginger *et al.*, 2004; Carbon Trust, 2008b; Lemming *et al.*, 2009).

7.8.4.3 Projected levelized cost of wind energy

A number of studies have estimated the cost trajectory for on-shore and off-shore wind energy based on learning curve estimates and/or engineering models (Junginger *et al.*, 2004; Carbon Trust 2008b; IEA, 2008; U.S. DOE, 2008; GWEC and GPI, 2008; Lemming *et al.*, 2009).

Using the estimates and assumptions for the expected percentage cost reduction in levelized cost of energy from these specific studies, a range of levelized cost trajectories have been developed for representative future on-shore and off-shore wind power plants (Figure 7.20(a,b)). In both of the graphics, a high, low, and mid-level starting point for the levelized cost of energy is calculated using various combinations of plant-level capacity factor and installed cost assumptions, representing a reasonable average range of 2009 values.[27] These levelized cost estimates for 2009 are the same as presented earlier in Figure 7.19. To forecast a range of future costs, high and low levelized cost reduction estimates were developed based on the literature cited above. That literature suggested a range of levelized cost reductions for on-shore wind of roughly 7.5-25% by 2020 and 15-35% by 2050, and for off-shore wind of roughly 10-30% by 2020 and 20-45% by 2050.[28]



(a) On-shore*

(b) Off-shore*

* Starting-point O&M costs are assumed to equal US$16/MWh (on-shore) and US$30/MWh (off-shore); a 7% discount rates is used throughout

Figure 7.20. Projected levelized cost of (a) on-shore and (b) off-shore wind energy, 2009-2050

Based on these assumptions, the levelized cost of on-shore wind energy could range from roughly US$30-110/MWh by 2050, depending on the wind resource, installed cost, and the speed of cost reduction. Off-shore wind energy is likely to experience somewhat deeper cost reductions, with a range of expected levelized costs of US$60-140/MWh by 2050.

Uncertainty exists over future wind energy costs, and the range of costs associated with varied wind resource strength introduces greater uncertainty. As installed wind power capacity increases, higher quality resource sites will tend to be utilized first, leaving higher-cost sites for later deployment. As a result, the average levelized cost of wind energy will depend on the amount of deployment. This “supply-curve” affect is not captured in the estimates presented in Figure 7.20: those projections present potential cost reductions associated with wind power plants located in specific wind resource regimes. The estimates presented here therefore provide an indication of the technology advancement potential for on- and off-shore wind energy, but should be used with caution.

7.9 Potential deployment

Wind energy offers significant potential for near- and long-term carbon emissions reduction. The wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050. On a global basis, the wind resource is unlikely to constrain further development (Section 7.2). On-shore wind energy technology is already being deployed at a rapid pace (Sections 7.3 and 7.4), therefore offering an immediate option for reducing carbon emissions in the electricity sector. In good to excellent wind resource regimes, the cost of on-shore wind energy averages US$50-100/MWh

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[27] Figures outside of this range are certainly possible, however. Moreover, because of the cost drivers discussed earlier in this chapter, wind energy costs in 2009 were higher than in some previous years. Applying the percentage cost reductions from the available literature to the 2009 starting point is, therefore, arguably a conservative approach to estimating future cost reduction possibilities.

[28] The absolute range suggested by the studies reviewed is somewhat larger than that used here.

(Section 7.8), and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems (Section 7.5). Continued technology advancements and cost reductions in on- and off-shore wind energy are expected (Sections 7.7 and 7.8), further improving the carbon emissions mitigation potential of wind energy over the long term.

This section begins by highlighting near-term forecasts for wind energy deployment (7.9.1). It then discusses the prospects for and barriers to wind energy deployment in the longer-term and the potential role of that deployment in meeting various GHG mitigation targets (7.9.2). Both subsections are largely based on energy-market forecasts and carbon and energy scenarios literature published in the 2007-2009 time period. The section ends with brief conclusions (7.9.3). Though the focus of this section is on larger on- and off-shore wind turbines for electricity production, alternative technologies for harnessing wind energy exist and have served and will continue to meet other energy service needs.

7.9.1 Near-term forecasts

The rapid increase in global wind power capacity from 2000-2009 is expected by many studies to continue in the near- to medium-term (Table 7.7). From the roughly 160 GW of wind power capacity installed by the end of 2009, the IEA [TSU: (2009b)] (IEA, 2009b) and U.S. Energy Information Administration (US EIA, 2010) *reference-case* forecasts predict growth to 295 GW and 277 GW by 2015, respectively. Wind energy industry organizations predict even faster deployment rates, noting that past IEA and EIA forecasts have understated actual wind energy growth by a sizable margin (BTM, 2010; GWEC, 2010a). However, even these more-aggressive forecasts estimate that wind energy will contribute less than 5% of global electricity supply by 2015. Asia, North America, and Europe are projected to lead in wind power capacity additions over this period.

Table 7.7. Near-term global wind energy forecasts

Study	**Wind Energy Forecast**		
	Installed Capacity	**Year**	**% of Global Electricity Supply**
IEA (2009b)*	295 GW	2015	2.8%
(US EIA, 2010)*	277 GW	2015	3.1%
GWEC (2010b)	409 GW	2014	not available
BTM (2010)	448 GW	2014	4.0%

* Reference case forecast

7.9.2 Long-term deployment in the context of carbon mitigation

A number of studies have tried to assess the longer-term potential of wind energy, especially in the context of carbon mitigation scenarios. As a variable, location-dependent resource with limited dispatchibility, modelling the economics of wind energy expansion presents unique challenges (e.g., Neuhoff *et al.*, 2008). The resulting differences among studies of the long-term deployment of wind energy may therefore reflect not just varying input assumptions and assumed policy and institutional contexts, but also differing modelling or scenario analysis approaches.

The IPCC’s Fourth Assessment Report assumed that on- and off-shore wind energy could contribute 7% of global electricity supply by 2030, or 8 EJ/y (2,200 TWh/y) (IPCC, 2007). Not surprisingly, this figure is higher than some commonly cited business-as-usual, reference-case forecasts (after all, the IPCC estimate is not a business-as-usual case). The IEA’s World Energy Outlook reference-case, for example, predicts 5.7 EJ/y (1,535 TWh/y) of wind energy by 2030, or 4.5% of global electricity supply (IEA, 2009b). The U.S. EIA forecasts 4.6 EJ/y (1,234 TWh/y) of wind energy in its 2030 reference case projection, or 3.9% of net electricity production from central producers (US EIA, 2010).

A summary of the literature on the possible contribution of RE supplies in meeting global energy needs under a range of CO_2 stabilization scenarios is provided in Chapter 10. Focusing specifically on wind energy, Figure 7.21 and Figure 7.22 present modelling results on the global supply of wind energy, in EJ/y and as a percent of global electricity supply, respectively; refer to Chapter 10 for a full description of the literature underlying these figures. Wind energy deployment results for 2020, 2030, and 2050 are presented for three CO_2 stabilization ranges, based on the IPCC's Fourth Assessment Report: 600-1000 ppm-CO_2 (baselines, or reference cases), 440-600 ppm (Categories III and IV), and 300-440 ppm (Categories I and II), all by 2100.

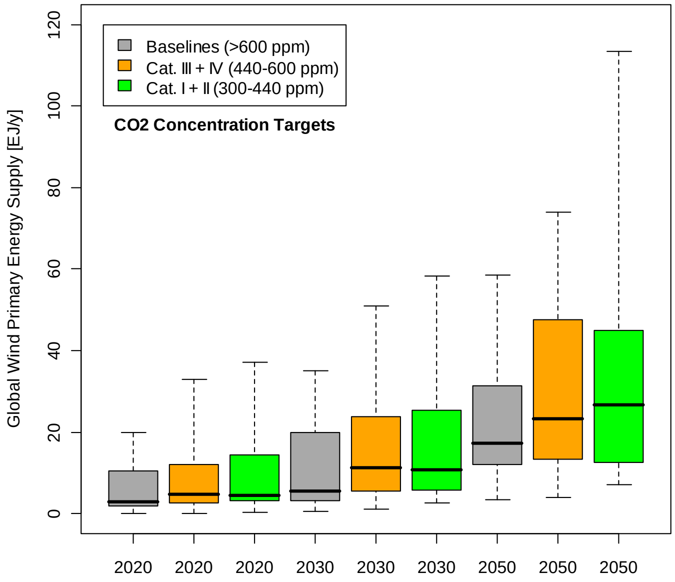

Figure 7.21. Global total primary energy supply of wind energy in carbon stabilization scenarios (median, 25th to 75th percentile range, and absolute range) [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

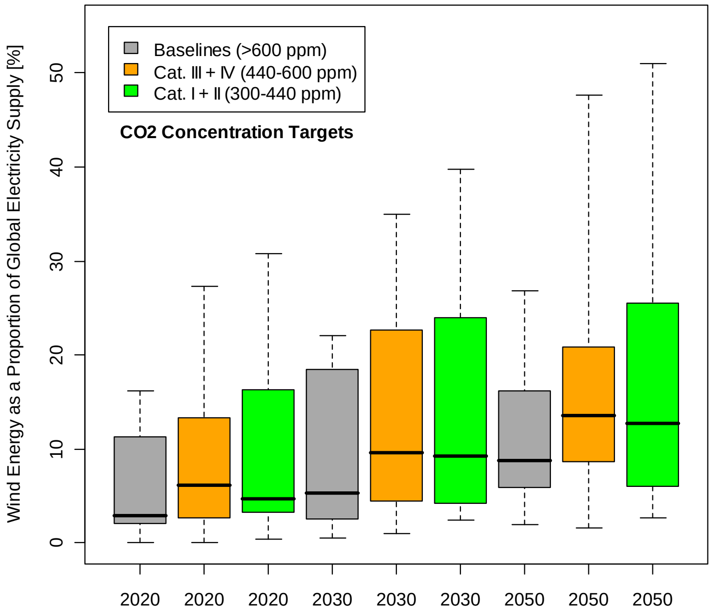

Figure 7.22. Wind electricity share in total global electricity supply (median, 25th to 75th percentile range, and absolute range) [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

The reference, or baseline-case (600-1000 ppm-CO_2) projections of wind energy's role in global energy supply span a broad range, but with a median of roughly 3 EJ/y in 2020, 6 EJ/y in 2030, and 18 EJ/y in 2050 (Figure 7.21). Substantial growth of wind energy is therefore projected to occur even in the absence of GHG mitigation policies, with wind energy's median contribution to global electricity supply rising from 1.8% by the end of 2009 to 9% by 2050 (Figure 7.22). Moreover, the contribution of wind energy grows as GHG mitigation policies are assumed to become more stringent: by 2030, wind energy's median contribution equals roughly 10 EJ/y (~9% of global electricity supply) in the 440-600 and 300-440 ppm-CO_2 stabilization ranges, increasing to 22-26 EJ/y by 2050 (~13% of global electricity supply).[29]

The diversity of approaches and assumptions used to generate these scenarios is great, however, resulting in a wide range of findings. Reference case results for global wind energy supply in 2050 range from 3-58 EJ/y (median of 18 EJ/y), or 2-27% (median of 9%) of global electricity supply. In the most-stringent 300-440 ppm stabilization scenarios, wind energy supply in 2050 ranges from 7-113 EJ/y (median of 26 EJ/y), equivalent to 3-51% (median of 13%) of global electricity supply.

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[29] In addition to the global scenarios literature, a growing body of work has sought to understand the technical and economic limits of wind energy deployment in regional electricity systems. These studies have sometimes evaluated higher levels of deployment than contemplated by the global scenarios, and have often used more-sophisticated modelling tools. For a summary of a subset of these scenarios, see Martinot *et al.*, 2007; examples of studies of this type include Deutsche Energie-Agentur, 2005 (Germany); EC, 2006; Nikolaev *et al.*, 2008, 2009 (Russia); and US DOE, 2008 (United States). In general, these studies confirm the basic findings from the global scenarios literature: wind energy deployment to 10% of global electricity supply and then to 20% or more are plausible, assuming that cost and policy factors are favourable.

Despite this wide range, the IPCC (2007) estimate for potential wind energy supply of roughly 8 EJ/y by 2030 (which was largely based on literature available through 2005) appears somewhat conservative compared to the more-recent scenarios literature presented here. Other recent forecasts of the possible role of wind energy in meeting global energy demands confirm this assessment, as the IPCC (2007) estimate is roughly one-third to one-half that shown in GWEC and GPI (2008) and Lemming *et al.* (2009). The IPCC (2007) estimate is more consistent with but still somewhat lower than that offered by the IEA World Energy Outlook (2009 [TSU: 2009b]; 450 ppm case).

Though the literature summarized in Figures 7.21 and 7.22 shows an increase in wind energy with increasingly aggressive GHG targets, that impact is not as great as it is for biomass, geothermal, and solar energy, where increasingly stringent carbon stabilization ranges lead to more-dramatic increases in technology deployment (see Chapter 10). One explanation for this result is that wind energy is already comparatively mature and economically competitive; as a result, continued deployment is predicted even in the absence of aggressive efforts to reduce carbon emissions.

The scenarios literature also shows that wind energy could play a significant long-term role in reducing global carbon emissions: by 2050, the median contribution of wind energy in the two carbon stabilization scenarios is 22-26 EJ/y, increasing to 45-50 EJ/y at the 75th percentile, and to more than 100 EJ/y in the highest study. To achieve this contribution requires wind energy to deliver around 13% of global electricity supply in the median case, and 21-26% at the 75th percentile. Other scenarios generated by wind energy and RE organizations are consistent with this median to 75th percentile range; GWEC and GPI (2008) and Lemming *et al.* (2009), for example, estimate the possibility of 32-37 EJ/y of wind energy supply by 2050.

To achieve these levels of deployment, policies to reduce carbon emissions and/or increase RE supplies would likely be necessary, and those policies would need to be of adequate economic attractiveness *and* predictability to motivate substantial private investment (see Chapter 11). A variety of other possible challenges to aggressive wind energy growth also deserve discussion.

Resource Potential: First, even the highest estimates for long-term wind energy supply in Figure 7.21 are below the global technical wind resource potential estimates presented in Section 7.2, suggesting that – on a global basis, at least – technical resource potential is unlikely to be a limiting factor to aggressive levels of wind energy deployment. Moreover, ample potential exists in most regions of the world to enable significant wind energy development. In certain countries or regions, however, higher deployment levels will begin to constrain the most economical resource supply, and wind energy will therefore not contribute equally in meeting the needs of every country.

Regional Deployment: Second, wind energy would need to expand beyond its historical base in Europe and, increasingly, the U.S. and China. The IEA WEO reference-case forecast projects the majority of wind energy deployment by 2030 to come from OECD Europe (40%), with lesser quantities from OECD North America (26%) and portions of Asia (e.g., 15% in China and 5% in India) (IEA, 2009b). Under higher-penetration scenarios, however, a greater geographic distribution of wind energy deployment is likely to be needed. Scenarios from GWEC and GPI (2008), EREC and GPI (2008), and IEA (2008), for example, show North America, Europe, and China to be the areas of greatest wind energy deployment, but also identify a number of other regions that are projected to be significant contributors to wind energy growth in high-penetration scenarios (Table 7.8).[30] Enabling this level of wind energy development in regions new to wind energy would be a challenge, and would benefit from institutional and technical knowledge transfer from those regions that are already witnessing substantial wind energy activity (e.g., Lewis, 2007; IEA, 2009a).

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[30] Many of these other regions have lower expected electricity demands. As a result, some of the regions that are projected to make a small contribution to global wind electricity supply are still projected to obtain a sizable fraction of their own electricity supply from wind energy.

Table 7.8. Regional distribution of global wind electricity supply (percentage of total worldwide wind electricity supply)

Region	GWEC / GPI (2008)***** **2030** ***'Advanced' Scenario***	EREC and GPI (2008) **2050** ***'Energy Revolution' Scenario***	IEA ETP (2008) **2050** ***'BLUE' Scenario***
Global Supply of Wind Energy (EJ)	20 EJ	28 EJ	19 EJ
OECD North America	22%	20%	13%
Latin America	8%	9%	10%
OECD Europe	15%	13%	23%
Transition Economies	3%	9%	3%
OECD Pacific	9%	10%	7%
China	19%	20%	31%
India	10%	7%	4%
Developing Asia	9%	7%	3%
Africa and Middle East	5%	5%	6%

* For GWEC/GPI (2008), percentage of worldwide wind power capacity is presented.

Supply Chain Issues: Third, while efforts would be required to ensure an adequate supply of labour and materials, no insurmountable long-term constraints to materials supply, labour availability, or manufacturing capacity are envisioned if policy frameworks for wind energy are sufficiently economically attractive *and* predictable (e.g., US DOE, 2008). The wind energy industry has scaled rapidly over the last decades, resulting in greater globalization and competition throughout the value-chain (see Section 7.4). Annual additions and manufacturing volume reached 38 GW in 2009, and the significant further scaling needed to meet the increased manufacturing demands of higher-penetration scenarios (see Section 10.3) appears challenging, but feasible.

Technology and Economics: Fourth, due to resource and siting constraints in some countries and regions, greater reliance on off-shore wind energy, particularly in Europe, is likely to be required. Estimates of the proportion of total global wind energy supply likely to be delivered from off-shore wind energy in 2050 range from 18% to 30% (EREC and GPI, 2008; IEA, 2008; Lemming *et al.*, 2009), while the IEA forecasts a 20-28% share by 2030 (IEA, 2009b). Increases in off-shore wind energy of this magnitude would require technological advancements and cost reductions. Though R&D is expected to lead to incremental cost reductions for on-shore wind energy technology, enhanced R&D expenditures by government and industry may be especially important for off-shore wind energy technology given its less mature state (see Section 7.7).

Integration and Transmission: Fifth, technical and institutional solutions to transmission constraints and operational integration concerns will need to be implemented. Analysis results and experience suggest that many electric systems can operate with up to roughly 20% wind energy with relatively modest integration costs (see Section 7.5 and Chapter 8). Though comparatively few studies have explored wind electricity supply in excess of 20% in detail, there is little evidence to suggest that an insurmountable technical limit exists to wind energy's contribution to electricity supply.[31] Nevertheless, the concerns about (and the costs of) operational integration and

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[31] Some studies have looked at wind electricity penetrations in excess of 20% in certain regions, often using somewhat-less-detailed analysis procedures than formal wind energy integration studies, and often involving the use of structural change in generation portfolios, electrical or thermal storage, plug-in hybrid vehicles and the electrification of transportation, demand response, and/or other technologies to manage the variability of wind power output (e.g., Grubb, 1991; Watson *et al.*, 1994; Lund and Münster, 2003; Kempton and Tomic, 2005;

maintaining electric system reliability will grow with wind energy deployment, and efforts to ensure adequate system-wide flexibility, employ more-restrictive grid connection standards, develop and use improved wind forecasting systems, and encourage load flexibility and electrical storage are warranted. Moreover, given the locational dependence of the wind resource, substantial new transmission infrastructure both on- and off-shore would be required under even the more modest wind energy deployment scenarios presented earlier. Both cost and institutional barriers would need to be overcome to develop this needed transmission infrastructure (see Section 7.5 and Chapter 8).

Social and Environmental Concerns: Finally, given concerns about the social and environmental impacts of wind power plants summarized in Section 7.6, efforts to better understand the nature and magnitude of these impacts, together with efforts to minimize and mitigate those impacts, will need to be pursued in concert with increasing wind energy deployment. Prominent environmental concerns about wind energy include bird and bat collision fatalities and habitat and ecosystem modifications, while prominent social concerns include visibility and landscape impacts as well various nuisance effects and radar interference. Though community and scientific concerns need to be addressed, streamlined planning, siting, and permitting procedures for both on- and off-shore wind energy may be required to enable the wind power capacity additions envisioned under these scenarios.

7.9.3 Conclusions regarding deployment

The literature presented in this section suggests that wind electricity penetration levels that approach or exceed 10% of global electricity supply by 2030 are feasible, assuming that cost and policy factors are favourable towards wind energy deployment. The scenarios further suggest that even-more ambitious policies and/or technology improvements may allow wind energy to ultimately reach or exceed 20% of global electricity supply, and that these levels of supply would be economically attractive within the context of global carbon mitigation scenarios. There are, however, a variety of barriers that would need to be overcome if wind energy was to achieve these aggressive levels of penetration. In particular, the degree to which wind energy is utilized in the future will largely depend on: the economics of wind energy compared to alternative power sources; policies to directly or indirectly support wind energy deployment; local siting and permitting challenges; and real or perceived concerns about the ability to integrate wind energy into electric supply systems.

Denholm, 2006; DeCarolis and Keith, 2006; Lund, 2006; Black and Strbac, 2006; Cavallo, 2007; Greenblatt *et al.*, 2007; Hoogwijk *et al.*, 2007; Leighty, 2008; Lamont, 2008; Benitez *et al.*, 2008; Lund and Kempton, 2008; Kiviluoma and Meibom, 2009). These studies confirm that there are no insurmountable technical barriers to increased wind energy supply; instead, as deployment increases, transmission expansion and operational integration costs will increase, constraining growth on economic terms. These studies also find that new technical solutions that are not otherwise required at lower levels of wind energy deployment, such an expanded use of storage and responsive loads, will become increasingly valuable at higher levels of wind energy development.

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 8

Integration of Renewable Energy into Present and Future Energy Systems

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(Sub)Section:	All	
Author(s):	CLAs:	W. Krewitt†, P. Mercado. R. Sims
	LAs:	G. Bhuyan, G. Jannuzzi, S. Khennas, Y. Liu, L. J. Nilsson, J. Ogden, K. Ogimoto, H. Outhred, O. Ulleberg, F. van Hulle
	CAs:	T. Demayo, A. Lee, M. O'Malley
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Chapter 8 has been allocated a total of 102 pages in the SRREN. The actual chapter length (excluding references & cover page) is 110 pages: a total of 8 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened in terms of text and/or figures and tables.

Chapter 8: Integration of Renewable Energy into Present and Future Energy Systems

Executive Summary

Integration of large shares of renewable energy (RE) into the energy supply system (presently dominated by fossil fuels) will require a major paradigm shift rather than just making simple, minor adjustments. Due to the variable nature of most RE sources, either over seasons or within minutes, cost-effective integration into present heating/cooling networks, natural gas grids, liquid transport fuel supply and distribution, buildings, industrial processes, and in particular into electricity supply systems, has proven to be challenging. Many examples exist of successful integration of specific RE technologies, often as a result of supporting local and national policies and measures that depend on the RE cost-effectiveness, social acceptance, reliability and co-benefits including energy security. However, if greater shares of RE are to be accommodated, other energy markets may need adapting and expanding and to avoid continued growth of GHG emissions from fossil fuel combustion, the rate of RE penetration will need to be more rapid than has been the case to date.

In the long-term, RE has the technical potential to provide the major share of global energy. Indeed some regions and towns are already close to achieving 100% RE supply, including for heat and local transport. Through measured system integration, there are few, if any, technical limits to the level of RE penetration in the many parts of the world where sufficient resources exist. RE could provide the full range of desirable energy services to both large and small communities in both developed and developing countries. The necessary transition will require considerable investment in new infrastructure, (including novel transport methods, distributed energy systems, energy storage, electricity transmission on- and off-shore, intelligent grids) together with improvements in energy efficiency for both the supply-side and final end-use.

Increased deployment of RE in both urban and rural areas will depend upon local and regional resources, energy demand patterns, project finance, and current markets. Limitations to deployment exist where specific site conditions, local RE resource characteristics and energy demand profiles are not conducive. The general and specific requirements to overcome barriers preventing greater penetration of RE into heating, cooling, electricity, gas and liquid networks, autonomous buildings and communities, are reasonably well understood. Several real-world case studies have been included in the chapter to outline the benefits of RE and to illustrate how integration approaches can be successfully achieved through an optimum combination of technologies, markets and social and institutional mechanisms that suit a specific energy market.

Few comparative cost assessments for RE integration options have been presented in the literature. A European study of up to 20% wind energy penetration found additional power system operating costs to be around 10% of the total wind generation costs. However, a similar US study identified the additional costs to be more wide ranging, between 7% and 32% of capital expenditure for different power supply systems. The contrasting future visions for decentralised, small-scale, energy supply systems ("intelligent grids") or large-scale, RE project integration, also make determination of future RE integration costs and potentials difficult. For RE heat, the additional cost of integrating biomethane into natural gas distribution systems can range between US$ 5-15 /GJ [TSU: figure will need to be adjusted to 2005 US$] varying with gas clean-up standards and whether transport is by pipeline or truck. For the transport sector, when and to what extent hydrogen fuel cell, hybrid biofuel, or electric vehicles might displace the current light duty vehicle fleet partly depends on the cost of developing the supporting infrastructure. Given all these uncertainties, further research and analysis will be required if useful integration cost data is able to be provided for scenario modelling.

Several risks and impacts involve the integration and deployment of RE. These include the sustainable use of land, water and materials, capacity building, technology transfer, and financing. For each of the transport, building, industry and agricultural sectors of the global economy, these risks are reasonably well understood, but no single integration pathway to gain increased RE uptake has been identified. Developing a coherent framework in preparation for higher RE penetration levels requires a good understanding of the diverse range of global energy supply systems.

- For the electricity sector, it is not possible to standardise on a single method for the transition from a traditional system to a highly flexible one. Whether large or small, each has its own particular governance, inter-connection, technology, market and commercial issues to deal with. In most systems, RE sources that do not fluctuate over the short term, and use mature technologies, are dispatchable and can be feasible as baseload options, in particular reservoir-hydro, geothermal and bioenergy. International experience of the integration of variable RE, mainly wind, has shown that high levels of penetration (>20%) can be feasible if facilitated by methods and investments that increase the flexibility of a conventional system. These include the provision of inter-connection between power systems, sufficient network infrastructure and capacity, system control and operation across the network, accurate forecasting, demand-side response, energy storage, more flexible thermal power plants and an enabling electricity market framework. To increase the penetration of RE resources, the stakeholders associated with a given “electricity system” will need to determine their unique pathway, whether the system serves a village or a continent.
- Transport presently has low shares of RE, mainly as liquid biofuels blended with petroleum products. Advanced biofuels are more fungible with petroleum production and distribution systems so once developed cost-effectively could encourage greater penetration. The on-going development of electric- and hydrogen-powered vehicles could enable utilization of a greater variety of RE sources available in a region. However, cost reduction challenges are evident and uncertainties remain concerning the source of the energy carriers, the related infrastructure and future technology developments.
- In the building sector, many successful examples exist of heating and cooling systems using biomass (for domestic cooking, space heating, district heating); geothermal (for high temperature process heat or low temperature ground source heat pumps); and solar thermal (for water and space heating, as well as for active cooling, at the domestic, community or district scales). Building-integrated electricity generation technologies provide the potential for building owners to become energy suppliers rather than just energy consumers. Integration of RE into existing urban environments, combined with efficient “green building” design, is key to further deployment.
- Integration of RE by the industrial sector is site and process specific, whether for very large, energy-intensive, basic material industries to numerous small and medium-sized processing enterprises. Direct fossil-fuel substitution on-site is often feasible (such as bioenergy for co-firing or CHP generation). For energy systems at the large industrial scale, RE is usually integrated with energy efficiency, materials recycling, and, perhaps in the future, CCS strategies. In addition, local industries can provide demand-response services for electricity supply systems (and in particular for future designs based around intelligent grids).
- Agriculture, ranging from large corporate-owned farms to subsistence peasant farmers, is a relatively low energy consuming sector, with pumping of water for irrigation and indirect energy for manufacturing fertilisers the greatest contributors. RE sources such as wind, solar, crop residues, animal wastes, are often abundant for the landowner to utilise locally or to earn additional revenue from exporting useful energy carriers (such as electricity or biogas) off-farm.

Integration across transport, electricity, building and industry energy supply systems is conceivable in the future, thereby creating a paradigm shift and a step towards an energy transition. Regardless of the energy systems presently in place, whether in energy-rich or energy-poor communities, increased RE integration with the existing system is desirable. The rate of penetration will depend on an integrated approach that will include life-cycle analysis, comparative cost/benefit evaluations, policy framing and recognition of the social co-benefits that RE can provide.

8.1 Introduction

This chapter examines the means by which larger shares of renewable energy (RE) can be integrated into energy supply systems at national and local levels. To enable RE systems to provide a greater share of global heating, cooling, transport fuels and electricity will require the modification of conventional power supply systems, natural gas grids, heating/cooling applications, and liquid transport fuel supply and distribution networks, so that they can accommodate greater supplies of RE than at present (Fig 8.1).

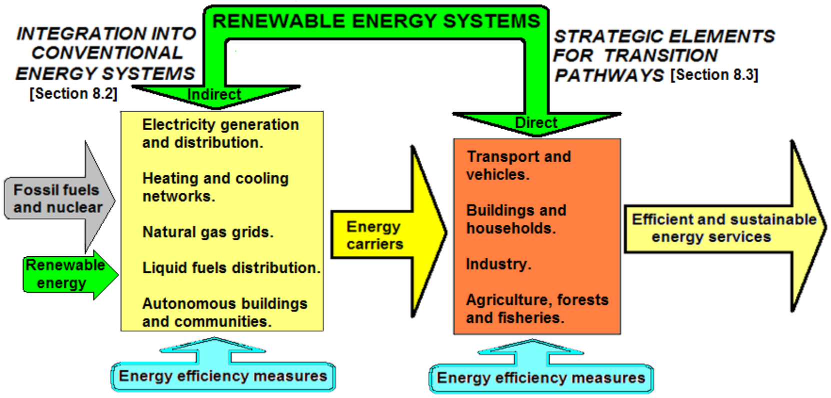

Figure 8.1: RE sources, additional to those presently being utilised in conventional energy systems, can be deployed indirectly through enhanced integration into energy carriers or directly on site by end-use sectors.

Overcoming specific technical barriers to increase deployment of a single RE technology are discussed in chapters 2-7. This chapter outlines more general barriers (including social ones) to RE integration at higher penetration levels and identifies possible solutions to overcoming them. Differences between geographic regions for the potential integration of RE vary with the current market status and the varying political ambitions of OECD and non-OECD countries. Diversifying supply by increasing domestic capacity, and by integrating a portfolio of local RE sources to meet an increased share of future energy demand growth, can make a positive contribution to improved energy supply security and reliability (Awerbuch 2006). Other than this and climate change mitigation benefits, RE systems can offer opportunities for sustainable development (Chapter 9), employment, improved health, and mitigation of supply risks from energy market instabilities, and hence improved security of energy supply. However, RE systems carry their own risks such as technical system failure, natural variation in resource availability from hourly to seasonally, price volatility, physical threats from extreme weather events, import dependence (e.g of biofuels), and relatively high capital costs under some conditions (IEA 2009).

Conventional energy systems are mainly based on oil, coal, gas, as well as nuclear, large hydro and traditional biomass. To achieve a rapid transition of the global energy sector away from the present dominance of fossil fuels will require uptake of more low carbon technologies. Nuclear power and carbon dioxide capture and storage (CCS) linked with coal- or gas-fired power generation as well as industry applications, will have a role to play alongside RE (Metz, Davidson et al. 2007). The transition of the energy sector will take time and involve significant investment costs (IEA 2009).

At present, the total shares of consumer energy supplied by RE systems remain low (Fig. 8.2). Shares in 2007 were around 16% of global electricity generation from hydro and 2-3% from wind, geothermal, bioenergy and solar; 1.5% of total transport fuels from biofuels; and 2-3% of total direct heating from solar thermal, geothermal and bioenergy (excluding domestic consumption of traditional biomass that accounts for around 10% of world primary energy) (IEA 2009). Annual average growth of primary RE between 2000 and 2007 was around 1.22 EJ/yr and could rise to 1.57 EJ/yr by 2030 under business-as-usual as shown in the IEA 2009 World Energy Outlook's Reference Scenario (*ibid)*. However, to make the necessary energy supply transition in order to achieve acceptable GHG atmospheric concentration stabilisation levels, the wide range of RE technologies will each need to continue to increase market shares out to 2030 as shown by the IEA 450 ppm Policy Scenario (Fig. 8.2), requiring an annual average rate of deployment growth at around 3.0 EJ/yr.

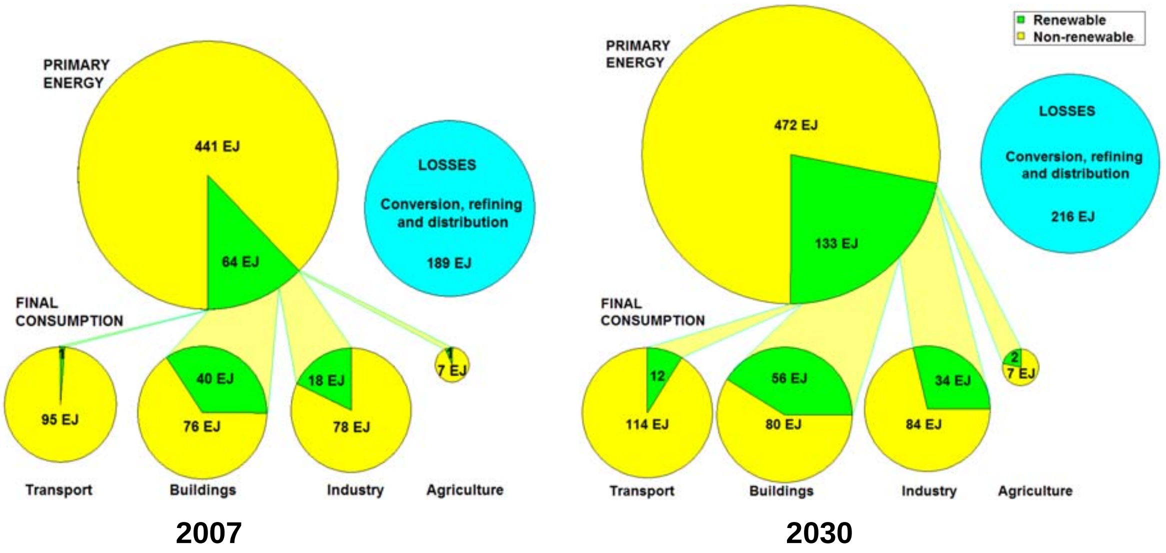

Figure 8.2: RE shares of primary energy and final consumption in the transport, buildings, industry and agriculture sectors in 2007, and indication of the increasing shares needed by 2030 to meet a 450 ppm stabilization target (IEA 2009).

Notes: Area of circles approximately to scale. "Non-renewable" energy includes coal, oil, natural gas (with and without carbon dioxide capture and storage (CCS) by 2030) and nuclear power. Energy efficiency improvements included in the 2030 projection. RE in the buildings sector includes traditional solid biomass fuels used for cooking and heating as used, along with coal, by 3 billion people in developing countries (UNDP 2009). This demand is projected to be replaced, in part, by more modern bioenergy systems by 2030.

Examples of successful integration of RE with conventional energy systems include both OECD and non-OECD countries such as:

- Brazil, with over 50% of light duty transport fuels supplied from sugar cane ethanol (Zuurbier and Vooren 2008);
- China, where two thirds of the world's solar water heaters have been installed (REN21, 2010);
- Denmark, with around 19.7% (7180 GWh) of total power in 2007 generated from wind turbines integrated with other forms of generation (mainly coal- and gas-fired) (DEA 2009);
- Spain, where the 2000 Barcelona Solar Thermal Ordinance resulted in over 40% of all new and retrofitted buildings in the area having a solar water heating system installed (EC 2006); and
- New Zealand and Iceland where the majority of electricity demand has been met from hydro and geothermal power plants for several decades.

It is anticipated that increased urbanisation will continue and that the more than 50% of world population living in cities and towns today, by 2030 will rise to 60% of the then 8.2 billion people (UNDP 2007). There is potential in many of these growing urban environments to capture local RE resources and thereby help meet an increasing share of future energy demands (Droege, Radzi et al. 2010). The potential exists to integrate RE systems into the buildings and energy infrastructure as well as to convert municipal and industrial organic wastes to energy (Chapter 2). However, existing local government planning regulations may restrict the deployment of such technologies (IEA 2009).

The required capacity, and hence cost, of a RE system will be less if it can be designed to meet a lower energy demand. Many energy scenarios show that a wide range of energy efficiency initiatives across the building, industry, transport and energy supply sectors will probably reduce future energy demand baseline projections significantly (Metz, Davidson et al. 2007). Whether reduced energy demand will encourage the greater uptake of RE over and above other energy sources is difficult to determine, but a lower demand could facilitate having a greater share of RE in a growing energy market (Verbruggen 2006). For example, before contemplating the installation of solar water heating, a wood pellet stove for space heating, or a small roof-mounted wind turbine for power generation, a building owner or developer should be encouraged to initially invest in energy saving measures and building design (IEA 2009).

Integration of RE into the energy supply system and infrastructure of many non-OECD countries today raises challenges that differ from those of OECD countries. A technology that is successful in one region may not be so in another, even where conditions are similar. There are significant regional and local differences in the potential and government support schemes (Chapters 10 and 11) with many developing country governments placing a higher priority on future economic development and security than on climate change mitigation, their major aim, as in India (MoP 2006) to supply electricity to the millions of people currently with limited or no access to modern energy services (UNDP 2009). The deployment of low-carbon technologies, particularly RE, could be a win/win solution (Chapter 9). Integration of RE into a new autonomous energy system in a rural region without energy infrastructure differs markedly from RE integration into regions which already have high shares of RE or where cross-border transmission options are possible. Small-scale, distributed, RE systems may be able to avoid the high capital cost of constructing infrastructure presently lacking (ARE 2009).

8.1.2 Objectives

A major objective of this chapter is to determine how problems of integration might affect the future deployment of RE technologies into conventional energy systems. For any given location, issues relating to a RE project can be complex as they can impact on land and water use; need to adhere to national and local planning and consenting processes; and require acceptance by the general public (as also would a fossil fuel, nuclear or CCS plant). Additional uncertainty results from some mature RE technologies failing to gain wider acceptance in the market, whereas others only close-to-market, are enjoying early integration into the energy supply system due to government support schemes. Co-benefits can drive governments to offer supporting policies (IEA 2008) (Chapter 9) regardless of relative costs. Many energy models have been produced that project how various energy supply sources could, together, meet future energy demands (Chapter 10). It is not the aim here to attempt to assess the potential rates of RE penetration or the future shares as a result of enhanced integration.

This chapter assesses the integration of RE into centralised, decentralised and autonomous, off-grid systems to provide desirable energy services (heating, cooling, lighting, communication, entertainment, motor drives, mobility, etc.). Regional differences between deploying various RE systems are highlighted, as are the barriers to deployment that depend on the system presently in place. Successful deployment depends upon the local energy resources, current energy markets, density of population, existing infrastructure, the ability to increase supply capacity, financing options and credit availability. The specific costs for each of the various technologies are covered in Chapters 2 to 7. It has not been possible in this chapter to accurately evaluate the future additional costs of system integration and deployment that modellers might wish, given the complexities, site-specificity, uncertainties and deficit of analysis in the literature (other than for wind, see Chapter 7). This poor understanding of integration costs is a barrier to wider deployment, so further analysis would be useful.

Ideally, energy systems need to be flexible enough to cope with future integration of the full range of RE technologies as they evolve. As market shares increase, competition between technologies as well as with incumbent fossil fuel-based technologies could result. Failing to recognise future competition can result in an over-estimation of the potential for any single technology. For example, if a local municipality supported the development of a large biomass-fuelled district heating scheme, existing solar and geothermal heating systems could become stranded assets. At the larger scale, should a large nuclear plant, or coal-fired power plant with CCS, be developed in a region to provide enough capacity to meet future electricity demand, then this would compete with investment capital and could potentially constrain the development of RE plants in the region for several decades, even where good RE resources exist. Similarly, for road transport, it is uncertain whether infrastructure for biofuel distribution for hybrid vehicles, electric vehicle recharging, or hydrogen production and storage will become dominant, or indeed if they will compete (section 8.3.1).

Factors such as technology experience cost curves, advances in existing technologies and RD&D developments are discussed in the technology chapters 2 to 7 that also examine issues of integration related to their specific technology. This chapter looks at the more complex cross-cutting issues relating to RE integration across technologies such as energy distribution and transmission through energy carriers, system reliability, energy balances, storage, system flexibility, ownership, project financing, market operation, supply security, social acceptance of the technology, public awareness, and providing a sense of independence. External factors such as future carbon and oil prices are covered in Chapter 10.

8.1.3 Structure of the chapter

Section 8.2 discusses the integration of RE systems into existing and future supply-side systems for electricity, heating and cooling networks, gas grids and liquid fuel distribution as well as autonomous systems. Where relevant, the integration costs and benefits of system design, technology components to facilitate integration, operation and maintenance strategies, markets and costs are discussed. The contrasting opportunities for small-scale distributed energy systems for heat, power and biofuels compared with large-scale district heating, high voltage, trans-continental, super-grid systems and liquid fuel pipelines are compared.

Section 8.3 outlines the strategic elements and non-technical issues needed for transition pathways for each of the transport, building, industry and agriculture sectors in order to gain greater RE deployment. The relevance of improved energy efficiency measures is included. The current status, possible pathways to enhance adoption of RE, related transition issues, and future trends are discussed for each sector. Major differences between sites and regions, as well as the different approaches necessary for centralised, decentralised and stand-alone RE supply systems, are assessed for both OECD or non-OECD countries.

8.2 Integration of renewable energy into supply systems

Conventional energy systems have evolved over many decades to enable efficient and cost-effective distribution of electricity, gas, heat and transport fuels to provide useful energy services to end-users. Increasing the deployment of RE systems requires their integration into these existing systems leading to more sustainable ones. This section outlines the issues and barriers involved as well as some solutions. It begins with the complexities of the various electricity systems operating around the world that differ markedly. Prerequisites for efficient and flexible energy conversion, mutual support between energy sectors, and an intelligent control strategy involve coherent long-term planning and taking a holistic approach to enable the whole energy system to provide electricity, heating, cooling and mobility. Electricity systems could ultimately become the backbone of future RE-based energy supply should an increase in global electricity demand result from a higher than anticipated share of "green" electricity being substituted for fossil fuel demand in the heating and transport sectors.

8.2.1 Electric power systems

"Achieving high penetration of renewable technologies with their variable generation characteristics will require many fundamental changes in the ways that electric power systems are planned and operated to maintain reliable energy service and to do so economically" (PSERC 2010).

Within a power supply system, some RE sources (such as reservoir-hydro, bioenergy and geothermal) are dispatchable whereas others (such as fluctuating wind, wave and solar PV) are non-dispatchable[1]. Efficient integration of large shares (generally above 20% but depending on the prevalent generation sources available for a specific power system) of these variable RE sources into an existing electricity generation system will require a major paradigm shift in the design and operation of a power system rather than making minor adaptations. This is an essential part of the transition from conventional systems with zero or very limited shares of variable, non-dispatchable generation together with a predominantly inflexible load demand, to more innovative systems encompassing high penetration of non-dispatchable plant, highly flexible generation plant, as well as flexible demand. Such a transition would need to be carefully managed over many years which could be a challenge, especially for countries with less political stability. Increasing the penetration[2] of RE in any given system will vary depending upon the existing plant and infrastructure, methods of operation, system flexibility and market design.

8.2.1.1 Features and structure of power systems

There are many textbooks and papers that discuss electric power systems at various levels of specialization (Freris and Infield 2008; El-Sharkawi 2009; Ummels 2009). This section therefore will provide only a brief summary of the issues relevant to RE integration. The overall aim of any power supply system, small or large, autonomous or inter-connected, is to balance supply with continually fluctuating demand at all times in order to avoid outages and maintain quality of supply (Box 8.1). The technical components (that are a subset of an electricity industry) include the processes of generation (converting primary energy forms in power stations into electrical energy), transmission (transferring electrical energy at high voltage over large distances up to 1000s of kms), distribution (transferring electrical energy at low voltage over local networks), and delivery to power end-use appliances that provide valued energy services. Consumers can, in principle, provide a proactive response by controlling at least part of their demand.

Most modern power supply systems have a portfolio of grid-connected generation technologies, often including large hydro and a relatively small share of other RE technologies, mainly wind, geothermal, bioenergy CHP and solar. The most common conventional "thermal" generation

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[1] The term non-dispatchable should be interpreted with care. In this report it denotes the characteristics of a variable RE source that at the system level can be dispatched to a major extent only by decisions of the system operator (for delivering positive and negative regulating power) if primary energy (wind or solar) is spilled (not used). Equally, if variable RE resources are not used in a must-run mode, primary energy will be spilled. There is always, however, a portion of "non-dispatchable" sources that can be dispatched, especially when used at a large scale, due to the correlation between load demand and the resource.

[2] Penetration of RE in a power system is the share of the total gross annual electricity consumption.

technology is based on steam turbines using coal, natural gas or a nuclear reactor to heat water and produce steam that spins the turbine connected to a generator. In a gas turbine, compressed air is passed into a combustion chamber fired by natural gas or oil and the hot compressed gas spins the turbine. Steam and gas turbine technologies can be linked in a combined-cycle plant by passing the exhaust gas from the gas turbine into a heat-recovery boiler to produce steam. Transmission networks have usually evolved within the boundaries of a nation or state before, in some cases, later becoming inter-connected to reach continental scale. They use specialized switches, transformers and overhead and underground cables to transfer electric current between generators and grid connection points to local distribution networks. Distribution networks convey electrical energy from the grid connection points to the premises of consumers. Embedded generation that is connected directly to the local distribution network is becoming more significant, especially for smaller scale RE generation.

8.2.1.1.1 Design and operation of power systems

Electricity supply involves a complex technological system made up of a vast number of individual components which may have many different owners and operators. Electrical energy is not storable in a cost-effective manner so special attention must be paid to the design and operation of the overall system (Box 8.1). Its operation requires managing second-to-second short-term fluctuations through to long-term horizons for the planning of future investments in new assets. Spinning reserve plants (usually hydro or thermal plants in part-load operation) are able to respond quickly to load changes as a contingency to help manage the short-term balancing of supply and demand and the quality (voltage, frequency) of electrical energy. These, and other network resources, provide ancillary services which can be used in the decision-making processes of power system operators for system security management and to provide system robustness and reliability (Billinton and Allan 1996).

Forecasts of future industry operations out to days ahead can be used to support security management and other operational decisions such as unit dispatch and unit commitment, and out to a year ahead for fuel purchasing, reservoir-hydro scheduling and planned maintenance of generation and network assets. Longer-term forecasts are used for planning system expansion.

Box 8.1: Principles of power balancing in the system

Power system operation covers time scales ranging from seconds to days and, within those timeframes, it is the responsibility of the transmission system operator (TSO) to ensure a continual balance between generation and consumption. The essential parameter is the system frequency (typically 50 or 60 Hertz (cycles per second)); if generation exceeds consumption at any particular moment, the frequency rises, and if consumption exceeds generation it falls. Small supply-demand imbalances occur all the time, and running or primary reserve is activated automatically to maintain power balance and a near constant system frequency. Large imbalances occur less often, for example due to the tripping of a thermal unit, the sudden disconnection of a significant load, or the tripping of a major transmission line. Secondary reserves are held to deal with such contingencies. In the event that these prove inadequate, automatic shedding of pre-determined load is used as a last resort to bring the power system back into balance. Failure at this point results in the disconnection of all generation leading to a system collapse or “black-out”.

Consumption of electrical power varies by the minute, hour, day and season, usually following a distinct load profile. Economic dispatch decisions for scheduling generation plants are made in advance as a response to anticipated changing trends in demand (while primary and secondary controls continue to respond to unexpected imbalances). Coal-fired, and some bioenergy and geothermal generators, require several hours to be started and synchronized to the grid, and for shutting down. These are usually run continually as base load, as are nuclear and also RE plant such as run-of-river hydro where operating costs are low due to no fuel requirements. Plant with more rapid response times, such as gas turbines or reservoir-hydro, are generally used for meeting peak loads as needed.

The TSO managing the balancing task normally has access to real-time information provided by major generators (such as plant output, state of readiness, planned maintenance), the electricity market and other players on consumption, inter-connector usage schedules, load projections and where RE becomes more important, forecasts of RE generation hours or even days ahead. Where wholesale electricity markets exist, power producers bid in at a fixed time ahead, (usually ranging from 5 to 60 minutes, or up to days when dispatching balancing reserve power). Bids are then accepted or rejected.

8.2.1.1.2 Electricity demand characteristics

Electricity load reflects user requirements for energy services and the characteristics of the appliances installed to deliver those services, such as heating, cooking, motor drives, lighting etc. Operating a large inter-connected power system differs from a small isolated system. Traditionally, the design and operation of a power system has been centrally managed by the TSO. However with the introduction of smaller scale RE generation embedded directly in the distribution network, this is outside the monitoring and control of the TSO. The continued growth of such generation alongside significant transmission-connected RE capacity, is leading to a reappraisal of the role of central power system control. It also highlights the need to move away from traditional system balancing, when load control is a last resort, to a situation where, to a significant extent, load is designed and controlled to follow available variable generation.

In analyzing and predicting demand behaviour, it is useful to group end-users into residential, commercial, industrial and miscellaneous categories. Residential and commercial consumers tend to have strong diurnal, weekly and seasonal patterns, but sensitive to weather conditions, whereas industrial consumption is usually steadier over time. Traditional residential electricity tariffs normally have few time-dependent characteristics and supply is regarded as an “essential service”. Therefore little attempt to date has been made to actively engage residential or small commercial end-users in electricity industry decision-making, for example to modify peak load demand curves by tariff design. For large commercial and industrial end-users, more attention has been paid to tariffs that result in active engagement in operation and investment decision-making, particularly for those who own and operate embedded generators. With the advent of electronic electricity meters and advanced communication and control equipment, more attention is now being paid to active end-user and embedded generator engagement (Lund 2007). This is reflected in the growing international attention being given to the concept of the “smart grid” (Schweppe, Tabors et al. 1980; Cheung 2010) that envisages coordinated, decentralized decision making involving all electricity industry participants. The concept could assist with wide scale RE integration but is only at an early stage of development (8.2.1.6). Critical evaluations are in progress as it may have unintended consequences as yet undefined.

8.2.1.1.3 Institutional and regulatory issues

Power systems were traditionally organized as either state-owned or privately-owned regulated monopolies within the borders of individual nations or states. Today, competitive electricity models first introduced in the early 1990s are becoming more common. A successful transition from a state-owned, monopoly to a competitive industry structure (usually with an independent regulator) can take decades. As a result, the transition to higher penetration levels of RE generation is often taking place in the context of a partially completed transition, thereby adding additional complexity and risks. In addition, transitions are also often taking place in the context of increasing international connectivity between previously independent power systems. This may allow additional RE generation to be successfully integrated but new forms of governance could add further complexity. From experience, market regulation is critical as countries well advanced in market development have suffered significant problems due to inappropriate regulation. It remains unproven whether markets can deliver stable low electricity costs to consumers and to this is added the challenge of moving power systems to a more environmentally sustainable basis.

8.2.1.2 Characteristics of RE generation

There are differences between RE and 'conventional' (thermal, nuclear and large hydro) generation plants since several RE generation types have distinctive characteristics that relate to large-scale integration as they cannot always be dispatched to meet changing demand. Understanding these characteristics, and their interaction and impacts with other parts of the power system, is the basis for successful RE system integration. A major issue is the additional imbalances potentially introduced by variable RE sources but these can be largely accommodated by various means to increase grid flexibility (IEA 2008). Typically, the technical characteristics of variable RE generation can differ from conventional generation with respect to variability and predictability; resource location; electrical conversion system characteristics and power plant capabilities.

8.2.1.2.1 Variability and predictability

The power output from variable RE generation such as wind, solar PV, concentrating solar power (CSP) without storage, tidal and wave energy systems (IEA 2008), fluctuates with the variability of the local resource. From a system operation point of view, they are therefore regarded as non-dispatchable. Their fluctuations can be predicted with various levels of accuracy but do not necessarily correlate with fluctuating power demand. Depending on the share of the total demand covered by variable RE, the increased variability and uncertainty in the power system may necessitate changes in system operation (8.2.1.3).

Analyzing RE variability at different time scales is necessary to understand and deal with the impacts on the power system (IEA 2008; Holttinen, Meibom et al. 2009). The variability time-scale for reservoir-hydro power, biomass, geothermal, ocean salinity and ocean thermal systems ranges can be seasonal to decadal, whereas solar and wind can vary within seconds (Fig. 8.3).

Figure 8.3: Time-scale of the natural cycles of RE sources (IEA 2008).

Over large areas, the aggregation of output from variable RE plants located over a wide geographic region is often small due to variations in the RE resource at any given moment (Giebel 2007). As a consequence the aggregated "smoothed" output of multiple RE generators can fluctuate less in fractional terms than that of individual plants (IEA 2008; Holttinen, Meibom et al. 2009). Hence, the frequently-used term “intermittent” for variable RE technologies is considered misleading as when aggregated at the system level and over different types of RE, the total output does not change instantaneously between zero and full power (such as is the case when a thermal or nuclear plant trips out). Rather, it varies at a rate dictated by meteorological and geo-physical effects (EWEA 2005; IEA 2008).

Experience has shown that integration and accommodation of variable RE resources in the system can become more manageable from the technical and economic perspectives if methods of predicting variability over short time scales (from a few hours to a few days ahead) are sufficiently accurate. Major improvements in the accuracy of short-term forecasting methods of wind power have been accomplished (Giebel, Brownsword et al. 2003; Kariniotakis, Waldl et al. 2006; Lange, Wessel et al. 2009), with beneficial consequences on integration costs. Aggregated PV and wind generation over a wide geographic area is more predictable as a result of the smoothing effect (3.5.4 and 7.5.2), whereas diurnal tidal variations are fully predictable being deterministic. Estimation of wave characteristics can be more certain than for wind speeds owing to their slower frequency of variation and direct dependence on wind conditions over the wave fetch.

8.2.1.2.2 Resource location

The broad locational characteristics of RE have consequences for distribution and transmission network infrastructure (8.2.1.3). Small-scale RE systems (such as small biogas plants, solar PV integrated into buildings, and run\-of-river hydro) can often be installed at or near the demand centre. Medium-scale wind, biomass CHP and hydro power plants are often widely dispersed over a network but can usually be located reasonably close to demand centres. Such distributed RE-based generation can bring advantages for some grids but can also pose new challenges, mainly requiring better controls, smart meters and intelligent grids (IEA 2009) (8.2.1.6). Large-scale RE systems can be more remote such as solar PV and CSP plants located in deserts, remote on-shore and off-shore wind, geothermal, forest biomass and reservoir-hydro plants. Where RE plants are installed in areas primarily linked to the location of the resource and away from the load or existing electricity networks, substantial new transmission infrastructure may be required.

8.2.1.2.3 Electrical characteristics and power plant capabilities

Electrical conversion systems, especially of variable RE systems, can be different from the classical constant speed, synchronous generator systems. Consequently, power quality characteristics such as power and voltage fluctuations, harmonic injections, active and reactive power control capabilities, and frequency response characteristics, can be different from conventional generators (Ackermann 2005). In addition, RE generation, (especially when connected through power electronic converters as are most new wind power and solar PV plants), does not inherently provide the rotating mass inertia of large conventional turbines that is important for stabilizing the grid in the case of faults or changes in frequency (DBCCA 2010). These differences have consequences on specific ancillary grid services (shared by conventional and variable RE generation), and on the specific connection requirements to be complied with by generators to give secure grid operation (8.2.1.3. Issues and challenges).

New technology innovations enable wind plants to function more like conventional power plants by meeting a major part of the control requirements made on traditional power plants, and by delivering ancillary services (Burges, De Broe et al. 2003). In a broader sense, experiences from different projects show that RE can give significant support for power system operation, especially by the creation of virtual power plants (VPP) (Styczynski and Rudion 2009) (8.2.1.6). However these capabilities are inherently linked, or limited to, specific technologies used, where the cost to deliver a specific ancillary service, and more generally to participate in the power market, is an important consideration (Jansen, van der Welle et al. 2007; Waltham 2009).

8.2.1.3 Challenges for integrating renewable energies

8.2.1.3.1 Impacts

The magnitude and type of impact that RE generation could make on a given power system are primarily dependent on the penetration level of RE. On several systems in the mid-term, this may reach more than 20-30% of total annual electricity demand (EWEA 2009) and in the long-term, up to 100% may be possible (Greenpeace 2007). Analyses for large-scale wind power integration (EWEA 2005; Holttinen 2008) provided an overview of the effects from increasing RE generation on a power system and indicated the possible contributions towards impact mitigation and power system support that RE might provide.

Impact studies on various power systems, both in time (from seconds to years) and geographical scales (from local to system-wide), have been undertaken for wave and tidal power (Khan, Bhuyan et al. 2008) and wind (Holttinen, Meibom et al. 2009). The summary for wind (Fig. 8.4) could be worthwhile considering when analysing the combined impacts on power systems for all types of RE. Higher levels of RE integration depend upon whether a given power system can successfully deal with these impacts and identifying in advance any specific challenges that should be addressed.

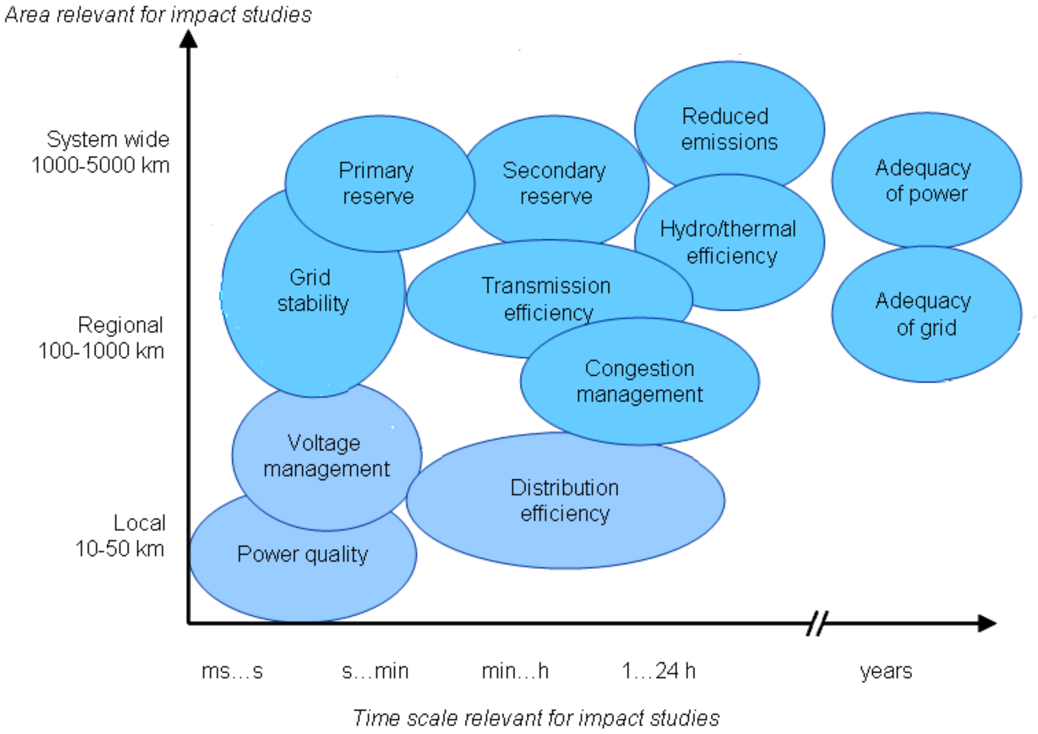

Figure 8.4: Impacts of wind power penetration on power systems by time and geographic area (Holttinen, Meibom et al. 2009), represent similar impacts from other variable RE sources.

8.2.1.3.2 Issues and challenges

The challenges brought by integrating variable and distributed RE systems highlight the need to address specific aspects of a power system. Integration issues have been analysed in several system studies, primarily for wind power to date, some for penetration levels reaching up to 50% (Eriksen and Orths 2008; EnerginetDK 2009). The experience with wind energy has more general relevance for other variable RE sources because it represents a challenging case in view of its high variability and relatively high penetration levels in some systems. There still is, however, a knowledge gap on integration issues for RE penetration levels higher than 20-30% of the demand. A current US project “The Western Wind and Solar Integration Study” is attempting to address this by studying the operational impact of up to 35% penetration from wind, PV and CSP (Lew, Milligan et al. 2009).

Based on wind energy integration experience (EWEA 2005; Holttinen, Meibom et al. 2009; Milligan, Lew et al. 2009), the main technical, economic, management and institutional challenges relate to:

- power system design, stability and operation at both generation and transmission levels;
- network reinforcement, extension and inter-connection of national and regional networks;
- network connection requirements for RE generation;
- system adequacy with high penetration of RE due to the low capacity value[3] (Giebel 2007) of several variable RE technologies; and
- electricity market design and corresponding market rules.

Power system design, stability and operation at the generation level

- *Increased reserve requirements* System balancing requirements (Box 8.1) are made more difficult by increased fluctuations and forecast errors, both of variable RE supply and load demand, since these are generally not correlated. This has consequences for the various types of system reserves in terms of additional capacity, plant efficiency and fuel requirements, and increased cycling of thermal plant. For wind energy, these effects have been analysed for several national and regional power systems up to penetration levels of 40% (Holttinen, Meibom et al. 2009). Fourteen studies from Europe, Scandinavia and US indicated increased reserve requirements in the order of 1-15% of installed wind power capacity were required at 10% penetration, and 4-18% at 20% penetration. With increasing penetration, there was no indication of a steep rise in additional reserve requirements and balancing costs. Deployment of a more flexible generation mix with increasing penetration of variable RE over time is expected to result in only a steady increase in integration costs (DeCarolis and Keith 2005). To meet a very large share of demand from RE by having a mix in a more flexible generation system, a knowledge gap remains concerning increased reserve requirements and costs.
- *Need for short-term forecasting.* An essential element when operating systems with a significant share of variable RE is accurate, short-term forecasting of wind and other variable RE sources (Kariniotakis, Waldl et al. 2006). This has been confirmed by experience in countries with significant wind power penetration including Denmark (Orths and Eriksen 2008), Spain (Giraut 2009), and Germany (Lange, Wessel et al. 2009). Such forecasts, numerical weather prediction data, power output forecasts etc. are used by TSOs, energy traders and plant operators to reduce costs and improve system security. Accurate forecasting also enables variable RE to be better integrated into the scheduling system and traded, whilst ensuring that demand and power supply remain in balance. Solar radiation forecasts for use by PV and CSP generators can give benefits similar to wind forecasts (Cao and Lin 2008; Reikard 2009).
- *Excess RE production.* Where RE output exceeds the amount that can be safely absorbed by the system to meet the current load while still maintaining adequate reserves and dynamic control, and where insufficient transmission capacity is available for export, a part of RE generation may have to be discarded (Beharrysingh and van Hulle 2009; Ummels 2009). To avoid spilling RE

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[3] The capacity value (also known as capacity credit) of variable RE generation in a power system is equal to the amount of conventional generation capacity that can be replaced by this capacity without diminishing the security of supply level.

requires taking operational and infrastructure measures as well as developing economic solutions for demand side management and control (8.2.1.6).

- *Ancillary services.* Apart from the balancing requirements, a power system requires other ancillary services (such as black start capability after an outage) to ensure operational security and system stability. RE plants can provide some of these services such as reactive power control (Burges, De Broe et al. 2003; Jansen, van der Welle et al. 2007; Styczynski and Rudion 2009), although if operating reserve is provided by variable RE, it is at the cost of lost production. Hence RE is not normally the first or most frequent option to deploy, especially at low penetration levels. Therefore appropriate equipment should be maintained in the system to provide the ancillary services that cannot be delivered by RE plants.

Power system design, stability and operation at transmission and distribution level

Increasing penetration of RE generation has implications for the operation and management of the network.

- *Management of transmission grids.* Specific combinations of RE generation and load demand in terms of penetration level and geographical locations, can cause changes in the magnitude and direction of power flows and differences between scheduled and actual physical flows in the transmission grid (EWIS 2010). Operational issues include the need for:
    - increased monitoring and forecasting to maintain sufficient network reliability;
    - improved congestion management;
    - voltage and reactive power management;
    - priority access for RE plants;
    - priorities for curtailment of RE in critical situations (for example during the combination of low demand with high RE generation); and
    - operating distributed RE generation in the event of transmission failures so as to keep at least parts of the system operational and hence avoid total black-outs.
- *Management of distribution networks.* Connection of RE generation to low-voltage distribution networks introduces similar effects as in transmission grids. These include changing direction and quantity of real and reactive power flows and harmonic distortion from the use of power electronic converters which may affect operation of grid control and protection equipment. In general, there is less active management of distribution networks than of transmission grids (Ackermann 2005; Lopes, Hatziargyriou et al. 2006). Nevertheless, distribution networks may have to cope with varying RE generation levels without reducing the quality of supply. Embedded RE generation has the potential to support weak distribution grids and improve power quality by contributing to grid voltage and quality control (Lopes, Hatziargyriou et al. 2006).

Network reinforcement, extension and inter-connection of national and regional networks

Transmission systems in several parts of the world have been confined within countries or to limited areas. National or regional TSOs and regulators traditionally deal with grid issues, balancing, and power exchange as determined by legislation, grid topology, geographical situation and historical developments. Evaluating the adequacy of transmission capacity to enable significant additions of RE generation needs to account for other factors traditionally not taken into account. These include locational dependence of the RE resources; relative smoothing benefits of aggregating distributed RE generation over a large area; opportunities for transmission optimisation created by combining different types of RE generation (GE_Energy 2010); and evaluating the transmission capacity required to access the flexible resources needed to manage RE variability.

Long term transmission planning to enable gradually increasing RE penetration levels is a complex process which has to proceed carefully through various stages.

- Relatively low penetration (<10%) of variable RE in existing networks could add to existing transmission congestion (Van Hulle, Tande et al. 2009; EWIS 2010). The extent to which transmission upgrades are required depends on the effectiveness of congestion management (see above) and optimization of the system, such as by the utilisation of dynamic line rating (8.2.1.6).
- At higher penetration levels, or in order to access new remote RE resources, new lines may have to be built. Several studies have identified the need for expansion of transmission systems to accommodate RE (Corbus, Milligan et al. 2009; Van Hulle, Tande et al. 2009; EWIS 2010; GE_Energy 2010). Planning methods are facing the classic 'chicken and egg' problem as for both transmission and RE power projects, the planning uncertainty of one is a risk for the other. An individual RE plant can be approved and built within one or two years whereas its transmission lines can take a decade to plan, permit, and construct. Public opposition to new transmission lines is expected to continue to be a major constraint for the integration of large amounts of RE in countries where public consultation planning processes exist (DBCCA 2010).

Network connection requirements for RE generators

Known as "grid codes", network connection requirements impose constraints on RE plants, just like on any other generation plants, in order to give system security, prevent negative impacts occurring on the network, and minimise operational threats to the power system as a whole. Where significant RE generation is being deployed, the specific grid codes for variable RE are continually being refined (8.2.1.6). Wind farms, for example, are now commonly expected to ride through faults, such as experienced at the point of grid connection during a temporary collapse of network voltage. They can also be expected to contribute to power system frequency regulation and local voltage support, as well as to limit power ramp rates that might make power system balancing difficult. This is to enable greater RE penetration whilst maintaining an adequate and reliable power supply.

Grid codes have been viewed as a hindrance to developing new variable RE projects, although they could be better considered as a prerequisite for ensuring efficient integration, even if less justified at very low penetration levels (Ciupuliga, Gibescu et al. 2009). Grid codes are country and system-specific, so result in a wide disparity of requirements that RE equipment manufacturers, developers and plant operators have to face across the globe. Internationally harmonized connection requirements for RE plants, (such as through the European Network of Transmission Operators (ENTSO-E) that was founded to coordinate network planning across Europe), could avoid unnecessary costs for RE plant manufacturers and operators (Ciupuliga, Gibescu et al. 2009).

System generation adequacy with high penetration of variable RE

Variable RE capacity can replace only a minor portion of conventional power plant capacity in the short to medium term, (although the generation share may not be negligible). Consequently, when deploying variable RE at a large scale, existing conventional thermal or nuclear plants may have to be retained in the system before gradually being replaced with more efficient and flexible dispatchable RE plants. Furthermore, generation adequacy at higher variable RE penetration levels, especially when aiming at 100% penetration in the long-term, needs to be supported with other integration solutions such as cross-border transmission, demand response and energy storage where cost-effective to do so.

Wind power experience demonstrates that the load carrying capability (capacity value) per unit of rated capacity of variable RE generation, depends on several system-related parameters and on the level of penetration (Giebel 2007; Holttinen, Meibom et al. 2009). In situations with low wind penetration but high aggregated wind power capacity factors at times of peak load, the capacity value can be as high as 40%. On the other hand at high wind penetration, the capacity value can be as low as 5% when regional wind power output profiles correlate negatively with system load profiles (Boyle 2007; Holttinen, Meibom et al. 2009).

Electricity market design and corresponding market rules

Technical solutions will not work unless matched by market design enhancements including market aggregation and close-to-real-time operation. For example, long gate closure times ahead of generation lead to larger forecast errors of both variable RE production and load demand. This results in higher balancing costs because forecast accuracy inherently decreases with longer forecast horizons (Kariniotakis, Waldl et al. 2006; Lange, Wessel et al. 2009). In a fragmented electricity market, balancing is more expensive than in a consolidated market where more balancing solutions are available. In addition, forecast errors can be reduced by the aggregation of uncorrelated, geographically dispersed, variable RE production (Holttinen, Meibom et al. 2009; EWIS 2010). Therefore, a re-design of market structures and procedures is a pre-condition if significant amounts of RE are to be integrated into national and international networks (Van Hulle, Tande et al. 2009; Waltham 2009). Case studies (8.2.1.5) and future options (8.2.1.6) provide further discussion concerning institutional aspects of RE integration.

8.2.1.4 Benefits & costs

In broad terms, the benefits of RE generation arise from:

- the displacement of fossil fuels, with ensuing reductions in fuel costs and external impacts such as GHG emissions and acid rain;
- reduced reliance on importing energy, under contract from either other power systems or other countries, thereby giving energy security and balance of trade benefits; and
- the development of a RE industry with ensuing benefits of employment, export earnings and the fostering of an innovation culture.

There is a lack of information in the literature on the costs of large-scale RE grid integration other than for wind power which is the most advanced in this regard. A roadmap for CSP systems with or without thermal storage (IEA, 2010), and a study of solar PV in RE system inter-connection (Kroposki, Margolis et al. 2008) provide some cost data. The investment and operating costs associated with integration of RE generation arise from:

- network augmentation to accommodate fluctuating electricity flows associated with variable RE generation;
- network extension to connect new RE power plants; and
- investment in, and operation of, complementary electricity generation, storage and end-use technologies that can respond in a flexible and efficient manner to the additional fluctuating energy flows associated with non-storable RE forms.

RE generation types with intrinsic energy storage, such as biomass, geothermal energy, reservoir-hydro, or pumped-storage power plants, behave in a similar manner to fossil fuel thermal generation and thus raise no additional technology-specific costs from being integrated into existing power systems except for context-specific connection costs. However, the situation is different for variable RE generation without intrinsic storage.

For large-scale integration of wind power, transmission network upgrades are often needed (Corbus, Lew et al. 2009; Holttinen, Meibom et al. 2009; Lew, Milligan et al. 2009; EWIS 2010). Various assumptions in the literature for estimated cost allocation, distance, and grid reinforcements vary widely with specific conditions (Holttinen, Meibom et al. 2009). This results in a wide cost range between US$ (2005) 100-200 /kW of rated wind power capacity for penetration levels up to 50%. However, where grid reinforcements benefit the whole system, their costs should not be allocated solely to wind power. Overall a fairly moderate increase of additional balancing costs can result from increasing wind penetration (Fig. 8.5).

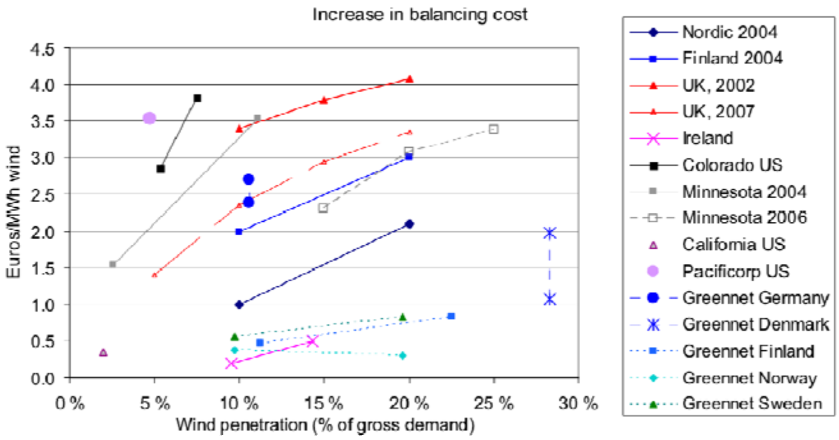

Figure 8.5: Additional balancing costs for the entire power system are higher at greater levels of wind penetration, as shown by several studies for sites in US and Europe (Holttinen, Meibom et al. 2009)

Note: Costs were harmonized using currency exchange rates of EUR 1 = GBP 0.7 = US$ 1.3 [TSU: Figure will need to be redrawn to present figures in 2005 US$]

Wind penetrations of up to 20% of gross energy demand were estimated to need additional system operating costs (arising from wind variability and uncertainty) for around 10% of the total cost of wind generation (Holttinen, Meibom et al. 2009), although a US study showed such additional costs were uncertain, ranging from 7-32% of capital expenditure based on installed costs around US$(2005) 1800 /kW (USDOE, 2008a). Large, unconstrained transmission regions, flexible complementary resources and efficient intra-day trading, are factors that can help to minimise the costs of wind energy integration (Holttinen, Meibom et al. 2009). Augmenting wind energy with high penetration of other RE technologies such as solar PV could help to smooth variability and thus also reduce overall integration costs.

Carefully chosen policies and commercial incentives may be required to bring forward an appropriate mix of “complementary resources” including generation, networks, storage and flexible end-uses, and to maximise the benefits that non-storable RE resources can bring whilst minimising the costs. For any given power supply system, the resulting generation mix, and the effectiveness of such a strategy, will be context-specific and need to evolve over time.

8.2.1.5 Country case studies - based on real experience of RE integration

Six case studies were chosen to demonstrate that different approaches to gaining increased RE deployment in national power supply systems are possible, but that there can be no single preferred approach as each situation depends upon the existing system design, local RE resource availability, current market shares and targets (Fig. 8.6), type of market, cost comparisons with conventional generation, and government policies.

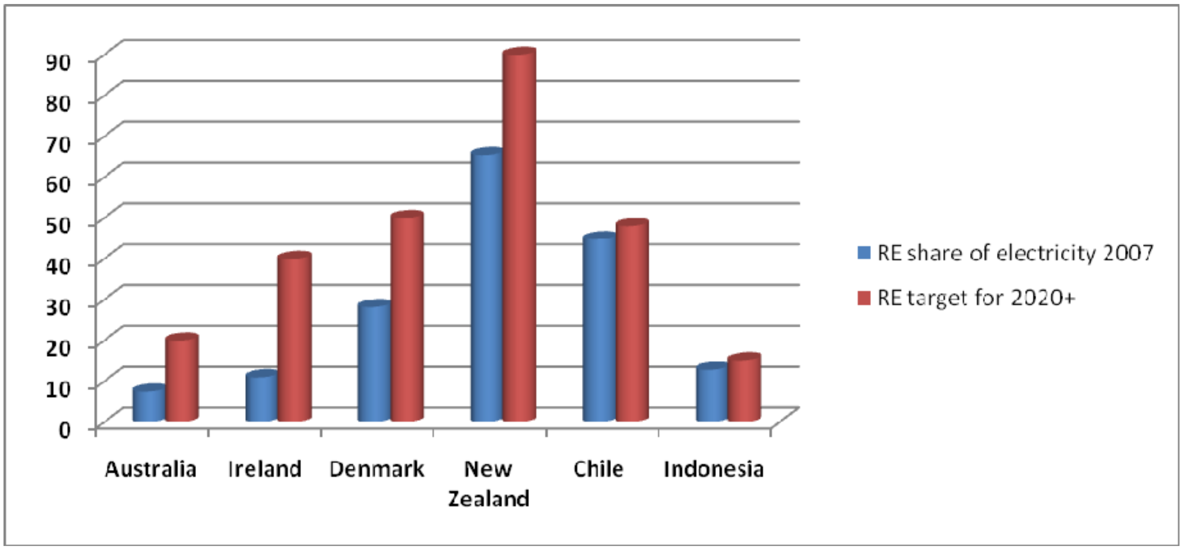

Figure 8.6: Current share of RE electricity generation and targets for countries selected (IEA 2008; ADB 2009; IEA 2009; IEA 2009).

Australia –*increasing the low RE share by market reform and inter-state connection.*

The Australian national electricity market (NEM) encompasses approximately 90% of Australia’s 22 million population and about half its 7.7 Mkm^2 land area. NEM accommodates non-storable RE resources via a coherently designed decision-making framework that includes a real-time, security-constrained, 5-minute dispatch spot market, associated derivative and frequency control ancillary services markets (Outhred and Thorncraft 2010),, and a fully integrated wind energy (and potentially solar energy) forecasting system[4]. The market design is technology-neutral and based on concepts proposed in 1980 that foreshadowed high levels of RE penetration (Outhred and Schweppe 1980; Schweppe, Tabors et al. 1980). Wind farms connected at transmission-level can participate and compete with other generators for transmission access and to provide ancillary services. However, wind farm operators have to pay for ancillary services that they are deemed to incur.

The NEM has an annual energy of about 210 TWh, a peak demand around 35 GW, and with 1.9 GW of installed wind capacity and another 6.5 GW proposed by 2020. In the South Australian region of the market, wind supplied approximately 15% of the 13.1 TWh of electricity consumed in 2009 (ESIPC 2009) and at one stage reached 57% penetration with no operational problems. When wind penetration in the NEM is high, electricity prices tend to be low and vice versa, giving a disincentive to invest in additional wind farms but an incentive to invest in complementary resources (generation, storage and flexible demand) as wind penetration increases (Outhred and Thorncraft 2010). As a result the initial focus of wind developers in the South Australian region has now evolved into a broad pattern of wind farm development that provides more appropriate balance between the geographical patterns of wind resources and demand.

The Australian Energy Market Commission recently completed a comprehensive review of electricity and gas market frameworks in the light of climate change policies (AEMC 2009). It concluded that “the energy market framework is generally capable of accommodating the impacts of climate change policies efficiently and effectively” given some proposed changes including removal of retail price regulation (or at least greater regulatory flexibility), introduction of

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[4] See www.aemo.com.au/electricityops/awefs.html for the Australian wind forecasting system.

transmission charges between NEM regions, a regular review of the spot market price cap (presently approximately US$ 10,000 [TSU: figure will need to be adjusted to 2005 US$]), and the effectiveness of the reliability intervention powers of the Australian Energy Market Operator (AEMO).

Ireland – *increasing the low present RE share with limited inter-connection.*

Ireland published a national RE action plan in June 2010 under the European Renewables Directive (2009/28/EC), June 2009. The EU has an overall target of 20% of EU energy consumption from RE sources by 2020 with variations across member countries. Ireland's target of 16% RE for 2020 includes 40% of electricity generation (giving 10% of total primary energy consumption). As the vast majority of new RE capacity will be provided by on-shore wind, this target is a significant challenge for the Irish wind industry. By January 2010, the installed wind energy capacity had reached 1,264 MW accounting for approximately 11% of total electricity generation. So to meet the 40% target if by wind alone, an additional ~5,000 MW of capacity will be needed within the next 10 years.

The peak demand on the network is just over 5 GW with annual energy consumption around 28 TWh (Eirgrid 2009). The system currently has one HVDC connection to Scotland but has no synchronous connections to any other system, although a 500 MW HVDC link between Woodland and Wales is planned which could possibly reduce the wind constraints slightly. Approximately 45% (579 MW) of existing wind farm capacity is connected to the transmission system (>110 kV) with the remaining 55% (685 MW) connected to the distribution network (<38 kV). The maximum output reached by this portfolio of wind turbines was 1094 MW, occurring in March 2010. Wind has reached over 40% penetration on multiple occasions, once reaching 45%.

The governments of Northern Ireland and the Republic of Ireland commissioned an *All Island Grid Study* (DCENR 2005) to investigate the technical issues associated with the integration of high levels of RE generation and the resulting costs and benefits. It concluded that, if substantial investment in transmission reinforcement and the second inter-connector to Wales were undertaken, then RE generation equivalent to 40% of the total demand could be integrated into the system, delivering around 25% reduction of CO_2 emissions for a maximum of 7% increase in total system costs (DCENR 2005). The key challenges to successfully integrate this RE generation include the following.

- *Complementary portfolio* of non-renewable generation with the flexibility to complement the variable RE generation without excessive cost or CO_2 emissions and ensuring that the market and regulatory structures can facilitate the delivery and continuing commercial viability of the required plant.
- *System control* of the power system so as to ensure continuing stability and therefore reliability while facilitating the delivery of the RE.
- *Connection* applications for both RE and conventional generation received by the TSOs would be more than adequate to deliver the 2020 targets. The Commission for Energy Regulation has mandated a grouped connection process known as "Gate 3" to provide certainty for generation developers and to optimise network development (CER 2008).
- *Network reinforcement to enable* the connection of large amounts of new RE and conventional generation, the closure of existing fossil-fuelled generation and the development of new inter-connectors. EirGrid is implementing a grid development strategy to deliver the transmission required but there is a risk that opponents of constructing new electricity transmission facilities will delay implementation.

Since wind is a variable resource, it is recognised that in addition to a flexible plant portfolio, electric loads also need to be more flexible. Trials in smart metering and customer behaviour are under way using a sample of 8,000 dwellings which should enable a significant step forward to be taken in domestic demand side management. Electric vehicles (EVs) could complement wind generation by storing electricity and providing flexible demand. The Government has therefore set an electric vehicles target of 10% of the total by 2020 with 2,000 on the road by 2012 and 6,000 by2013 (DCENR 2010). The first recharging points have been installed in Dublin with 3,500 more scheduled to be rolled out across the country giving 2,000 domestic charging points and a further 1,500 on-street.

Denmark – *aiming to increase high wind penetration through a flexible energy system.*

The Danish TSO, Energinet, has investigated the consequences of doubling the present installed wind power capacity (~3,000 MW) before 2025 (Eriksen and Orths 2008; EnerginetDK 2009). About 2,000 MW is expected to be installed off-shore. Wind penetration could then increase from the current 20% of electricity consumption to 50%. The energy balance, fuel consumption, emissions, power balance, and the need for ancillary services and transmission grid upgrades have been assessed, as has the extent that integration of 50 % wind energy into the electricity system would place on system flexibility, the grid and load demand. The study confirmed that both domestic flexibility and cross-boundary power markets are pre-requisites for maintaining security of supply and maximising the economic value of wind power; connecting the power system to district heating schemes, the transport sector via electric vehicles, and energy storage systems would be vital for successful integration (Fig. 8.7); and a whole range of measures for generation, transmission, demand side and the market would be needed.

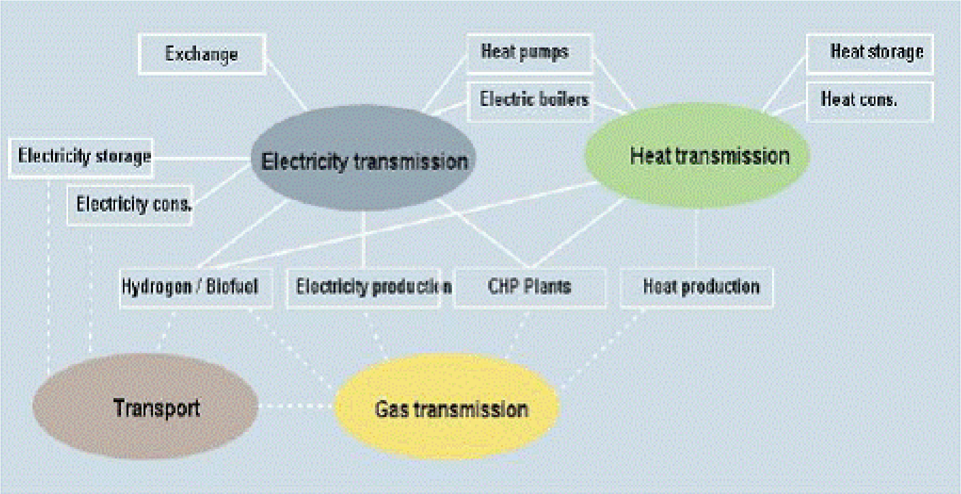


Figure 8.7: Possible linkages between the heat, transport, gas and electricity sectors to ensure successful large-scale wind power integration in Denmark (Eriksen and Orths 2008).

To prepare a coherent power system to support 50% wind penetration could need a holistic planning approach and modifications to the various sectors of the system as follows.

- *Generation*: a) Geographical dispersion of off-shore wind farms. b) Utilization of an electricity management system that regulates generation, mobilises regulating resources and new types of plants, and further improves local scale production units working on market terms.
- *Transmission*: Reallocation of grid connection points for off-shore wind power plants, increased grid transmission capacity, and reinforcement and expansion of the domestic grid and its inter-connections.

- *Demand*: Further development of price dependent demand; strengthening the coupling to heating systems (including electric boilers and heat pumps); linking the power system to the transport sector (using electric vehicles as a component of price dependent demand), and introduction of energy storage (possibly hydrogen, compressed air, or batteries).
- *Market*: Connection to the NordPool-EEX network to increase the possibilities of sharing reserves, improve intra-day trading possibilities and provide exchange of ancillary services.

These methods, investigated by the Danish TSO and partners to enable the required additional 3,000 MW capacity, would be applied over different time frames (EnerginetDK 2009).

New Zealand – *good RE resources leaving market to increase present high RE share*.

The New Zealand power supply currently generates around 67% from RE, varying in dry years. It is dominated by hydro (~55%) along with geothermal (~8%), wind (~3%), bioenergy (~1%), and solar PV (<0.5%) with the balance coming from gas and coal. In 2009, 43.7 GWh was generated from 8,508 MW installed capacity to meet the total demand of the 4.2 million population. A HVDC cable joins the North and South Islands with 1040 MW capacity north to south and 600 MW south to north. Inter-connection to Australia at 3000 km is impractical.

No supporting policies exist for RE plants which compete within the wholesale electricity market. Average retail electricity prices around US$(2005) 0.16/kWh domestic and US$(2005) 0.07/kWh industrial (including the fixed line charges spread across a typical year's supply), are higher than in Norway, similar to USA and Australia, but significantly less than those in Ireland, UK and Germany. Wind competes due to the high mean annual wind speeds giving capacity factors over 50% on some sites. Several wind farm and landfill developers, such as Palmerston North City Council, (IEA 2009) have sold carbon credits to support project costs.

The share of RE has declined steadily since 1970 due to the more rapid growth of thermal, partly as a result of reliability concerns during dry hydro years. Consequently, increases in CO_2 emissions have resulted, currently reaching around 280 g CO_2 /kWh (compared with Australia 860 g; US 570 g; Ireland 580 g; UK470 g; Germany340 g and Norway 5 g) (Yale 2008). The revised emissions trading scheme will add NZ$ 12.50 (US$(2005) 7.86) /t$CO_2$ to thermal generation when the power sector joins the scheme after 2011.

An analysis of power plants under construction, planned, or due to be decommissioned (IPENZ 2010), showed that to meet the projected 2015 total load demand of 48.8 GWh (allowing for projected improvements in energy efficiency), wind would rise to a 4-5% share, geothermal to 12-13%, hydro would decline to 46% with little increases from bioenergy, solar PV or ocean energy. By 2025, the 65% RE share of the 55.4 GWh demand would be met mainly from hydro (46%), geothermal (12.2%) and wind (8.3%). Wind industry analyses included other identified sites and showed the potential could reach 10.8 GWh (19.4%) (Strbac, Pudjianto et al. 2008). Even so, the government target to reach 90% RE by 2025 (Fig. 8.6) appears to be ambitious, although the possible contribution from rapid deployment of distributed generations systems has not been included.

As wind penetration increases, so does the need for additional peaking and back-up plant and the contribution of hydro to firm up wind power is reduced. To gain high wind penetration, higher peak capacity margins would be needed to maintain system reliability, ranging from 30% at 5% penetration in a dry year to 40% at 20% penetration (Strbac, Pudjianto et al. 2008). Hydro enhances the capacity value of wind (which is relatively high due to the high load factors). The total additional generation costs attributed to wind at 20% penetration were between US$ (2005) 5 - 7 /MWh.

Chile – *aiming to increase present limited RE share to provide energy security.*

Being the fastest growing economy in Latin America has resulted, in part, from the electricity sector becoming competitive following privatization in the 1980s. Since 1982 when only 38% of rural and 95% of urban households had power connections, this non-OECD country has successfully increased electricity access to almost everyone. With hydropower shortages now occurring every 2-3 years due to reduced precipitation levels, the shares of coal- and oil-fired power stations have increased (IEA 2009) leading to CO_2 emissions rising to 3.7 tCO_2/capita /yr (CNE 2008). The country depends on imported fossil fuels for 75% of its primary energy. Hence the government is consequently evaluating a more diverse mix of RE systems (along with nuclear and inter-connections) to provide enhanced energy security. The 4 800 km long country has three separate electricity markets. The Central system provides power to 90% of the 17 M population, has 35 generators, 20 companies owning 14,500 km of transmission lines, and 26 distribution companies. The spot market (with nodal pricing) usually sells at around US$(2005) 90 /MWh but this has spiked to around US$(2005) 320 /MWh during recent drought periods.

RE currently supplies around 26% of total final energy demand of which 70% is biomass, mainly used for domestic heating and cooking. Around 5% of power generation comes from 166 MW of on-site CHP installations and 40% from hydro (3393 MW reservoir-based, 1550 MW run-of-river and 159 MW mini-hydro at <20 MW scale). A further 433 MW of hydro capacity is under construction. The first wind farm was built in 2007, and 193 MW installed capacity is planned by end of 2010. The technical potential of wind has been estimated to be 1,500 MW, geothermal at 3,350 MW, solar PV and CSP at 40-100GW, mainly in the north of the country. Through diversification, RE could therefore reach 44% of electricity capacity by 2020 and become a key element of security, although more coal, LNG, diesel and fuel oil plants are also planned (Fig. 8.8).

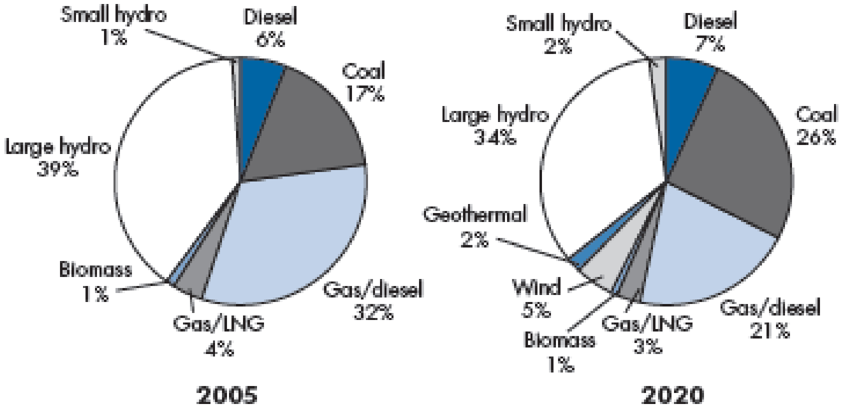


Figure 8.8: Projected installed capacity shares of power generation technologies in Central and North regions of Chile by 2020 (22.8 GW total) compared with 2005 (11.9 GW) (CNE 2008).

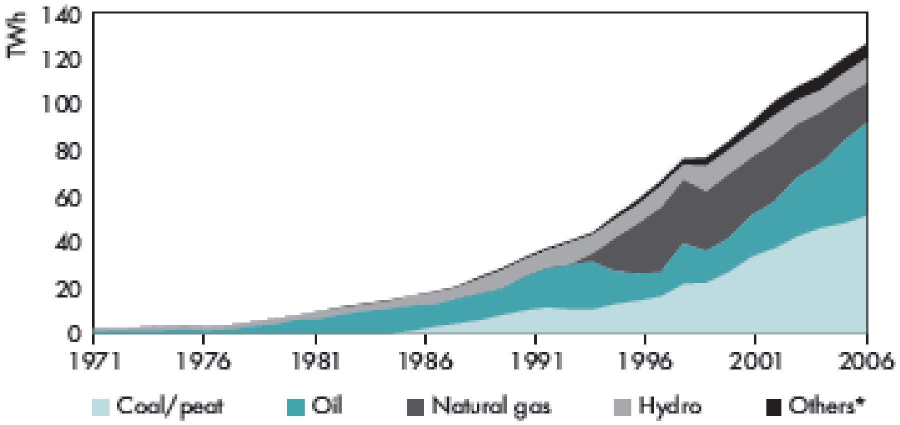
Accelerated deployment of private sector finance for RE is being sought by government along with training and R&D investments. Chile has been successful in securing finance from the Kyoto Protocol clean development mechanism (CDM) projects with 33 registered in June 2009 (36.2% for landfill gas, 17.4% hydro, and 10.2% bioenergy). Government policies to support more RE integration include penalties imposed on generators that do not secure sufficient back-up for dry years; exemption of transmission costs; rights to participate in the market regardless of scale; grants for pre-investment stages; sustainable geothermal concessions; tenders sought to build a 0.5W PV and a 10 MW CSP plant in the north; and an obligation that all generators are to produce at least 5% of total generation from non-hydro RE sources in 2010-2014, rising by 0.5% per year to reach 10% in 2024 and lasting till 2034 with penalties for non-compliance. To ensure this happens and that the expected 1400MW of new RE capacity by 2020 is built, electricity retailers will be established to give real competition and the TSOs given greater independence (IEA 2009).

Indonesia *–aiming to increase RE share to supply rural poor and reduce oil dependence.*

Energy supply to meet the demands of 200 million people living on Java, Madura and Bali and 40 million on 6000 other islands, is currently fossil fuel dominated, but good potential exists to increase the share of RE. In spite of good RE resources being available, around 35% of the population remain without electricity. Indigenous oil supplies are declining, energy demand is increasing, and there is severe poverty in rural areas that have poor access to energy services and high unemployment. RE could provide solutions as well as social and environmental benefits but will have to compete against coal and gas. Hydro power capacity is projected to increase by 2030 but its current share of electricity (8.4%) is projected to decrease to 4.3% due to rapid growth in coal- and gas-fired plants, whereas other RE generation, particularly geothermal could more than double to 11.9% (ADB 2009).

The lack of investment in electricity generation capacity and supporting infrastructure is resulting in demand exceeding system capacity, power restrictions, blackouts, transmission system failures, breakdown of generation plant, fuel supply disruptions and power quality issues. This is having a serious impact on the Indonesian economy, investment, and society in general. The state-owned utility, PT PLN, owned 86% of total capacity (24,887 MW) in 2006, with independent and private power producers the rest. Oil and gas dominated (Fig. 8.9). Current annual demand growth of around 8% requires around 3000-4000 MW capacity installed each year. In addition the government's target to supply 93% of the population with power by 2020 will add to the growing demand.

In 2005, around 12% (~15 TWh) of total generation was RE generated. Hydro had 4,200 MW installed capacity with around 72 GW potential and geothermal 1090 MW with 21 GW potential. Bioenergy (445 MW), small-hydro (<500 kW) (86 MW), solar PV (12 MW) and wind (1 MW) were mostly not grid-connected but have good potential in remote areas (MEMR 2008).



* Includes geothermal, solar, wind, combustible renewables and waste, etc.

Source: Energy Balances of Non-OECD Countries, IEA/OECD, Paris, 2008.

Figure 8.9: Electricity generation in Indonesia by fuel source from 1971 till 2006. [TSU: Figure will need to be redrawn as original and source listed in reference list.]

Energy price caps and subsidies imposed by government have kept electricity prices below market levels for many years so that power remains affordable for more people. Retail prices around US$(2005) 55 /MWh in 2006 were around half the average cost of generation. This policy has been costly to administer, constrained public and private investment, reduced the ability of enterprises to accommodate the cost of environmental compliance, and undermined energy efficiency and RE programmes (IEA 2008). The government has made major efforts to shift policy in order to accelerate the deployment of RE technologies into the marketplace, use locally available energy sources, create jobs and generate income in rural areas. However a new law (Indonesia 2009) that mentions prioritizing RE as a principle under the National Energy Policy "to ensure the sustainability of energy supply" outlines no means of so-doing. Phasing out price caps on electricity tariffs and fossil fuel subsidies have begun, together with an education campaign to explain why cost-reflective prices are now necessary. Establishment of a transparent independent regulator during the planned liberalization of the electricity industry has been recommended to provide incentives and clarity to investors on issues relating to the bidding procedure for new projects. Cost-effective RE feed-in tariff incentives, based on avoided costs as determined by the regulator, are proposed to attract the necessary investments and encourage continuing RE deployment. In the future the aim is for incremental costs of RE systems to be reflected in the tariffs to the electricity consumer rather than recovered from the government budget.

Currently, the 5 700 MW of RE technologies installed represent only 2% of the estimated technical potential (MEMR 2008). The current RE share of 4.3% total primary energy could rise to 17% (including biofuels) by 2025 with particular growth projected in geothermal capacity and decentralized power systems through local government initiatives together with local stakeholders. Financing may come from the regional government budget (especially for off-grid RE systems). The Ministerial Decree on Small Distributed Power Generation Using Renewable Energy was launched with the objective of promoting small-scale (<1MW) RE power plants by allowing enterprises to sell power to the local utility's power grid (where accessible). The challenge is to continue to give a strong focus to RE implementation by introducing cost-effective incentives that will attract the necessary investments to achieve the 2025 RE projection.

8.2.1.6 Options to facilitate the integration of RE

The necessary transition to a truly sustainable global energy supply system will be in the context of the increasing demand for energy services, partly driven by bringing populations within developing countries out of poverty. Integration of electricity from RE sources could become a dominant component of this transition and, in the long term, become the major energy carrier by also meeting loads for the transport and heat supply sectors. If so, challenges to the sector will be way beyond current knowledge or experience (Freris and Infield 2008). This section discusses how to manage integration challenges (8.2.1.3).

Assessing how to balance the power systems of the future across the range of relevant time-scales will be a major challenge. High levels of variable RE generation may not be schedulable[5], so matching supply to demand cannot always be achieved using conventional operational procedures developed historically. With more RE generation in the mix, together with potentially inflexible base load generation such as nuclear, it can be expected that flexible conventional plant would be needed for load-following and cycling. Most present systems have a significant proportion of generation coming from thermal power plants which if made more flexible, could assist TSOs achieve higher RE penetration levels. Co-firing of biomass with coal- or gas- fired plants is another RE integration option, that can be easy to manage in the power supply system and competitive depending on the delivered cost for the biomass (Chapter 2) and the investment cost for extra fuel handling equipment and boiler conversions (Rodrigues, Faaij et al. 2003). Many examples exist using blend levels around 5-10 % biomass by energy and there is future potential to link with CCS technologies and hence reduce atmospheric CO_2 concentrations. Experience and analysis leads to the following engineering and institutional approaches to electricity market reforms.

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[5] The term "dispatchable" used in 8.2.1.1 implies generation resources that can be dispatched by the power system operator to generate power at any specific time to meet demand, so here "schedulable" is preferred.

8.2.1.6.1 Engineering approaches

Technology options that could help solve the design and operation issues of reliability, stability and adequacy of a power system with high variable RE penetration include transmission design and upgrades, energy storage, demand-side control and centralized/decentralized energy management.

Transmission design and upgrades. In the short term, even at relatively low levels of RE penetration, transmission upgrades often coincide with methods for congestion management and optimisation of the transmission system. Technical measures that avoid or postpone network investments do not necessarily involve high expenditure. A number of technologies have significant potential to accelerate increased capacity as well as support RE implementation.

- Rewiring of existing lines with low sag, high-temperature conductors offers the potential to increase the overhead line capacity by up to 50% as the electrical current carrying capacity directly depends on the power line sag and the line temperature. Depending on the specific situation, rewiring may therefore be possible without the need for permit procedures, thus offering a fast method of transmission capacity enhancement.
- Dynamic line rating (DLR) monitors the temperature of existing power lines to prevent over-heating and therefore maximise transmission capacity. Solar power output tends to be highest during the hotter times of day when transmission capability is therefore lower. DLR can benefit solar since in many circumstances transmission line capacity limits tend to be conservative but can be exceeded if closely monitored. Since wind tends to be stronger at night and during cooler periods of the year, wind power output is highest when the lines are cooler anyway. DLR is already in use by the industry to give solutions to over-capacity, but standardisation of the method is required.
- Power flow control devices can help optimise utilisation of the grid. In large transmission networks there is often a physical lack of controllability which can lead to congestion on one transmission line whilst there is still capacity on an alternative line. Power flow control, installed in selected places, can ensure that existing transmission lines are utilised to the maximum and hence possibly avoid reinforcement of the present system and any associated planning difficulties (Van Hulle, Tande et al. 2009). Overloading of transmission components should not occur in properly engineered systems but, where it does, can be alleviated through an appropriate combination of power flow control technologies, system operation and expansion (Ye and Kazerani 2006). Voltage regulation technologies are fully commercialized but their performance can be further enhanced through R&D investment in power electronic devices (Xu, Yao et al. 2006).
- Increasing high-voltage, transmission capacity and coordination between different parts of an inter-connected system, enable more alternatives for TSOs to manage and help compensate for the variabilities of both demand and RE generation (Milligan and Kirby 2008). Transmission capacity expansion is most economic if planned for quantities of RE much larger than the size of an individual generation plant. So there could be rationale for planning, upgrading and building new transmission in anticipation of growth in RE, rather than to simply connect more new individual plants (Mills, Wiser et al. 2009) (though in politically unstable countries, such a long-term approach might be difficult). Proactive transmission expansion will vary depending on geography, the design of the existing power system, and the regulatory environment. The EU is considering ways to integrate RE particularly through improving transfer capabilities between TSOs by coordinating network planning through ENTSO-E (EASAC 2009; Smith, Holttinen et al. 2010).
- High voltage direct current (HVDC) transmission has potential for long distance, high capacity “highways” for example for large-scale RE integration super-grids. HVDC VSC[6] transmission

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[6] HVDC voltage sourced convertors (VSC) offer greater controllability than HVDC line commutate convertors (LCC).

technology offers advanced controllability over HVAC (Ruan, Li et al. 2007). On land, although it can be more expensive, point-to-point transmission over long distances is already used. HVAC undersea cables are presently the standard means of connecting off-shore wind farms to shore, but there are limits to the distances that can be accommodated (Bresesti, Kling et al. 2007). For connections where only subsea cables can be used, HVDC already out-performs HVAC over distances >100 km. As more off-shore wind and ocean energy capacity is installed (Bhuyan, Khan et al. 2010), meshed VSC-HVDC networks become attractive (Andersson and Liss 1991; Hendriks, Boon et al. 2006; Haileselassie, Milinas et al. 2008) to connect multiple plants to each other and possibly with multiple shore connections. This could also potentially be combined with, for example, providing capacity for trade of power between different market areas around the North Sea. Meshed HVDC networks are not yet an engineering reality and many technical issues need to be solved to provide effective network protection (Liu, Xu et al. 2003). However, various research teams are exploring different converter topologies and control schemes (Haileselassie, Milinas et al. 2008; Jiuping, Srivastava et al. 2008).

Energy storage. A range of energy storage technologies are available or being developed (EnergyPolicy 2008; Hall and Bain 2008; Inage 2009). Electricity cannot be stored so has to be converted to other forms of energy (chemical, mechanical, potential, heat, etc.) then later reconverted, when the electricity is required, giving efficiency losses. Storage is not economically viable for most power supply applications but if located near to a RE generation plant, it could help compensate for power flow fluctuations and, ultimately, voltage regulation (Molina and Mercado 2010; Suvire and Mercado 2010). Storage systems can provide instant response to demand fluctuations and, as a consequence, add flexibility to the system in terms of load levelling. There are many varieties of energy storage technologies (Table 8.1) but currently, they tend to be more expensive than reactive power control technologies, so are not used just to stabilize voltage.

Pumped-hydro storage is a site-specific technology that could be deployed more widely than it is today but it is usually more costly than plentiful, low cost, reservoir-hydro that can provide storage. Compressed air energy storage is also site-specific but with only two plants deployed to date, in Germany and the USA (Chen, Cong et al. 2009). At the smaller scale, the lead-acid battery is widely used as an uninterruptible power supply resource but other technologies are under development.

Table 8.1: Technical characteristics of some energy storage systems (Chen, Cong et al. 2009).

Storage technology	Power rating MW	Discharge time*	Cost US$/kW	Energy density Wh/kg	Life years	Number of cycles
Pumped hydro	100-5000	1 to 24 h	600-2000	0.5-1.5	40-60	
Compressed air	5-300	1 to 24 h	400-800	3-6	20-40	
Lead acid battery	0.0001-20	secs to hrs	300-600	50-80	5-15	500-1000
Ni-Cd battery	0.0001-40	secs to hrs	500-1500	60-150	10-20	2000-2500
Lithium ion battery	0.0001-0.1	mins to hrs	1200-1400	200-500	5-15	1000-10000+
Vanadium redox flow	0.0001-0.01	secs to 10h	600-1500	10-30	5-10	12000+
Zn-Br flow battery	0.05-2	secs to 10h	700-2500	30-50	5-10	2000+
Flywheel	0.01-0.25	msecs - 15min	250-350	10-30	5-10	20000+
Super capacitor	0.0001-0.3	msecs – 15min	100-300	25-45	20+	100000+

Notes: *Short discharge times can be useful for uninterruptible power supply (UPS), power quality and reliability needs; longer times for energy management, load levelling, peak shaving and emergency back-up.

Not included are Na-S battery, Na-Ni-Cl (ZEBRA) battery, metal-air battery, polysulphide bromine flow battery, superconducting magnetic storage systems.

It is uncertain which, if any, of the alternative energy storage systems could eventually become commercially viable (Black and Strbac 2006). However, there are presently several generation modes where storage can at times be integrated beneficially, although not always cost-effectively:

- to compensate for a temporary loss of a generating unit in a conventional system (contingency reserve) and hence fulfil any commercial obligations for maintaining quantities of pre-sold electricity supply and avoid contractual penalties;
- to add value by improving RE generation predictability in order to obtain higher tariffs (e.g. wind for pumped-hydro to enable power to be dispatched during peak periods); and
- to minimise the running of back-up diesel generators in small-scale, autonomous, mini-grids and buildings that rely on variable RE sources and so often include battery storage.

In future, battery-powered and plug-in hybrid electric vehicles (8.3.1) could be used as storage for distributed energy systems (Kreith and Goswami 2007) depending on battery development to improve durability, economy and capacity for power control applications.

System level storage is not usually an economically attractive option in inter-connected power supply systems until high RE penetration exists (Holttinen, Meibom et al. 2009; Ummels 2009; GE_Energy 2010)(O'Malley, 2008). The requirement for energy storage should then be determined by the difficulty of balancing aggregated power supply with demand and the cost. In isolated power systems with high RE penetration there is a greater need for dedicated energy storage.

Demand-side control. Demand response (DR) is the time-shifting of power demand in response to an institutional incentive to improve demand/supply balance by responding to variations in RE generation. The power demand of heat pumps, electric water heaters, refrigeration units, and the charging of electric vehicles could all become responsive. Simple "ripple control" of electric hot water systems has been used for decades to reduce peak loads, but to enable wider control to be achieved, advanced metering infrastructure, energy management technologies, control interface technology for appliances used in buildings and factories, and information technology for communications are now available (NETL 2008).

Centralized or decentralised energy management. In order to manage more frequent and wider variations of RE generation, system monitoring of centralized or decentralised energy management is required to realize more robust power system control (Wang, Dou et al. 2007) and to improve system performance including rapid recovery from various system disturbances (Zhang, Xie et al. 2008).

Rural electrification involving RE generation requires a long-range view, the use of comprehensive planning methodology, and possibly involving the use of geographical information systems (GIS) (Amador and Dominguez 2006). This approach is more appropriate in OECD countries than in some developing countries where the key decision, based on a total life cycle analysis of the alternatives (Kaijuka 2007), is usually whether a particular rural community should be provided with an isolated off-grid, autonomous system (8.2.5) or be integrated into a larger power supply system by extending the grid.

8.2.1.6.2 Institutional approaches and market reforms

An electricity industry involves institutional decision-making for governance, security and technical regimes that differ from commercial regimes (Outhred and Thorncraft 2010). Institutional decision-making plays a key role in the long-term energy planning of regulated monopoly electricity industries but in competitive industries, such decisions may be delegated to a market that is supported by advisory functions. In either type of industry, systematic and coherent institutional decision-making can facilitate the integration of high-levels of RE generation. Tasks identified to facilitate high levels of RE generation in North America (NERC 2009), could be relevant elsewhere for either monopoly or competitive industries.

- Deploy advanced control technology designed to address ramping, surplus supply conditions and voltage control.

- Deploy complementary, flexible resources such as demand response, reversible energy storage and performance enhancements for non-renewable generation that can provide ramping and ancillary services to facilitate higher penetration of the variable resources.
- Enhance and extend transmission networks to move energy reliably from the new RE generators to demand loads and support the use of complementary resources.
- Improve market designs for energy and ancillary services to provide appropriate commercial incentives and penalties for variable RE and complementary resources.
- Enhance measurement and forecasting of variable RE generation output.
- Adopt more comprehensive planning approaches, from the distribution system through to the bulk power system.
- Explore further possibilities for inter-connection to extend the geographical scope of power systems that have high penetrations of variable RE generation.

At penetration levels above 20% on an annual energy basis, both the design and operation of a power system and electricity markets need new directions to give consistent policy decisions (Van Hulle 2009). Decision-making processes on grid reinforcement, technical standards, market rules etc. need to be well considered. In Australia, where a holistic approach to integrate non-storable RE resources into the national electricity market has been taken since 2003 (8.2.1.5), similar conclusions were reached.

A recent study on optimal wind power deployment in Europe (Roques, Hiroux et al. 2009) highlighted the need for more cross-border inter-connection capacity, greater coordination of European RE support policies, and electricity market designs and support mechanisms to provide local incentives. It has been suggested (Van Hulle, Tande et al. 2009) that integration of wind power had been constrained by planning and administrative barriers, lack of public acceptance, a fragmented approach by the main stakeholders, and insufficient economic incentives for network operators and investors to undertake transmission projects of European interest. The European Wind Integration Study (EWIS 2010) exemplifies an institutional approach to defining the tasks involved when integrating large amounts of RE generation.

8.2.1.6.3 Visions for possible future power supply systems

A number of speculative approaches to future power system designs have been suggested. These commonly involve a combination of:

- more highly connected power systems with greatly extended transmission infrastructure as, for example, are being planned in the EU (DLR 2005) and the USA (USDOE, 2008);
- ensuring loads, as far as possible, are temporally responsive to supply availability;
- making much greater use of distributed data collection, communication and control;
- employing adapted unit commitment, economic dispatch methods and short-term forecasts;
- improving management of distribution grids to cope with additional functions; and
- adapting market structures to combine balancing solutions and to provide incentives for building flexible generation capacity within the necessary time frames.

Integration of large-scale RE generation

In Europe, the projected growth of wind, wave and tidal stream capacity has raised issues of grid integration to a new prominence and highlighted the need for appropriate network reinforcement. In-feeds that vary over time need to be managed so as to maintain the reliability of supply, ensure that frequency can be properly controlled, and give confidence that the power system would be stable and robust in the event of faults. Specific technical challenges include dynamic matching of supply and demand (Smith and Kintner-Meyer 2003); local control of reactive power/voltage; robust and stable operation under abnormal conditions such as grid faults; and overall control of network frequency. Aggregation of the wind resource over a very large geographical area, and integrated with other RE sources, could result in firmer generation capacity. To date most studies that have examined such aggregation have been based on hourly data at best, and, although useful, cannot truly establish whether such power systems would be feasible.

Distributed generation

Traditional power systems have been based on centralised generation, designed to deliver power from large-scale generation plants in one direction to consumers (Fig. 8.10). This model is now being challenged by increasing levels of distributed generation (DG), such as CHP plants, wind farms, diesel engine gensets, or solar installations in buildings (IEA 2009) embedded in the local low-voltage, distribution network (Fig. 8.11). The possibility of DG completely taking over from centralised generation is unlikely to happen even in the long term, but integration of DG into existing supply systems could be technically feasible (Chicco and Mancarella 2009), as could autonomous DG mini-grids in remote rural areas or on small islands. Depending on the further development of the technologies and associated cost reductions, DG could make a substantial contribution to total power generation (ENARD 2010).

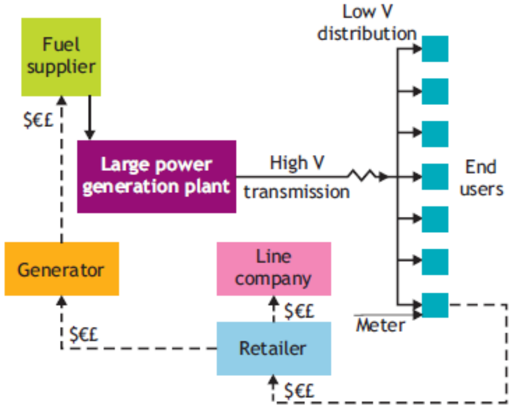

Figure 8.10: Simplified representation of a centralised power supply system with energy flowing one way (solid lines) and revenue the other (dashed lines) (IEA 2009).

Power systems can benefit from the aggregation of a large number of different generation resources and types of demand that together can help provide more reliable operation. Systems with access to tens or hundreds of different DG resources could potentially be less expensive than if attempting to provide the same level of reliability with only a few power plants (Awerbuch 2006). The benefits of aggregation could be accessed through a network and communication infrastructure that allowed for the transfer of power, and coordinated throughout the network with energy, revenue and information flowing in several directions (Fig 8.11). In a power system with high penetration levels of distributed and variable RE generation, to keep the supply-demand in balance it will be necessary to deploy innovative and effective measures such as ‘smart grids’ (Holttinen 2008), also termed ‘active networks’, ‘intelligent grids’ or ‘intelligent networks’. These still need clearer definition, further analysis (PSERC 2010) and demonstration.

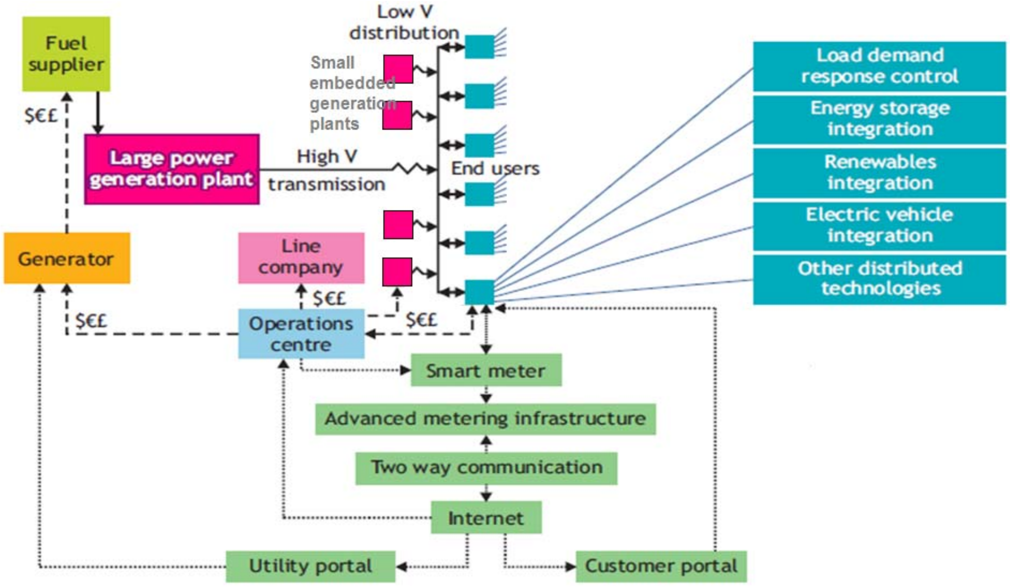

Figure 8.11: Simplified representation of a complex distributed generation system with two-way flows of electrons (solid lines), revenue (dashed lines) and information (dotted lines) through smart meters and intelligent grids (IEA 2009).

The EU has been investigating smart grid technologies under the European Technology Platform initiative since 2005 (Bouffard and Kirschen 2008). In the US, smart grids have been incorporated into energy policy by the Energy Independence and Security Act (EISA 2007) which promotes their development through a matching programme for states, utilities and consumers. The EISA has assigned the National Institute of Standards and Technology as the coordinating body for the development and modification of a number of standards that relate to smart grid interoperability (Molitor 2009). The US Department of Energy also commissioned a major “Renewable Systems Inter connection” study to address the challenges to high penetrations of distributed RE technologies (Kroposki, Margolis et al. 2008).

Projected growth in DG is prompting extensive research into the best way to integrate small-scale generation into the electricity system (IMechE 2008; Thomson and Infield 2008). DG is linked with related R&D investigations to explore the potential for low cost communication and IT infrastructure to improve the overall performance and cost effectiveness of power supply systems (Cheung 2010). In this context, the use of controlled, dynamic loads to contribute to network services such as frequency response, is now an active research area (Short, Infield et al. 2007).

As the generation sources become more distributed, co-ordinated system operation and control can become more problematic for TSOs. At this stage, there is no emerging agreement as to how such complex power systems should be designed and operated. Under certain fault conditions, particular power system dynamics can be excited and it is possible that the combined characteristics of a projected multitude of distributed RE resources might exacerbate these problems. If instabilities are detected, the challenge will be for control engineers to devise technically suitable and cost effective means of stabilisation. Dynamic control of the loads on the power system will become an increasingly important element as power systems evolve and accept higher RE shares to achieve improved environmental sustainability.

In a decentralized system, load demands could be harmonized with power system operation by information exchange together with energy management realizing demand-side control of residential or commercial buildings, or of an industrial area. As well as a means to balance an electricity system, a smart grid could, at least in theory, also provide power system stability and security of operation. Power production and consumption are monitored when supplying a load and the demand-supply balance would be maintained through an appropriate energy management control system (Van Dam, Houwing et al. 2008). A virtual power plant (VPP) is a combination of generation, monitoring and control technologies that could result in a business model akin to a single power utility. Distributed locations of substantial amounts of accumulated generation capacity can be regarded as a virtual single generation plant (see case study below).

8.2.1.6.4 Case study concepts for future power supply systems

Large-scale wind integration: European TradeWind

A study of wind integration across the power systems of Europe assumed a more highly inter-connected system than presently exists. It was undertaken between 2006 and 2009 by the TradeWind consortium and coordinated by the European Wind Energy Association (EWEA) with sponsorship from the European IEE Programme (Van Hulle, Tande et al. 2009). The aim was to investigate the adequacy of European power systems for large-scale wind integration. It assessed the options for improved inter-connection between European member states and the corresponding power market design needed to enable large-scale wind energy integration. Optimal power flow simulations were carried out with a European wide network model to examine the effects of increasing wind power capacity and, more specifically, of possible grid dimension situations on flows across borders. Future wind power capacity scenarios up to 300 GW in the year 2030 were investigated.

Simulations showed that increasing wind power capacity led to increased cross-border energy exchanges and more severe transmission bottlenecks, especially for the amounts of wind power capacity projected in Europe after 2020. The effect of passing storms on cross-border power flows was investigated. Wind forecast errors resulted in deviations between the actual and expected cross-border flows on most inter-connectors during a substantial part of the time and further exacerbated congestion. Significant economic benefits resulted from network upgrades that would relieve existing and future structural congestion in the inter-connections. A phased upgrade of 42 inter-connectors would benefit the European power system and its ability to integrate wind power, and lead to savings in operational costs of €1500M /yr (US$(2005) 1730/yr), thus justifying investments in the order of US$(2005) 25.4 billion for wind power up to 2030 (Van Hulle, Tande et al. 2009).

The project specifically examined the benefits of trans-national, off-shore grid topologies for the future integration of wind power. A meshed grid linking 120 GW of off-shore wind farms in the North Sea and Baltic Sea to the on-shore transmission grid, compared favourably to the alternative of radial connections of individual wind farms. This was due to higher flexibility and the benefits it offers for international trade of electricity. The study assumed further upgrades of the on-shore network but this will need further evaluation (EWEA 2009)[7].

Aggregating wind energy production from multiple countries strongly increased the capacity value in the system: the greater the geographic area, the higher the capacity value. When comparing a situation with and without wind energy exchange between the countries, the relative increase of capacity value was found to be 70%.

The TradeWind project also evaluated the effect of improved power market rules in terms of reductions in the operational costs of generation. The introduction of intra-day markets for cross-border trade was found to be of key importance for market efficiency, leading to savings in system

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[7] EWEA has proposed a long-term plan for off-shore grid development. The technical, economic and regulatory options for such a grid delivering 12% of Europe's demand are further researched in the IEE Offshore Grid project (www.offshoregrid.eu).

costs in the order of US$(2005) 1.15-2.30 billion /yr compared to a situation where cross-border exchange must be scheduled a day-ahead. To ensure efficient inter-connection, costs should be allocated directly to the market via implicit auction.

Intra-day rescheduling of the generation portfolio, taking into account wind power forecasts up to three hours before delivery, resulted in a US$(2005) 300 /yr reduction in operational costs (compared with day-ahead scheduling). This was due to the decrease in demand for additional system reserves. Consequently, the TradeWind analysis recommended intra-day rescheduling of generators and trading, a consolidation of market areas, and increased inter-connection capacity in order to enable more efficient wind power integration.

Large-scale RE power integration - Desertec

The "Desertec Industrial Initiative GmbH" was initiated in 2003 by the German Club of Rome global think-tank. In 2009, a consortium of 12 German and Spanish engineering, financial and energy companies launched a US$(2005) 500 billion investment assessment scheme with the aim to produce 15% of Europe's electricity demand in 2050 (Global_Insight 2009). The concept aims to harness solar energy from the desert areas of Middle East and North Africa (MENA) using mainly concentrating solar power (CSP) spread over nearly 17,000 km^2 and inter-connected with wind and hydro generation plants (Fig. 8.12). Transmitted to Europe through HVDC cables and the reinforcing of existing transmission lines, the project theoretically could enable the present 16% share of RE electricity in Europe to rise to 80% in 2050 (Trieb and Műller-Steinhagen 2007). Provision of water supply through desalination is part of the concept (DESERTEC 2009). The locations of the curved solar mirrors, turbines and solar thermal storage systems of the CSP plants are yet to be decided. The usual water demand for CSP cooling towers could be replaced by dry air cooling (or hybrid wet/dry cooling) but with an efficiency penalty (IEA, 2010). The venture is in the very early stages of evaluation with major technological, fiscal, logistical and political barriers yet to be overcome.

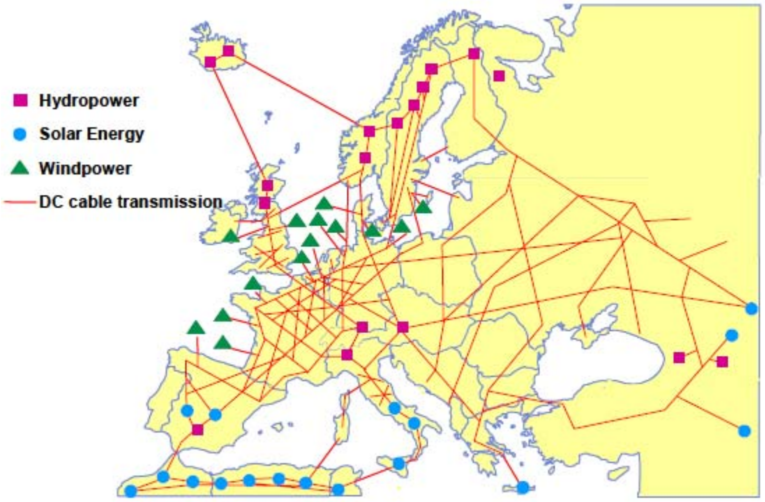


Figure 8.12: The concept of an inter-connected electricity grid between Europe, Middle East and North Africa based on HVDC transmission "highways" to connect with the existing AC grid and other power plants (Asplund 2004).

Around 85% of the projected investment cost will be for the CSP plants and the remainder for the 20 or more new transmission cables. One partner, Abengoa, has experience of developing CSP demonstration plants integrated with natural gas, combined-cycle plants (Abengoa 2010) including:

- a 472 MW plant in Ain Beni Mathar, Morocco of which 20 MW is CSP from 183,000 m^2 of parabolic troughs; and
- a 155 MW system in Hassi R'Mel, Algeria of which 25 MW is a parabolic CSP system.

The share of electricity generation from the CSP is likely to remain relatively small at this stage since establishing commercial-scale CSP facilities has been constrained by their relatively high cost at around US$(2005) 120-330/MWh (IEA, 2009a). However, there is an expectation that these costs will decline to US$(2005) 70-200 /MWh by 2030 (IEA, 2009a).

The electricity demand of MENA nations is projected to rise over three times by 2050 from around 1000 TWh/yr today, with a further 500 TWh/yr probably needed for desalination to meet the projected water deficit (Trieb andMűller-Steinhagen 2007). Therefore the concept of exporting power from the region may prove difficult to promote. There is also unresolved debate whether improved energy efficiency measures and the advent of DG (including solar PV) will be a cheaper option than investment in the Desertec project infrastructure and upgrading the existing transmission networks throughout Europe (Global_Insight 2009). Further analysis is warranted to assess the combined effects and costs of integrating a wider portfolio of RE.

Until 2012 the Desertec consortium will concentrate on accelerating the implementation of the concept by creating a favourable regulatory and legislative environment and developing a plan for development (DESERTEC 2009). It will consider how to manage the political issues, ensure the technological barriers can be overcome, assess whether the CSP plant components can be manufactured at the rate required, and evaluate whether transmission losses can be kept low enough to make the venture profitable.

Another similar concept, the Meditarranean Solar Plan was established by Mediterranean countries in 2008. It also intends to export electricity to Europe from 20GW of RE (mainly CSP and wind) installed in the south and eastern parts of the Mediterranean basin (Lorec 2009). Several North African states already have solar targets for the medium term and in Algeria and Morocco feed-in-tariffs are in place.

Renewable virtual power plant

This combined RE power plant system concept, an initiative of several German manufacturers of RE technologies, aims to demonstrate the feasibility of using RE to meet 100 % of electricity demand by producing a model virtual power plant (VPP) and hence dispel the major arguments against a major penetration of RE, including variable generation, poor predictability and lack of controllability (Mackensen, Rohrig et al. 2008). The project is supported by partners from the RE industry and the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) based at the University of Kassel, Germany. A prototype computer model has been in operation since May 2007.

A VPP can consist of numerous decentralized RE generating stations, as well as storage devices and non-RE power plants).These are combined by means of a central control unit (CCU) consisting of system management, forecasting and primary controls (Arndt, von Roon et al. 2006). The VPP combi-plant model uses only existing RE technologies and is designed to represent a future scenario for meeting the annual electricity load of a small town of 12,000 households. The first step in creating this 100% RE scenario was to estimate the wind, solar PV and biogas potentials. The system then aggregated and controlled the power generation from three distributed wind farms (12.6 MW total capacity), 20 solar PV plants (5.5 MW total), four biogas-fired CHP plants (4.0 MW total), and a 1.06 MW pumped storage hydro system (Fig. 8.13) in such a way that the output matches the varying specified load at all times. The assumed capacities and outputs of the system components reflect current technologies and made it possible to compare the model results using real power plant output data. The total electricity produced (including imports/exports and storage losses) was 43.5 GWh /yr (with around 60% from wind, 15% PV and 25% biogas). Around

10,000 such VPPs would therefore be needed to supply all of Germany (Mackensen, Rohrig et al. 2008).

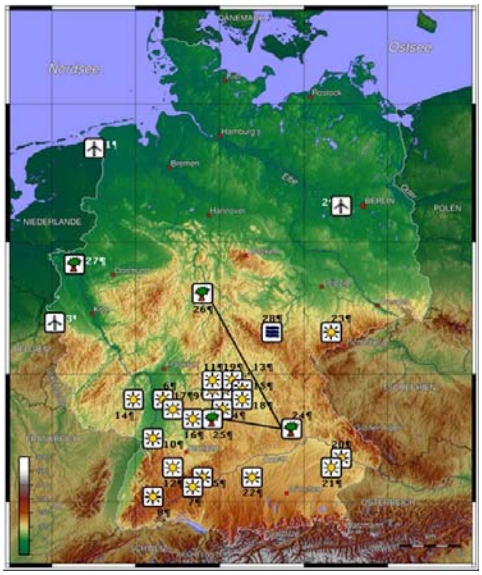


Figure 8.13: Technology components used in the German renewable VPP model are wind (1-3), solar PV (4-23), biogas (24-27) and pumped hydro (28). (Mackensen, Rohrig et al. 2008).

The variable wind and solar power components were geographically spread in order to take advantage of smoothing effects due to different weather conditions experienced at any given time. These were combined with dispatchable biogas-fired CHP outputs and the pumped-hydro storage reservoir. All the generation plants in the assessment are real and currently feed electricity into the public grid. The pumped-hydro storage device has yet to be developed (Mackensen, Rohrig et al. 2008).

The use of intelligent control, regulation technology and forecasts enabled the decentralized installations to be linked together so that fluctuations in the amount of electricity fed into the grid could be balanced. The CCU balanced the various output forecasts and measurement values. Based on the data (Mackensen, Rohrig et al. 2008), the control process was carried out in two steps.

- *Forecast and scheduling*. The CCU received weather and demand forecasts. Based on these, it anticipated the amount of power to be produced by wind and solar plants (Rohrig 2003). To balance the difference between the anticipated demand and the electricity generated by wind/solar energy, the CCU calculated a schedule and sent it to the biogas plant operators. A surplus or shortage was balanced out by using the pumped-storage power plant and, as a last resort, by exporting and importing to and from neighbouring grids.
- *Comparison of actual data*. The CCU received feedback from all the power plants on the actual real output and compared this data with the immediate demand. Differences compared with the forecast values were balanced through short-term adjustments to the biogas electricity outputs within minutes. The algorithms created for the concept were verified.

Running the model showed that to deal with a large portion of fluctuating power, it was necessary to install more total capacity than was needed at peak load demand. The VPP needed some storage capacity to be able to constantly meet the demand. When supply exceeded demand, the surplus could be shed, stored or exported to neighbours through ENTSO-E. Exporting electricity led to additional costs for grid reinforcement and expansion. Creating new storage capacity also involved a cost and storing and transmitting electricity always resulted in losses.

At higher penetrations of fluctuating RE sources, intelligent integration into the supply system was required to balance production with demand. Integration into electricity markets required an adequate payment system to replace the existing fixed tariffs as defined by the German Renewables Act, 2000 (EEG). A bonus payment for cogeneration or storage would allow transfer of the responsibility for compensating for variable generation to the producers. Under the existing law and the fixed tariff system, neither operators of RE plants nor TSOs have incentives to actively seek steady production, links with demand side management, or integration of storage devices. Valuable opportunities that arise when selling electricity on the free market appear more often because of rising prices and the declining tariffs of the EEG. The analysis confirmed that the concept could supply Germany (inter-connected with the European Union for the Co-ordination of Transmission of Electricity) with 100% renewable electricity but to achieve this will require R&D investment, political will and societal support.

Distributed generation (DG) - Danish project

The Danish TSO, Energinet, commissioned a Cell Controller Pilot Project (in association with the owners of wind-turbines and local CHP plants) with the aim of developing controllers, data acquisition, commands, and communication infrastructure for a pilot “Cell”. Evaluating the co-ordinated, intelligent control and integration of a DG grid was the objective. The Cell consisted of existing distributed assets including four 1 MW wind turbines, a 2 MWe and 8.8 MWe bioenergy co-generation facilities, and approximately 5 MW of residential and commercial managed loads. Test stages covered three areas of rural Denmark, each with wind and bioenergy cogeneration sites and with local villages linked by 150/60 kV distribution lines.

When a significant number of RE generation units are located within a low voltage distribution grid, special attention has to be paid to the coordinated planning and operation of the transmission and distribution networks. More intense use of the grid in order to co-ordinate greater shares of variable RE generation can lead to a reorganization of traditional structures and operational procedures. Revised architectures for power system control (“intelligent grids”) are needed for the active control of such distributed resources (Orths and Eriksen 2009).

Operation of the Cell was possible on a live power system. The primary functions of the Cell controller were:

- to manage the intentional islanding of the Cell from the transmission system;
- to assess the Cell’s continued operation using local, distributed generation;
- to analyse resynchronization problems of the Cell with the grid; and
- to control a combination of distributed assets as a VPP in grid-connected operation.

The Cell controller was first tested in a power system laboratory environment in order to validate all control algorithms and communication methods. The pilot-stage Cell was then deployed over a 100 km^2 area and the first comprehensive field tests undertaken in 2008 to assess support transmission operations during emergency conditions and to enhance market-based control over the assets during normal operations (Martensen, Kley et al. 2009).

The controller and its supporting equipment maintained the intentionally islanded Cell from the grid, meeting grid code requirements in all cases. The Cell was also successfully resynchronized with the grid. Based on these results, over 40 wind turbines and five CHP units will be added to the pilot Cell’s asset mix and the controller will be further developed to give emphasis on modularity and scalability and the inclusion of new functionalities, such as an expanded virtual generator control.

Examples of how the Cell project may benefit transmission and distribution companies include:

- each Cell being regarded as a VPP with the same or better controllability compared to a single traditional power station unit of similar capacity;

- local distribution companies attaining active distribution network on-line monitoring and control;
- automatic transition of a Cell to controlled-island operation in case of imminent transmission system break-down;
- black-start of the transmission system; and
- robust Cell controller designed to encompass all new types of DG units and controller functionalities (Martensen, Kley et al. 2009).

Energinet.dk and the Danish grid companies expect to obtain valuable knowledge through the completion of the project to encourage them to continue the long-term process of redesigning the Danish power system, thus enabling optimum integration of the growing volumes of local power generation. The major share of generation will come from wind and other RE sources. A control structure enabling intelligent and optimum utilisation of existing and future distributed generation resources through distributed control technology should result (EnerginetDK 2008).

8.2.2 Integration of renewable energies into heating and cooling networks

8.2.2.1 Characteristics

A district heating or cooling (DHC) network allows multiple energy sources to be connected to many energy consumers by pumping hot or cold water, and sometimes steam, as the energy carriers usually through insulated underground pipelines to meet demands for space conditioning, water heating and low temperature industrial heat. Centralised heat production can facilitate the use of low cost, and/or low grade, RE heat sources such as from geothermal, solar thermal, combustion of biomass including refuse-derived fuels and woody by-products that are not suitable for use in individual heating systems (Werner, 2004), and waste heat from CHP generation, industrial processes or biofuel production (Egeskog, Hansson et al. 2009).

This wide range of RE sources creates opportunities for district heating (DH) schemes to facilitate competition between various heating fuels and technologies (Gronheit and Mortensen 2003) by integrating a broad spectrum of fuels into a given scheme to enable switching between sources (see Swedish case study, Chapter 11). In many locations, individual heating systems in buildings using the direct use of natural gas, biomass boilers, electricity, heat pumps, solar thermal or geothermal systems (section 8.3.2) are strong competitors to DH (RHCAuthors? 2010) [TSU: Reference will need to be completed/corrected].

DH systems are most common in densely populated urban areas but can also be economically feasible in less densely populated areas, especially where an industrial low-to-medium grade heat load also exists (such as the kiln drying of timber). Historically, DH systems were mainly developed in countries with cold winters. After the oil crises in the 1970s, DH systems were developed in combination with (CHP) generation to reduce oil demand and increase overall energy system efficiency. As a result, several high latitude countries have a DH market penetration of 30-50% and in Iceland the share, using geothermal resources, reaches 96% (Fig. 8.14). World annual district heat deliveries have been estimated at 11 EJ but the data are uncertain (Werner 2004).

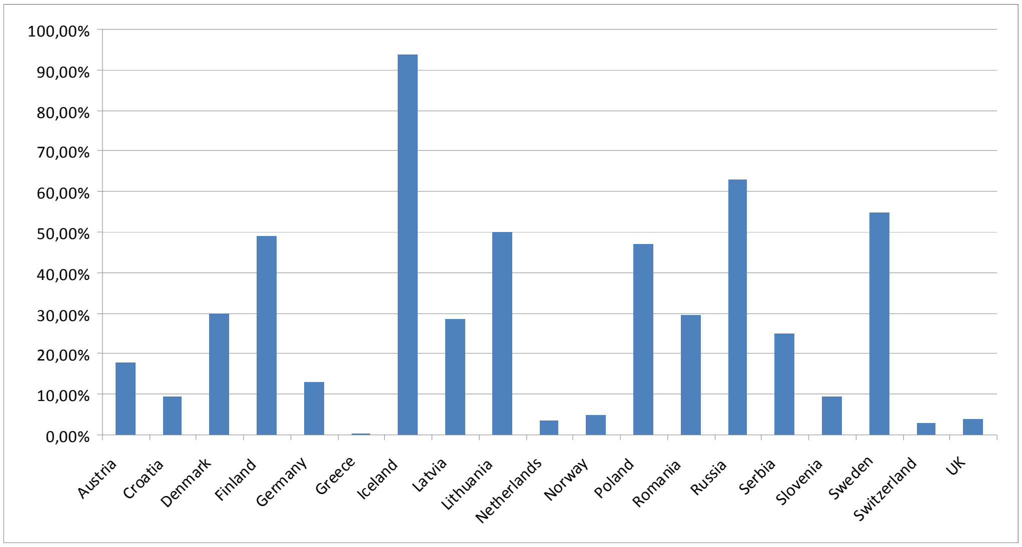


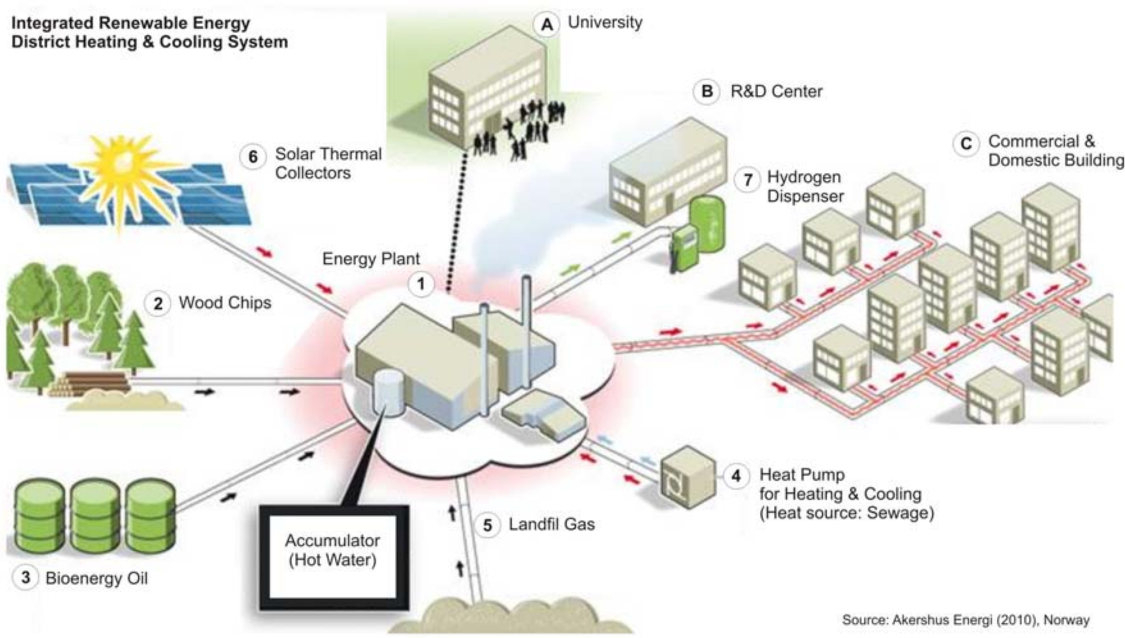
Figure 8.14: Share of district heating in total heat demand in selected countries (Euroheat&Power 2007).

DH is little used in lower latitude countries but district cooling is becoming increasingly popular in such regions, either through the distribution of chilled water or by using the DH network to deliver heat to run heat-driven absorption chillers. The Swedish town of Växjö, for example, uses excess heat from the biomass-fired CHP plant in summer for absorption cooling in one district, and a further 2MW chiller is planned (IEA, 2009b).

Combined production of heat, cold and electricity, as well as having the possibility for diurnal and seasonal storage of heat and cold, means that a high overall system energy efficiency can be obtained. However, the best mix of heat and cold sources together with the relevant technologies, depends strongly on local conditions, including demand patterns. As a result, the energy supply mix varies widely between different countries and systems (Euroheat & Power, 2006).
DHC systems can also provide electricity, through CHP system designs, and demand response options that facilitate increased integration of RE in power systems. This includes using electricity for heat pumps and electric boilers for DH with thermal storage used where excess electricity is generated (Lund et al., 2010). Using electricity for producing low grade heat may seem thermodynamically wasteful but other actions, such as spilling wind for example, can be even more wasteful.

8.2.2.2 Features and structure

Benefits of DH can occur on both the demand and supply sides (Fig. 8.15) through the use of geothermal, solar or biomass technologies and fuel flexibility. Occupiers of buildings connected to a DHC network can avoid operation and maintenance of individual heating equipment and rely on a professionally managed central system. An existing DHC network can be extended as appropriate to supply a larger number of customers and new low-carbon and RE sources can be integrated as they become available.



Source: Akershus Energi (2010), Norway

Figure 8.15: Integrated RE-based district heating and cooling system based on an actual installation in Lillestrøm, Norway, costing US$ 30 M [TSU: figure will need to be adjusted to 2005 US$] (Ulleberg 2010).

(1) Central energy system with 1,200 m^3 accumulator tank; (2) 20 MW_{th} wood burner system (with flue gas heat recovery); (3) 40 MW_{th} bio-oil burner; (4) 4.5 MW_{th} heat pump; (5) 1.5 MW_{th} landfill gas burner (5 km pipeline); (6) 10,000 m^2 solar thermal collector system (expected to be completed in 2012); (7) Demonstration of RE-based hydrogen production (water electrolysis and sorption enhanced steam methane reforming of landfill gas) for fuel cell vehicles (part of HyNor-project) to be completed in 2011.

Except in Iceland, the use of geothermal heat in DH schemes is small but the potential is great (Chapter 5). Also, enhanced geothermal systems (EGS) could be operated in CHP mode coupled with DH networks. The commercial exploitation of large heat flows is necessary to compensate for the high drilling costs of geothermal systems (Thorsteinsson and Tester 2010). In most cases, such a large heat demand is only available through DH networks, or to supply some industries (Hotson 1997).

Woody biomass, crop residues, pellets and solid organic wastes can be more efficiently used in a DH integrated CHP plant than in individual small-scale burners. Biomass fuels are important sources of district heat in several European countries particularly Sweden and Finland (Euroheat&Power 2007). The operation of a centralised biomass CHP plant with lower specific investment costs facilitates the application of cost-effective emission reduction measures also to reduce local air pollution.

In 2007, the more than 200 Mm^2 area of solar thermal collectors installed worldwide produced 146.8 GW_{th} but only a small fraction of that was for DH (Weiss, Bergmann et al. 2009). The costs of solar heating of water, space or a combination, might be reduced by shifting from small-scale, individual solar thermal systems to large-scale, solar heating plants. Higher solar shares can be achieved by using seasonal thermal storage systems, for which integration into a DH system with a sufficiently high heat demand is a prerequisite. Large central, solar thermal DH plants are found mainly in Germany, Sweden and Denmark.

An analysis of a future energy system in Denmark, based upon 100% RE by 2060, concluded that a gradual expansion of DH systems, and a switch to electric heat pumps for buildings that could not be connected to them, was the most efficient and least cost strategy for decarbonising space and domestic water heating (Lund, Möller et al. 2010).

8.2.2.3 Challenges associated with integration into heating/cooling networks

A DHC scheme involves a high up-front capital cost in piping networks. Distribution costs alone account for a significant share of total DH costs and are subject to large variations depending on heat density and the local conditions for building the insulated piping. Under Swedish conditions, DH, where available, can be competitive with alternative heating systems (Fig. 8.16).

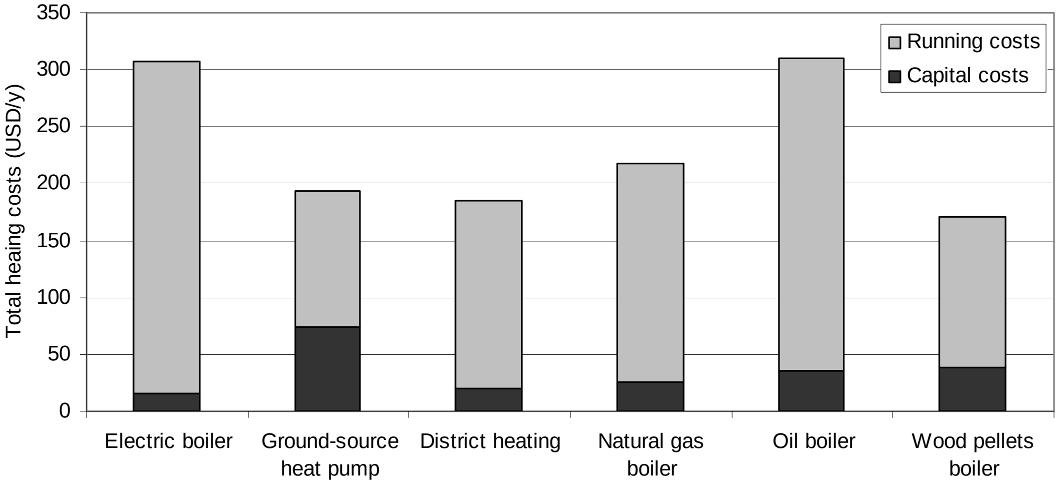


Figure 8.16: Average annual heating costs (US$2005 and including climate, energy and carbon taxes) for end-users in a typical 1000 m^2 multi-family building in Sweden using around 700 GJ/yr.

Notes: Capital costs are for end-user investment in the grid connection terminal, heat exchanger, boiler etc. Running costs are the payments to the utility. Date adapted from the Swedish Energy Markets Inspectorate (Ericsson 2009). See Chapter 11, case study for the fuel mix of Swedish DH systems.

Network capital costs and distribution losses per unit of heat delivered are lower in areas with high heat densities (expressed by kWh/m^2 or MW$_{peak}$ / km^2 or MWh/m of pipe length). Area heat densities can range from several hundred kWh/m^2 in dense urban, commercial and industrial areas down to below 20 kWh/m^2 in areas with dispersed single family houses. Corresponding heat distribution losses can range from less than 5% to more than 30%. The extent to which losses are considered a problem, however, depends on the heat source and cost.

Energy efficiency in buildings reduces the heat or cool demand and, as a result, total energy density is decreasing over time in some DHC systems. It can also flatten the load curve by reducing peak heating or cooling demand. Under some site specific conditions, investment costs for heat distribution networks could therefore become the predominant part of the total heating costs. Expected reductions in heat distribution costs through improved design and reduced losses suggest that the expansion of DH will remain economically feasible, even in areas with relatively low heat densities (Bruus and Halldor 2004). Improved designs include the co-insulation of smaller diameter forward and reverse flow distribution pipes.

8.2.2.3.1 Storage

Thermal storage systems can bridge the gap between variable, discontinuous and unsynchronised heat supply and demand. The capacity of thermal storage systems ranges from a few MJ up to several TJ; the storage time from hours to months; and the temperature from 20°C up to 1000°C.

These wide ranges are possible by using different storage materials (e.g. solid, water, oil, salt) and the corresponding thermal storage mechanisms.

In households with natural gas or electrical heating, hot water cylinder heat stores are commonly used. Solar systems can displace some or all of the energy demand, the gas or electricity becoming the back-up. For integrating large-scale, solar systems into DH networks, the development of systems for seasonal heat storage (Fig. 8.17) has made progress and several demonstration plants have been realised (Bauer, Marx et al. 2010). Heat and cold storage systems using latent heat of fusion or evaporation (phase change materials), or the heat of sorption, offer relatively high density storage (Bajnóczy, Palffy et al. 1999; Anant, Buddhi et al. 2008). Sorptive and thermo-chemical processes allow thermal storage for an almost unlimited period of time, since heat supply or removal occurs only when the two physical or chemical reaction partners are brought into contact. Both latent and sorptive heat storage technologies are in a relative early development phase.

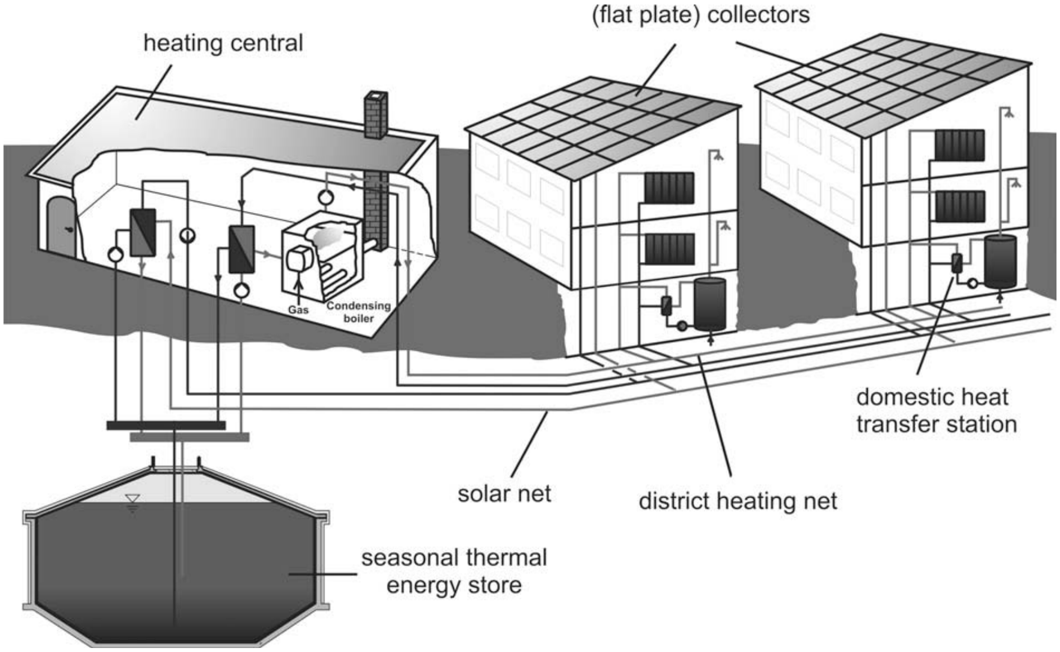


Figure 8.17: Central solar-supported heating plant with seasonal storage connected to a district heating system (Bodmann, Mangold et al. 2005)

The most suitable type of hot water storage system depends on the local geological and hydro-geological conditions, and the DHC system supply and demand characteristics. For short term storage (hours and days) the thermal capacity of the distribution system itself can be used for storage. Hot water storage in accumulator tanks is commonly used to even out hourly and diurnal variations in existing DHC systems. Longer term storage, often seasonal between winter and summer, is less common. In this case the main feature is having different types of geological storage, including duct storage systems and aquifer storage (Heidemann and Müller-Steinhagen 2006). With geological storage, relatively small temperature differences are employed. For example, heat may be injected during the summer to increase the temperature in an aquifer and then be extracted during the winter. Seasonal storage is likely to become more important with high shares of solar thermal energy in DHC systems.

8.2.2.3.1 Institutional aspects

DH schemes have typically been developed in situations where strong planning powers have existed, e.g., centrally planned economies, American university campuses, Western European countries with multi-utilities, and urban areas controlled by local municipalities.

Expanding the use of DHC systems would facilitate a higher share of RE sources such as deep geothermal and biomass CHP that require a large heat sink to be viable. Some countries are therefore supporting investments in DH as well as providing incentives for using RE. In Germany, for example, a market incentive programme supports new DH schemes through investment grants in existing settlement areas and for new development areas if the share of RE is above 50% (BMU 2009). In addition, the DH system operator receives a grant for each consumer connected to the new system. In Sweden, a high carbon tax has been a strong incentive to switch to RE heating options, biomass CHP in particular.

In the former centrally-planned economies, DH prices were regulated because of a social policy to sell heat below its market price. Today, in several countries with large DH schemes, an independent regulatory body ensures appropriate pricing where natural monopolies exist. In Denmark, for instance, a law that recognises the ownership of DH grids and the sale of heat as a monopoly, and hence regulates pricing and conditions of sale for the heat, has been a major factor in the development of the sector. A regulatory authority was established to oversee the formation of regulated prices and solve disputes between consumers and utilities (Euroheat&Power 2007).

In theory, third party access to DH networks could lead to a more competitive market for heating services, resulting in decreased heat prices and thus benefits for consumers. Markets for DH by nature are local, contrary to national and regional electricity and natural gas markets. If a new competitor invested in a more efficient and less expensive heat generation plant and could use the network of the existing DH utility, the incumbent utility may be unable to compete, the only choice then being to reduce the price or accept lost revenue. In this case, the stranded asset cost could be higher than the customer benefits obtained from having a new third party producer, resulting in a total net loss. More pronounced competition could be obtained if at least five producers operate in the same network. Most DH systems however are too small to host that many producers. Thus it remains debatable whether or not third party access in an existing DH system is financially sustainable and beneficial for the customer.

8.2.2.4 Options to facilitate integration into cooling networks

Cooling demands in buildings have grown recently because of increased internal heat loads from computers and other appliances, more rigorous personal comfort levels, and more glazed areas that increase the in-coming heat. The ratio of building surface to volume has also been rising but ingress of heat can be reduced by improved thermal insulation. Overall, modern building designs and uses have tended to increase the demand for cooling but reduced the demand for heating. This trend has been amplified by recent warmer summers in many areas that have increased the cooling demand to provide comfort, (particularly for those living in many low-latitude developing countries). Cooling load reductions can be achieved by the use of passive cooling options and active RE solutions. As for DH, the uptake of energy efficiency, deployment of other cooling technologies and structure of the market will determine the viability of developing a district cooling (DC) scheme.

Modern DC systems from 5 to 300 MW_{th} have been operating successfully for many years (in Paris, Amsterdam, Lisbon, Stockholm, Barcelona etc.). Where natural aquifers, waterways, the sea or deep lakes are utilised as the source of cold, then this can be classed as a form of RE source for cooling. Where a city or town is located near to a good water supply for the source of cold, then similar to DH systems, a network of pipes is used to carry the cold water from the supply to a series of buildings where it is passed through heat exchange systems. Sea water can be used but is more corrosive than cold, fresh water sources.

To use RE cooling most efficiently from a quality perspective, it is possible to set up a merit order of preferred cooling technologies from an economic point of view as below (IEA 2007), although the order may differ due to specific local conditions.

- Energy efficiency and conservation options in buildings and industry sectors, including white roofs and shading.
- Passive cooling options such as passive building design measures and summer night ventilation without the need for auxiliary energy.
- Passive cooling options using auxiliary energy, e.g. cooling towers, desiccant cooling, and aquifers.
- Solar-assisted, concentrating solar power, or shallow geothermal heat to drive active cooling systems.
- Biomass integrated systems to produce cold, possibly as tri-generation.
- Active compression cooling and refrigeration powered by renewable electricity.

Cooling demands located remotely from a cold water source could be met using complex, thermo-chemical sorption processes including chiller/heat pumps, absorption chillers, or compression chillers (IEA 2009). Such closed, active-cooling systems can be used for centralised or decentralised conditioning and involve a range of technologies to produce cooling driven by a RE source. Solar-assisted cooling (SAC) is promising with demonstration plants up to 3.6 MW_{th} (at Munich airport) but these technologies tend to be relatively costly at this early stage of their commercialisation, although the cost is declining with experience in system design (IEA 2007). One advantage of solar-assisted cooling technologies is that peak cooling demands often correlate with peak solar radiation and hence offset peak electricity loads for conventional air conditioners. Expansion of demand will depend, in part, on the other options available for cooling building space.

Ground source heat pumps (air-to-ground) can be used for space cooling virtually anywhere in the world in summer as well as for space heating (ground-to-air) in winter. Commercially available at small- to medium-scales (10-200 kW), they use the heat storage capacity of the ground as an earth-heat sink since the temperature at depths between 15 and 200 m remains fairly constant all year round at around 12 to 14°C. Vertical bores enable heat to be drawn out in the winter and concentrated within a building by a heat pump to reach the necessary temperature. The cost of drilling bores remains a high proportion of the total system cost so shallow horizontal pipes around 1-2 m depth can be an alternative, but less efficient system.

8.2.2.5 Benefits and costs of large scale penetration

The use of geothermal energy, solar energy or biomass in a DH or DC system provides heat at low or zero CO_2 emissions. The costs and benefits of a RE-based DH or DC system depends on site specific conditions such as the heat demand density or the availability of RE resources and appropriate infrastructure.

High penetration levels are not a technical problem for biomass or geothermal systems because of their high capacity factors. Many geothermal and biomass heating or CHP plants integrated into DH systems are successfully operating under commercial conditions. CHP as well as DHC developments often do not need financial incentives to compete in the market place, although government measures to address non-financial barriers, such as planning constraints, could aid greater deployment (IEA 2008).

Several large scale solar thermal systems with collector areas of around 10,000 m² were recently built in Denmark (Epp 2009). Under Danish conditions of high energy costs and carbon taxes, the integration of the solar collectors into existing DH systems will be redeemed in less than 10 years without any subsidies. At solar shares of up to 20%, the large number of customers connected to the DH system ensures a sufficiently large demand for hot water even in summer, so that high solar yields (~500 kWh/m²) can be achieved. Pilot plants with a solar share of more than 50% equipped with seasonal heat storage today demonstrate the technical feasibility of such systems (see the case study following).

8.2.2.6 Case studies

8.2.2.6.1 Solar assisted district heating system in Crailsheim, Germany

In Crailsheim, Germany, a new residential area with 260 houses, a school and sports hall has been designed to have more than 50% of the total heat demand covered by solar energy. A prerequisite for achieving such a high solar share is the use of a seasonal heat storage facility. The annual heat production of the system is 10.8 TJ, equivalent to the consumption of 300,000 litres of fuel oil.

Apartment blocks, new single houses and community buildings are equipped with solar collectors together with a 100 m³ buffer tank to directly cover instantaneous heat demand. A total annual heat demand of 4,100 MWh_{th} is expected to be met by the 7,300 m² solar collector area of which 700 m² are installed on a noise protection wall that separates the residential and commercial areas. Together with 75 boreholes at a depth of 55m and a second 480 m³ buffer tank, this provides seasonal storage. The integration of a 530 kW heat pump allows the discharge of the borehole storage system down to a temperature of 20°C, leading to reduced heat losses in the storage system and to higher efficiency of the solar collectors due to reduced return temperatures. It is expected that the borehole storage system will heat up to 65°C by the end of summer and the lowest temperature at the end of the winter heating period will be 20°C. Maximum temperatures during charging will be above 90°C. In a second phase, the heated residential area will be extended by 210 additional accommodation units requiring a total collector area around 10,000 m² and the seasonal storage system expanded to 160 boreholes (Mangold and Schmitt 2006). Solar heat costs in this advanced system are estimated to be around 0.24 US$/kWh[TSU: figure will need to be adjusted to 2005 US$] (Mangold, Riegger et al. 2007). By halving the fossil fuel consumption and by providing the remaining heat with a highly efficient fossil heating station linked to the existing DH network, emissions can be reduced by more than 1,000 t CO_2 /yr (Wagner 2009).

8.6.2.2.2 Biomass CHP district heating plant in Sweden

District heating in Sweden expanded rapidly between 1960 and 1985 having been entirely dependent on oil until the 1979 second oil crisis. Thereafter the fuel mix changed considerably and in 2007 biomass accounted for 44% of fuel supply in Swedish DH[8] (IEA 2009). Enköping is a documented and illustrative case of this transition that demonstrates an innovative approach integrating CHP, short rotation forestry and waste water treatment. The DH system was constructed in the early 1970s using oil-fired boilers until fuel switching started in 1979. After going through a period of using a mix of oil, solid biofuels, coal, electric boilers and LPG, the construction of a 45 MW_{th}, 24 MW_e biomass-fired CHP plant in 1994-1995 with the transition to near 100% biomass completed in 1998. This choice of fuel was driven by national CO_2 taxes, other policy instruments, and a local council decision to completely avoid fossil fuels (McKormick and Kåberger 2005).

Enköping differs from other DH systems due to a cooperation begun in 2000 between the local energy company, the sewage treatment plant and a local landowner. The energy company was

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[8] The remaining production was based on 35 PJ of municipal solid waste (18%), 20 PJ of industrial waste heat (10%), 10 PJ of coal (5%), 8 PJ TWh of oil (4%), 8 PJ of natural gas (4%), 10 PJ of peat (5%) and 20 PJ of heat from heat pumps (10%).

interested in diversifying fuel supply fearing that there may not be enough forest residue biomass in the region to meet future demand. The municipal sewage plant was obligated to reduce nitrogen discharges by 50%. The use of willow (*Salix*) was identified as a cost-effective approach to reduce nitrogen discharges by land treatment and at the same time produce biomass. An 80 ha willow vegetation filter was established in 2000 on nearby farmland. The farmer is paid for receiving wastewater and sewage sludge and for delivering biomass to the CHP plant at market prices. The success of this model is due to all parties being proactive and open to new solutions; advisors working as catalysts; regional and local authorities being positive and interested; and the risks being divided between the three parties (Börjesson and Berndes 2006). In 2008, the local area of willow plantations was increased to 860 ha and it is the ambition of the energy company to continue increasing the current 15% fuel share from *Salix*.

8.2.2.6.3 District heating in South Korea

Although most DHC schemes have been developed in Europe and North America, the Korea District Heating Corporation claims to be the world's largest DH provider (KDHC 2010) with heat production capacity from 11 plants exceeding 3.5 GW, including 1.5 GW of heat purchased from CHP plants operated by Korea Electric Power Corporation and from 85 MW of waste-to-energy incinerators owned by several municipal governments. The corporation has constructed over 1100 km of twin outward and return pipes as part of the Seoul metropolitan heating network. The corporation also aims to use biomass waste incineration facilities and solar heat to supply 30% of total heat energy to 10,000 new households by 2010.

It was established in 1985 as a government corporation for the purpose of promoting energy conservation and improving living standards through the efficient use of district energy. The state-run DH business aims to save energy as well as to promote the public benefits of DHC and its convenience. It provides DH to over 60% of the nation's total households with the aim to steadily expand the business and provide DHC services to 2 million households nationwide by 2015. Particular business emphasis is given to RE sources, including landfill gas.

8.2.2.6.4 District cooling systems

Few if any district cooling schemes have resulted from policy framing developments. Most have been commercial decisions made by the local municipality or building owners (IEA-SHC 2010). As a result of several successful demonstrations, the opportunity now exists for governments to encourage further deployment of RE cooling projects. Deep water cooling allows relatively high thermodynamic efficiency by utilizing water at a significantly lower heat rejection temperature than the ambient temperature. This temperature differential results in less electricity being consumed because a lower volume of cold water needs to be pumped. For many buildings, lake water is sufficiently cold that, at times, the refrigeration portion of the air-conditioning systems can be shut down and all the excess building interior heat transferred directly to the lake water heat sink. Power is needed to run pumps and fans to circulate the water and the building air but this is generally less than would be the electricity demand for refrigeration chilling to produce the same cooling effect.

Successful projects include 51 MW of cooling at Cornell University, Ithaca, USA, based on pumping around 20 m^3/min of 4°C water from the bottom of nearby Cayuga Lake through a heat exchanger before storing it in a 20,000 m^3 stratified thermal storage tank (Zogg, Roth et al. 2008). A separate water loop runs back 2 km before passing through the air-conditioning systems of the 75 campus buildings and Ithaca High School. In this US$(2005) 68 M scheme, the cooling water is discharged back to the lake at around 8-10°C and mixed by injection nozzles with the surface water to maintain stable water temperatures. The 1.6 m diameter intake pipe has a screen at 76m depth and this and the 38 discharge nozzles were carefully designed to minimise maintenance and environmental problems, having first closely monitored the ecology, hydro-dynamics, temperature strata and geophysics of the lake. Greenhouse gas emissions have been reduced significantly since the project started in 1999 compared with the original refrigeration based cooling system. This was due to both reducing the power demand for cooling by around 80-90% of the previous 25 GWh/yr and avoiding the 12-13t of CFCs that were used in the six chillers (Cornell 2005). There remain some concerns about bringing up phosphorus rich sediments from the bed of the lake and discharging them near to the surface, hence possibly encouraging algae growth.

Since 2004 Toronto has used cold water drawn from Lake Ontario 5 km away for a 207 MW cooling project of 3.2 Mm^2 of office floor area in the financial district. The lake water intake pipe at 86m depth runs 5 km out into the lake to ensure clean water is extracted since this is also the supply for the city's domestic water system. No warm water return discharge to the lake therefore results. Stockholm has a similar but smaller district cooling system based on extracting sea water from the harbour.

The Malaysian company Solar District Cooling Sdn Bhd (SDC) is planning to build its first solar district cooling plant having had experience of several solar absorption cooling projects for individual buildings (SDC 2010). The solar cooling technology will be located in Cyberjaya and used initially for office and residential applications. Although absorption chiller technology is reliable and becoming well understood, the typical payback time of more than 10 years has remained a deterrent to wider deployment to date. Policy support measures by interested governments could help bring down the manufacturing, project design and installation costs (IEA 2008).

8.2.3 Integration of renewable energy into gas grids

The main objective of a gas grid is to transport gaseous fuels from producers to consumers. A complete gas system consists of gas productions plants, transmission and distribution pipelines, gas storage, and gas dispenser/delivery systems for end-users. The design depends on the type and source of energy, the end-user demand, and locations of gas supply and demand.

8.2.3.1 Characteristics of RE with respect to integration into gas grids

Existing gas grids typically consists of different types of pipelines. High pressure transmission pipelines (40-70 bar) go between the production plant and the distribution network, passing over public land and third party properties, while distribution pipelines, including main feeders, station connections and valves, are usually contained on the property (generally owned by the customer) at the end-use point (EIGA 2004).

A gas transmission and distribution system is primarily designed to deliver adequate amounts of gas with a certain quality (e.g., heating value, pressure, and purity) to downstream users. The gas flow rate depends on the scale and physical attributes of the gas (such as molecular weight, viscosity, specific heat). The larger the pipeline diameter and the higher the pressure drop, the more gas volume that can be moved over a given distance (Mohitpour and Murray 2000). In the design of pipelines for high gas flow rates, there is an economic trade-off between increasing the diameter of the pipeline versus increasing the gas pressure. In order to balance supply and demand, gas storage also needs to be included at various levels in the system; the capacity depending on how the gas is produced, how the gas can be integrated into the gas grid and the end-use application. The size of gas storage is normally minimised to reduce costs and safety hazards.

The materials used in gas pipelines depend on the type of pipeline (transmission or distribution), location (sub-sea, over ground, underground), operating conditions (pressure, temperature, corrosion), and type and quality of gas to be sent through the pipeline. Metallic materials are mainly used in transmission pipelines or pipelines tolerant to higher pressures and temperatures, while plastics are used in distribution gas grids operating at lower temperatures (<100°C) and pressures (< 10 bar). Metal pipelines have the potential for internal and external corrosion problems (Castello, Tzimas et al. 2005).

Over the past 50 years large, integrated natural gas networks have been developed around the world. For example, the natural gas grid in the USA is a highly integrated transmission and distribution grid with more than 210 natural gas pipeline systems, 480,000 km of interstate and intrastate transmission pipelines, and 394 underground natural gas storage facilities (EIA 2007). European (EU27) natural gas has a total of 1.8 million km of pipelines and 127 gas storage facilities. The EU grid currently supplies more than 110 million customers, and is growing rapidly (Eurogas 2008).

Linking gas and electricity grids has been proposed by using surplus RE power to produce hydrogen by electrolysis and combining this, through the process of methanation, with CO_2 either from biogas, captured from fossil fuel combustion or extracted from the atmosphere, to produce methane as an energy store or carrier (Sterner 2009).

8.2.3.2 Features and structure of gas grids

Over the past decade there has been increasing interest in “greening” existing natural gas grids. In Europe the EU-directive 2003/55/EC opened up the gas grid to carry alternative gases such as hythane (a blend of hydrogen and natural gas), hydrogen, and biogas (Persson, Jönsson et al. 2006; NATURALHY 2009). In Germany the target for 2020 is to substitute 20% (by volume) of CNG (compressed natural gas used for transport) with biogas (1.12 PJ/year), while the target for 2030 is to substitute 10% of natural gas in all sectors with biogas (382 PJ/year) (Müller-Langer, Scholwin et al. 2009). Similar proposals have been made for the natural gas grid running along the West Coast of North America. In California a Bioenergy Action Plan has been introduced by the State Governor in an Executive Order on Biomass (CEC 2006).

Biogas can be upgraded to natural gas quality, blended with natural gas, and transported via existing or new gas grids. Until now most of the biogas produced around the world has been distributed in local gas systems primarily dedicated for heating purposes. In a few cases it has been transported via trucks to filling stations for gas-fuelled vehicles (Hagen, Polman et al. 2001; Persson, Jönsson et al. 2006). However, the biogas business is growing rapidly and is currently being commercialized by larger industrial players (Biogasmax 2009), and gas companies (e.g. National Grid, UK) that are now making plans on how to upgrade large quantities of biogas and inject this, at the required quality, into national/regional transmission gas pipelines (NationalGrid 2009) to offset some of the demand for natural gas in existing and future markets.

Synthetic gases, (syngas), a mixture of carbon monoxide, hydrogen, methane, higher hydrocarbon gases, and carbon dioxide, can be produced via gasification (partial oxidation) of coal, but also from biomass feedstocks (Chapter 2). Syngas derived from coal or solid organic waste is already widely used for cooking, heating, and power generation, especially in areas where natural gas is not available.

Once the energy feedstock for the biogas or syngas has been established, the end-use, heating, combined heat and power (CHP), raw material for chemical industry, or transport fuel, needs to be determined. The design of the gas clean-up, delivery and storage system will depend on the existing energy production and electricity system in the region where the gas grid is being considered. National and regional electricity and gas transmission grids can complement each other in the long-distance transport of energy. Similarly, local gas distribution grids could complement local heating and cooling networks (8.2.2).

Local gas distribution systems have traditionally used gas burning appliances to provide space and water heating. Using existing commercial internal combustion engine and micro-turbine technologies, biogas and syngas can also be used to fuel small to large CHP-systems. With the advent of commercial fuel cell technologies there are also new opportunities for small distributed, gas-based CHP-systems (DeValve and Olsommer 2006; Zabalza, Aranda et al. 2007).

Hydrogen can also be produced from RE sources. Future production and distribution will depend significantly on the interaction with existing electricity systems (Sherif, Barbir et al. 2005; Yang 2007). Over the next two to three decades, most of the pure hydrogen for fuel cell vehicle refuelling will probably be produced in distributed systems via small-scale, water electrolyzers or steam methane reformers (Riis, Sandrock et al. 2006; NRC 2008; Ogden and Yang 2009) and require local storage and distribution pipelines (Castello, Tzimas et al. 2005). In the long-term, large-scale production of hydrogen via water electrolysis using wind power, large-scale biogas-to-hydrogen reforming plants, and other technologies are conceivable (IEA 2006). Blending of hydrogen (up to 20%) with natural gas on a large scale and transporting the hythane mix long-distances in existing or new natural gas grids could be an option for a large-scale hydrogen economy (NATURALHY 2009), but the degree of pipeline leakage is uncertain.

8.2.3.3 Challenges caused by integration into gas grids

The economic and environmental viability of gas from local RE sources grids depends on reliability of supply and the energy infrastructure such as existing gas grids and electricity, heating and cooling networks. Having a clear policy for the end-use of the gas would avoid competition with other energy carriers.

The economic payback time to integrate biomethane into a gas grid depends on the location. If the installation is done at the end of a pipeline, as incremental capacity, the payback time can be relatively short. The community-scale biogas plant in Linköping Sweden is a good example of an economic and viable system since multiple organic wastes are treated and upgraded to biogas which is upgraded before distribution to a slow overnight filling station for buses, 12 public refuelling stations for cars, taxis and fleet vehicles, and for use in a converted diesel train with 600 km range (IEA 2010). The payback time is sensitive to the estimated long-term gas production and price that will be affected by taxation and carbon values as well as the future end-use demand of the gas. Local and regional differences in existing infrastructure (and energy supply and demand) make recommendations difficult for planning on a national and regional level.

Technical challenges relate to gas source, composition, and quality. The composition and heating value of biogas and syngas depends on the biomass source, gasification agent utilized in the process, and reactor pressure. The composition and parameters of fuel gases from different sources vary widely (Table 8.2). Commercial natural gas consists of 80-90% methane. Biogas from anaerobic digestion or landfill gas can be upgraded to reach similar methane composition standards as natural gas, for example, by stripping out the carbon dioxide content before being fed into the gas grids or used directly as fuel in combustions engines or fuel cells for stationary or mobile applications. Biomass derived syngas (produced from gasification followed by methanation) can consist of 83-97% methane along with 1-8% of hydrogen and hence has a similar heating value to commercial natural gas.

Table 8.2: Typical composition and parameters of gases from a range of sources including anaerobic digestion (AD) (Persson, Jönsson et al. 2006).

Parameter	**Unit**	**Landfill Gas**	**Biogas from AD**	**North Sea Natural Gas**	**Dutch Natural Gas**
Lower heating value	MJ/Nm^3	16	23	40	31-6
	kWh/Nm^3	4.4	6.5	11	8.8
	MJ/kg	12.3	20.2	47	38
Density	kg/Nm^3	1.3	1.2	0.84	0.8
Higher Wobbe index	MJ/Nm^3	18	27	55	43.7
Methane number		>130	>135	70	–
Methane	vol-%	45	63	87	81
Methane, variation	vol-%	35-65	53-70	–	–
Higher hydrocarbons	vol-%	0	0	12	3.5
Hydrogen	vol-%	0-3	0	0	–
Carbon oxide	vol-%	0	0	0	0
Carbon dioxide	vol-%	40	47	1.2	1
Carbon dioxide, variation	vol-%	15-50	30-37	–	–
Nitrogen	vol-%	15	0.2	0.3	14
Nitrogen variation	vol-%	5-40	–	–	–
Oxygen	vol-%	1	0	0	0
Oxygen, variation	ppm	0-5	–	–	–
Hydrogen sulphide	ppm	<100	<1000	1.5	–
Hydrogen sulphide,variation	ppm	0-100	0-10000	1-2	–
Ammonia	ppm	5	<100	0	–
Total chlorine(as Cl$^-$)	mg/Nm^3	20-200	0-5	0	–

Natural gas companies define the composition quality needed before accepting other gases into their distribution and storage system. This can create a market barrier for biogas and landfill gas producers, (more than for syngas) as only gases of a specified quality can be injected directly. Particulates and condensates need removal and there is low tolerance for other impurities.

- CO_2 can be removed by several methods but each with operational issues (Persson, Jönsson et al. 2006):
    - Absorption in water (water scrubbing) requires large amounts of water. Plugging of the equipment due to organic growth can also be a problem.
    - Absorption by organic solvents such as polyethylene glycols or alkanol amines require large amounts of energy for regenerating the solvent.
    - Pressure swing adsorption requires dry gas.
    - Separation membranes, dry (gas-gas) or wet (gas-liquid) require handling of the methane in the permeate stream (which increases with high methane flow rates in the gas stream).
- Cryogenic separation requires removal of water vapour and H_2S prior to liquefaction of the CO_2.
- Removal of corrosive H_2S from biogas is necessary to protect upstream metal pipelines, gas storage and end-use equipment. Micro-organisms can be used to reduce the level of H_2S in biogas by adding stoichiometric amounts of oxygen to the process (around 5% air to a digester or biofilter). Alternatively, simple vessels containing iron oxides can be used as they react with H_2S and can be easily regenerated when saturated.
- Siloxanes and organic silicon compounds, can form extremely abrasive deposits on pistons, cylinder heads and turbine sections and hence can cause damage to the internal components of an engine if not removed (Hagen, Polman et al. 2001; Persson, Jönsson et al. 2006).

Hydrogen needs purifying and drying before it is stored and distributed. For use in low temperature fuel cells it normally has to be high purity (> 99.9995% H_2 and <1 ppm CO). Industrial hydrogen with lower purity can be transported in dedicated transmission and distribution pipelines so long as there is no risk of water vapour building up, or any other substances that can lead to internal corrosion. Regular checking for corrosion and material embrittlement in pipelines, seals, and storage equipment is also important (EIGA 2004).

8.2.3.4 Options to facilitate the integration into gas grids

8.2.3.4.1 Technical options

The two main technical challenges when integrating RE-based gases into existing gas systems are pipeline compatibility and gas storage.

RE-based gas systems are likely to require large gas storage capacity to account for variability and seasonality of supply. Since RE-based gases can be produced regionally and locally, storage is most likely to be located close to the demand of the end-user. The size and shape of storage facilities will depend on the primary energy source and the end-use. In small applications, the pipelined can also be used for gas storage (Gardiner, Pilbrow et al. 2008). In case where there are several complimentary end-users for the gas, infrastructure and storage costs can be shared. Hydrogen can be injected into existing natural gas grids, but this may first require some upgrading of the existing pipelines and components (Mohitpour and Murray 2000; Huttenrauch and Muller-Syring 2006). Pure hydrogen has a lower volumetric density compared to natural gas so pipelines will need higher pressures or around 3 times larger diameter (in order to carry the same amount of energy per unit time as existing natural gas pipelines.

Dedicated distribution gas pipelines for RE-derived gas (biomethane, hydrogen, syngas, or gas mixture) can operate at low pressures and volume flow rates (but needing increased diameter to give similar energy delivery). This opens up the opportunity for simpler designs where gas with a lower volumetric energy density can be distributed locally in polymer pipelines made of less costly materials. The required gas quality could be less stringent than if injected into other gas pipelines but would be governed by the specifications for end-use applications.

After a RE gas has been upgraded, purified, dried, brought up to the prescribed gas quality, and safely injected into a distribution grid, the main operational challenge is to avoid leaks and regulate the pressure and flow rate so that it complies with the given pipeline specifications. Compressors, safety pressure relief systems, and gas buffer storage need to be available continuously in order to maintain the optimum pressures and flow rates in the grid.

Options for large-scale storage of biomethane are similar to those of natural gas, namely compressed (CNG) or liquefied (LNG). Small to medium-sized gas storage buffers tanks can be introduced into distribution systems to balance local supply and demand. Methane can be collected and stored for a few days in inflatable rubber or vinyl bags. In large, industrialized biogas process plants, upgraded gas is normally stored at high pressures in steel storage cylinders (as used for LPG), depending on the size of the production plant and mode of further distribution (truck versus pipeline). Ideally, a compressed biogas dispensing station for vehicles should be connected to a local biogas source and/or to a gas pipeline. Distribution of compressed biogas cylinders can be achieved using trucks as liquefaction before transport in tankers (as used for LNG) would likely add significant cost and complexity.

For RE-based hydrogen over the next few decades the general consensus is that it will mainly be produced in smaller distributed systems (Riis, Sandrock et al. 2006). For example, water electrolysers or small-scale steam methane reformers only require small to medium sized hydrogen storage whilst if in the long-term hydrogen is derived from large, integrated RE-systems, then larger hydrogen storage units might be needed. Small-scale storage of hydrogen can be achieved in steel cylinders around 50 l and at 200 bar. Composite-based hydrogen gas cylinders that can withstand pressures up to 700 bar have been developed and demonstrated in hydrogen vehicle-fuelling stations. Hydrogen can also be stored at low pressures in stationary metal hydrides, but these are relatively costly and can only be justified for small volumes of hydrogen or if compact storage is needed. In integrated gas grids, it is probably more suitable to use low-pressure (12-16 bar) spherical containers that can store relatively large amounts (>30,000 m^3) of hydrogen (or methane) above ground (Sherif, Barbir et al. 2005). For safety reasons, such storage will normally have to be situated far away from densely populated areas, and hence would require a longer gas pipeline to the end-user.

At the large-scale, hydrogen can be stored as a compressed gas or cryogenically in liquid form, but this would cost more than biomethane storage due to the lower volumetric density and boiling temperature (-253ºC). In practice, about 15-20% of the energy content in the hydrogen would be required to compress it from atmospheric pressure to 200-350 bar. Around 30-40% of total energy is required to store liquid cryogenic hydrogen (Riis, Sandrock et al. 2006). Natural underground options such as caverns or aquifers for large-scale, seasonal storage can be found in various parts of the world, but their viability and safety must be evaluated on a case-by-case basis.

8.2.3.4.2 Institutional options

The main institutional challenges related to integrating RE-based gas into existing gas systems are adequacy of supply, security, safety, and standards (McCarthy, Ogden et al. 2006). Adequacy of supply can be influenced by the variability and seasonality of the RE resource. For example, biomass resources can be seasonal and quantities can vary from year to year. If hydrogen is produced from a variable RE source, the fluctuations of the supply must be considered. Designing a system to provide gas on demand may require storage of the primary feedstock (e.g. baled straw, or pelletized biomass) or storage of the hydrogen energy carrier. Capacity of the gas transmission and distribution system also needs to be able to meet demand for the gas.

The security of a gas pipeline system involves assuring a secure primary supply and building robust networks that can withstand either natural or malicious physical events. Networks that carry several gases are likely to be more secure than a network wholly dependent on a single feedstock. Similarly, diverse local or regional RE resources used for gas production can offer more secure supply than a single source of imported natural gas. In order to enhance network security, gas pipeline networks often include some degree of duplication (such as having multiple pathways between supplier and user) so that a pipeline disruption in a single network cannot shut down the entire system. Assessing vulnerability to malicious attacks for an extensive pipeline system over thousands of kilometres is a daunting task, and may require technological solutions such as intelligent sensors that report back pipeline conditions via GPS technology to allow rapid location of a problem and corrective action.

Hydrogen is widely used in the chemical and petroleum refining industries and safety procedures and regulations for that application are already in place. Industrial hydrogen pipeline standards and regulations for on-road transport of liquid and compressed hydrogen have been established. However, there is a lack of safety information on hydrogen components and systems, which poses a challenge to the commercialization of hydrogen energy technologies. Codes and standards necessary to standardize technologies and gain the confidence of local, regional and national officials involved with planning the increased use of hydrogen and fuel cells, are being focused on developing safety and operational standards for hydrogen systems, both nationally (e.g. US DoE National Hydrogen Association (NHA); US Fuel Cell Council; Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW), Germany) and internationally (e.g. New Energy and Industrial Technology Development Organization (NEDO), Japan; the International Partnership for

Hydrogen Energy (IPHE); and the International Energy Agency's Hydrogen Implementing Agreement (HIA)).

Feed-in regulations can enable the introduction of biomethane into a natural gas grid in a similar way to RE power generation feeding into an electricity grid. There is no one single international gas standard for pipeline quality of biogas or hydrogen, although countries such as Sweden and Germany have developed their own national standards (Persson, Jönsson et al. 2006) (Table 8.3).

Table 8.3: National standards for biomethane injection into natural gas grids for Sweden and Germany (Persson, Jönsson et al. 2006).

Parameter	Unit	Demand in Standard
Sweden		
Lower Wobbe index	MJ/Nm^3	43.9 – 47.3 (i.e. 95-99% methane)
MON (motor octane number)	–	> 130 (calculated according to ISO 15403)
Water dew point	°C	$< T_{ambient} - 5$
$CO_2 + O_2 + N_2$	vol %	< 5
O_2	vol %	< 1
Total sulphur	mg/Nm^3	<23
NH_2	mg/Nm^3	20
Germany		
Higher Wobbe index	MJ/Nm^3	46.1 – 56.5 (> 97.5% HHV methane)
	MJ/Nm^3	37.8 – 46.8 (i.e.87-98.5% LHV methane)
Relative density	–	0.55 – 0.75
Dust	–	Technically free
Water dew point	°C	$< T_{ground}$
CO_2	vol %	< 6
O_2	vol %	< 3 (in dry distribution grids)
S	mg/Nm^3	< 30

8.2.3.5 Benefits and costs of large scale penetration of RE into gas grids

Benefits and costs can be assessed using both economic (capital expenditure, operation and maintenance costs etc.) and environmental (GHG emissions, local air pollution, energy input ratio, air pollution etc.) indicators. The relevant parameters are significantly affected by the type of RE gas source, the design of gas production, storage, and distribution systems, and the end-use applications (transport or stationary). Comparisons between various alternative transport fuels are discussed in Section 8.3.1). This section focuses on the benefits and costs related to the integration of RE into gas grids.

A clear benefit from expanding the use of RE-based gas, particularly methane, is its compatibility with existing gas infrastructure. The costs of transmission and distribution of biomethane would be similar to that of existing gas systems giving a straightforward transition path for integration into existing supply chains and gas grids. Biomethane is already well-established for heating, cooking, power generation, CHP and transport applications. More than 9 million CNG (and LNG) vehicles already operate worldwide (Åhman 2010) whereas the market for hydrogen-fuelled vehicles is limited to utility vehicles such as forklift trucks and demonstration cars and buses.

GHG emissions related to producing and upgrading a RE-based gas should be assessed before a system is implemented. Methane leakages to the atmosphere during the gas up-grading, storage and distribution process and from heat and power consumed during up-grading and compacting will affect the overall energy efficiency and GHG emissions (Fig. 8.18) (Pehnt, Paar et al. 2009). Other studies have shown that vehicles fuelled by landfill gas can reduce CO_2 emissions by around 75% compared to using CNG, or even higher if using biogas produced from manure (NSCA 2006). The general conclusion is that all the waste and residue resources should be utilized so that GHG-emissions are minimized.

To compete with other energy carriers, the cost of producing and up-grading biogas to the quality required for injection into an existing gas grid should be minimised. It depends on the choice of technology (e.g., for CO_2 removal; 8.2.3.3). A comprehensive study of several biogas plants in Sweden showed that the electricity consumed to upgrade biogas is about 3-6 % of the energy content of the cleaned gas, and the cost to upgrade biogas is about US$(2005) ~0.05-0.20 /MJ (Persson 2003).

The cost per unit of energy delivered using a gas pipeline is dependent on economies of scale and gas flow rate. The major cost is the pipe itself plus costs for installation, permits and rights of way. The cost of a local distribution pipeline depends mainly on the density of the urban demand with more compact systems yielding a lower cost per unit of energy delivered. When designing a new gas grid, planning for anticipated future expansions is recommended as adding new pipes can be a costly option. If demand grows rapidly, increasing the pressure to provide additional gas flow may be cheaper than adding new pipelines. Biomethane distribution and dispensing at the medium scale (assuming a mix of pipelines and via cryogenic bottles by truck with an average cost of US$(2005) ~7.6 /GJ) is US$(2005) ~6.4–15.3 /GJ (Fig. 8.19) which is substantially higher, than for liquid fuels at US$(2005) ~2.5-3.8 /GJ) (Åhman 2010).

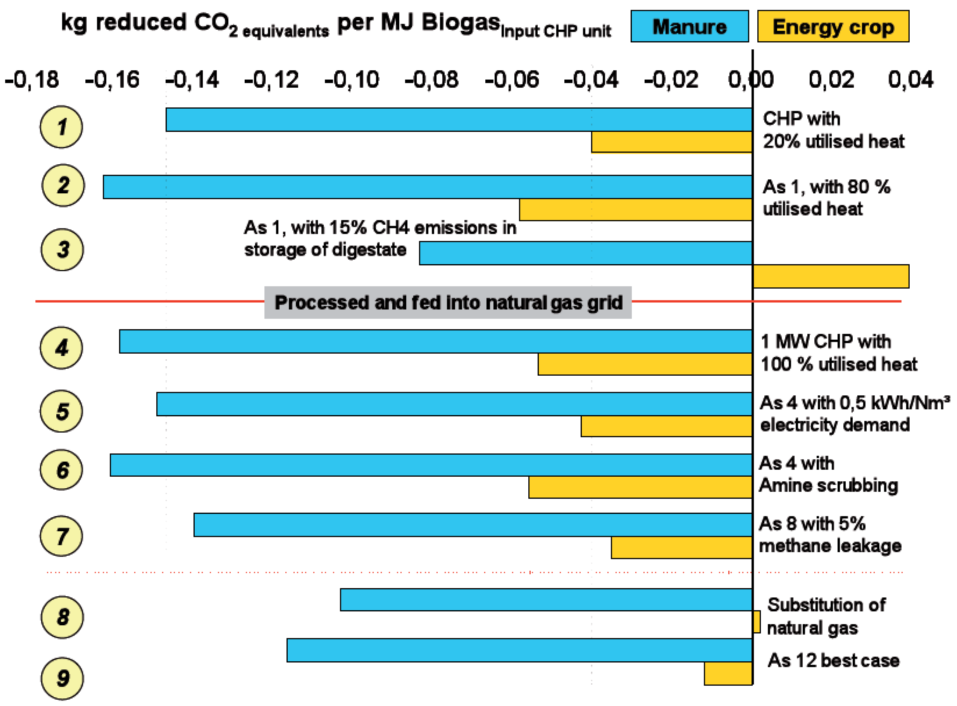

Figure 8.18: Potential reduction of greenhouse gas emissions by a biogas reference plant (kg $CO_{2\,eq}$ /MJ biogas input compared with the use of natural gas for several gas supply systems producing 500 kW_e from animal manures as feedstocks (blue) or corn silage (orange) (Pehnt, Paar et al. 2009). Note: Assumptions used found in more detailed study (Pehnt, Paar et al. 2009)

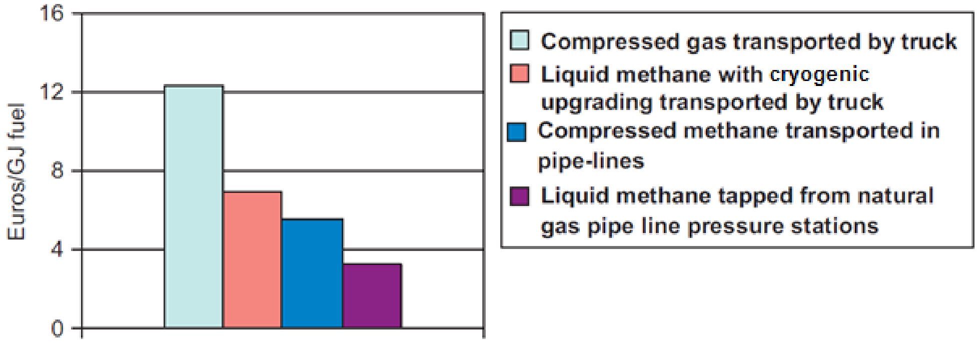

Figure 8.19: Cost for distribution and dispensing of biomethane at medium scale (Åhman 2010). Note: Cost data from 2006 when 1 EUR(2006) = 1.27 US$(2005).

In order to blend RE-derived gases into the gas grid, the gas source needs to be located near the existing system to avoid high delivery costs. For remote plants using the methane or hydrogen on-site would avoid the need for gas distribution. Blending syngas or hydrogen into the natural gas system could be feasible, but may require changes to gas distribution and end-use equipment designed for natural gas. "Town gas" city networks that currently employ fossil fuel-derived syngas may be good markets for biomass-derived syngas.

Potential for hydrogen production from RE resources is greater than for biogas or biomass-derived syngas. Limiting factors are likely to be capital costs and time involved in building a new hydrogen infrastructure. Hydrogen used as a transport fuel would require several hundred billion dollars invested over four decades to fully develop a suitable infrastructure for refuelling vehicles (NRC 2008). Incorporating variable RE sources could add to the cost because of the added need for storage.

The outlook for RE-derived gaseous energy carriers depends on how quickly they can penetrate the energy system and how much can they ultimately contribute. In Europe, biomethane could potentially replace 17.5 EJ of imported natural gas in 2020 (Fig. 8.20) (Müller-Langer, Scholwin et al. 2009) but depending on competition for the available biomass resource[9] (Eurogas 2008).

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[9] By way of comparison, total natural gas consumption in Europe (EU27) in 2007 was about 19.7 EJ, being 24% of total energy needs.

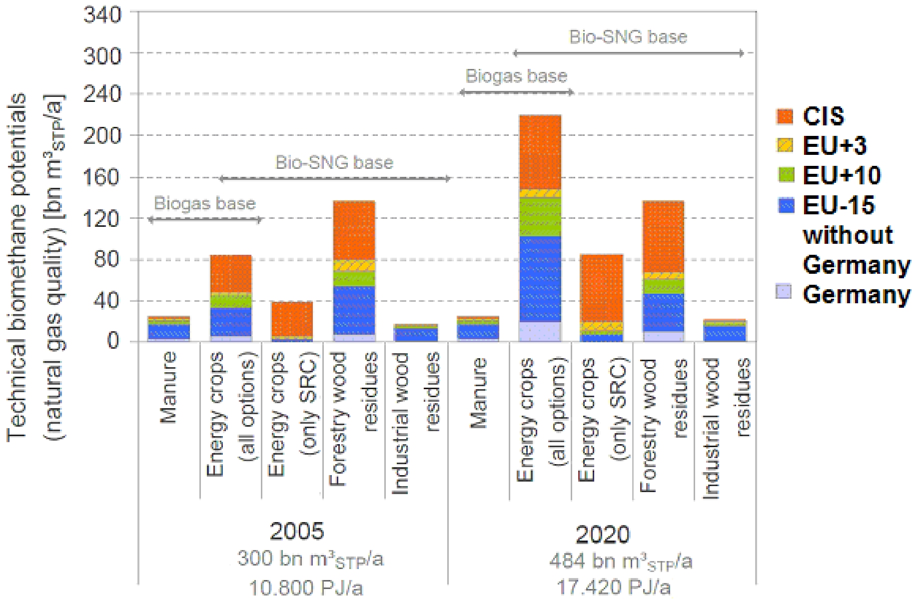

Figure 8.20: Technical potentials of biomethane at standard temperature and pressure (STP) in the EU-region in 2005 and 2020 (Müller-Langer, Scholwin et al. 2009).

8.2.4 Liquid fuels

8.2.4.1 Characteristics of RE with respect to integration

Renewable liquid fuels are basically produced from biomass sources (Chapter 2) or via solar fuels (Chapter 3). Currently most biofuels are produced from sugar, carbohydrate and vegetable oil food crops. Alcohol fuels can be used in blends typically up to 10% (in volumetric terms) with gasoline in regular spark ignition engines or blended in any proportion with gasoline for use in *flex-fuel* vehicles (Section 8.3.1). Biodiesel can be used in compression ignition engines either neat or blended with mineral diesel, though blends above 5% are not always covered by engine manufacturer warranties. Biogas methane, if it meets appropriate specifications, can also be combusted directly in spark-ignition internal combustion engines similar to those suitable for running on compressed natural gas (CNG). Solid ligno-cellulosic biomass sources can be converted to "second generation" liquid fuels by means of biochemical processes such as enzymatic hydrolysis or by thermo-chemical processes to produce synthesis gas (mainly CO + H_2) followed by the established Fischer-Tropsch conversion to produce a range of synthetic liquid fuels suitable for aviation, marine and other applications (Sims, Taylor et al. 2008).

The demand for large amounts of traditional solid biomass primarily in developing countries for cooking and heating could be replaced by more convenient fuels such as LPG but others produced from biomass such as ethanol liquid or gels (Utria 2004; Rajvanshi, Patil et al. 2007) or dimethyl ether (DME) (IEA 2008). Most of the projected demand for liquid biofuels, however, is for transport, though industrial demand for bio-lubricants and chemicals, such as methanol, for use in chemical industries could increase.

Liquid biofuels integrated into existing transport fuel systems can make use of existing infrastructure to transport and distribute oil products. Transition barriers would be relatively low as the biofuels could be introduced without costly modifications to existing petroleum storage and delivery systems, and can take advantage of existing infrastructure components already used (NAS 2009). Some related costs could eventuate for blending and for additional technical adaptations of fuel storage tanks, fuel pumps, or provision of new installations. The type of fuel storage and delivery system will vary depending on the properties of the biofuel and compatibility with the existing petroleum-based fuel system. Most common biofuels have fairly similar properties to gasoline and diesel so can be blended reasonably easily with these petroleum fuels, but cold weather conditions can represent difficulties, also for storage and transport, especially for some biodiesels which may form gels and stop flowing. At high levels of biofuel use, various transport and delivery modes from refinery to terminal might be used. Fuels could be transported from bio-refineries (Chapter 2) via truck, barge, tanker and/or pipeline to terminals and from there trucked to retail outlets. Storage and distribution costs would be similar for petroleum-based fuels. Bio-refineries are generally much smaller in capacity than oil refineries and could be widely located in geographic regions where the resource exists. In the United States for example bio-refineries are situated in the Mid-west or South-east whereas oil refineries are concentrated along the coasts.

Integration issues are particularly challenging for biofuels. Although the cost of delivery is a small fraction of the overall cost, the logistics and capital requirements for widespread expansion could present many hurdles if they are not well planned. Ethanol and gasoline blends (gasohol) cannot be easily stored, transported and delivered in the existing petroleum infrastructure because of the incompatibility of materials and water absorption by anhydrous ethanol in the pipelines. However, in Brazil alcohol produced from sugar cane has been successfully transported in the same pipelines used for oil products over the last 20 years. In addition, ethanol has only around two-thirds the volumetric energy density of gasoline, so larger storage systems, more rail cars or vessels, and larger capacity pipelines would be needed to store and transport the same amount of energy. This would increase the fuel storage and delivery cost.

The possibility exists to use some by-products of biofuel production as raw materials for electricity generation or biogas production. Electricity generation can be an integral part of biofuel production, for example from the sugarcane residue, bagasse. Integration with the existing electricity grid system is being successfully achieved in Brazil and elsewhere in cogeneration schemes (Chapter 2) after the energy demand of the processing plant has been met (Rodrigues, Faaij et al. 2003; Pacca and Moreira 2009). Since the sugar cane harvest period coincides with the dry season in Brazil, the greater availability of bioelectricity complements the country's hydroelectric system. Biogas production under current production methods for bioethanol and biodiesel, uses the by-products generated by these methods. Thus, biogas production systems also have the potential to be integrated in various existing bio-refinery models. The biogas could either be used for electricity generation as a vehicle fuel (Börjesson and Mattiasson 2008), or fed into gas grids.

8.2.4.2 Features and structure of liquid fuel supply systems

Ethanol is widely used today as a transport fuel additive or blend especially in USA, Japan, France and Brazil or as a neat fuel (Brazil, Sweden). The structure of a biomass-to-liquid fuel system for 1st generation biofuels is well understood (Fig. 8.21).

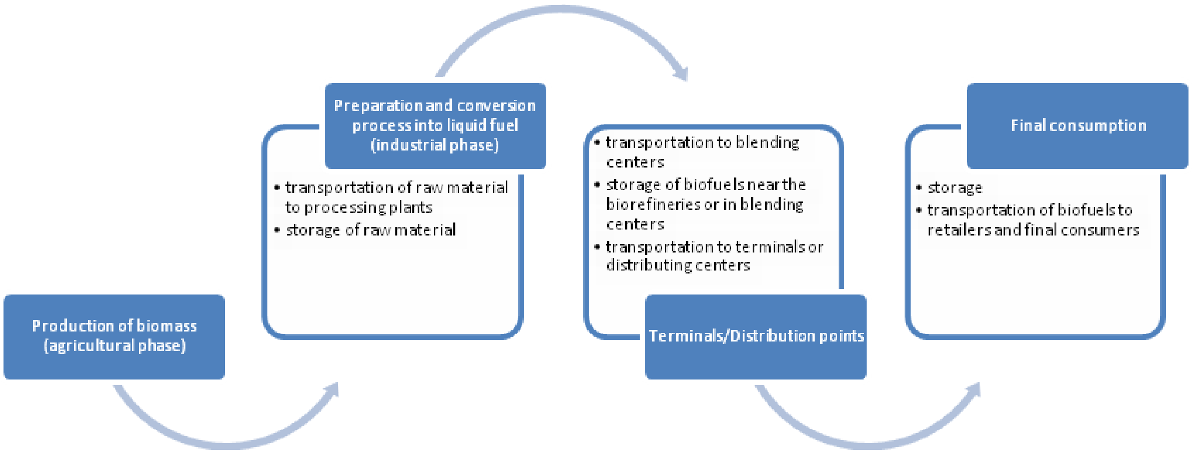

Figure 8.21: A typical biofuel production, blending and distribution system.

Transport of bulky, low energy density biomass feedstocks (sugar cane, corn grain, palm kernels, straw etc.) to a biorefinery by road or rail can be costly and produce some GHGs. Storage costs to provide all-year round supply as far as is feasible also play a critical role in the development of the industry (NAS 2009).

Ethanol and biodiesel can be transported by road tanker, rail, ship or pipeline (when production is geographically concentrated) (NAS 2009) and blended with gasoline or diesel respectively at refineries, production sites, or special blend centres during the distribution of fuels to vehicle service stations. For longer distances rail transport can be a more efficient and cost effective delivery mode than road but is not always available (Reynolds 2000). Biofuels and blends can be stored at their production sites, alongside oil refineries or storage tank facilities and at service stations in underground tanks. Similar care needs to be taken regarding safety and environmental protection, as for petroleum products. Due to the agricultural seasonality of crops grown specifically as feedstocks, storage of the biofuel produced is crucial to meet all-year-round demand. Biodiesel tends to be more prone to variation in composition during storage due to the action of micro-organisms leading to rises in acidity and corrosion than ethanol which is more biologically stable.

8.2.4.3 Challenges of integration

Decentralized biomass production, seasonality and remote agricultural locations not necessarily near existing oil refineries or fuel distribution centres can impact on the logistics and storage of biofuels.

Sharing oil-product infrastructure (storage tanks, pipelines, trucks) with biofuels, especially ethanol, can give problems of water contamination and corrosion, requiring new materials needed to preserve the lifetime of the equipment. Moisture from condensation in oil-product pipelines can increase the water content of the ethanol being transported and if it exceeds the technical specification for the biofuel, further distillation will be required. Ethanol can dissolve and carry any impurities present inside multi-product pipeline systems that are potentially harmful to internal combustion engines. Ethanol's affinity for water and its solvent properties may require use of a dedicated pipeline or improved clean-up procedures between products sent through multi-product pipelines. Moisture absorption and phase separation during pipeline shipment can be avoided by first shipping hydrous ethanol, which is then used directly by end-users or distilled, followed by anhydrous ethanol for direct blending with gasoline. An alternative strategy is sending a "sacrificial buffer" of neat (100%) ethanol down a pipeline to absorb any moisture ahead of sending the primary batches of ethanol or blends. The buffer shot is discarded or re-distilled.

Ethanol in high concentrations can lead to accelerated stress corrosion cracking (SCC) in steel pipelines and storage tanks, especially at weld joints and bends. This can be avoided by adding tank liners, using selective post-weld heat treatments, and coating of internal critical zones (at pipeline weld points, for example) but these all increase system costs. Ethanol may degrade certain elastomers and polymers found in seals and valves in pipelines and terminals as well as some engines so these may need replacement. New pipelines could be constructed with ethanol-compatible polymers in valves, gaskets, and seals and be designed to minimize SCC (NAS 2009).

8.2.4.4 Options to facilitate integration

8.2.4.4.1 Technical options

Technologies will continue to evolve to produce biofuels that are more compatible with the existing petroleum infrastructure (Sims, Taylor et al. 2008). In some countries, the revision of liquid transport fuel standards to enable biofuels to be incorporated whilst assuring the integrity of the existing fuel distribution system, has been a slow process. This can inhibit the integration of biofuels into the supply system. Quality control procedures also need to be implemented to ensure that biofuels meet all applicable product specifications (Hoekman 2009) and facilitate integration. International trade in biofuels instigated a need for international standards to be developed. Blending of biofuels needs to account for regional differences in the predominant age and type of vehicle engines and local emission regulations. Variations exist in the current standards for regulating the quality of biodiesel reaching the market due to the different oil and fat feedstocks available, though less so for ethanol since it is a single chemical compound. This translates to variations in the performance characteristics of each biofuel.

A comparison was made of existing biofuel standards in U.S., Brazil and the EU) (Task Force, 2007). The standards for biodiesel in Brazil and US reflect its use as a blending component in conventional mineral diesel fuel, whereas the European standard allows for its use as a blend or neat fuel. Bioethanol technical specifications differ with respect to the water content but do not constitute an impediment to international trade (NIST 2007).

8.2.4.4.2 Institutional aspects

Agencies in charge of regulating oil-product markets could also include biofuels under their jurisdiction. These agencies are appropriate institutions to deal with issues such as security of biofuel supplies, safety and technical specifications (or standards) and quality control at both the production and retail levels. This is currently the case for Brazil where the regulator for the oil sector also regulates biofuels.

8.2.4.5 Benefits & costs of large scale penetration

Existing transport, storage and dispensing equipment at vehicle refuelling stations can be modified to handle biofuels and blends as has been successfully achieved in the US, Brazil, Germany and elsewhere. Underground storage-tank systems, pumps, and dispensers need to be converted to be compatible with higher biofuel blends and to meet safety requirements. Issues relating to the retrofitting of existing facilities are similar to those associated with pipeline transport (8.2.4.3) including phase separation, SCC, and the degradation of incompatible materials (NAS 2009).

Ethanol terminals usually have one or more storage tanks ranging from 750 to 15,000 m^3capacity. New ethanol storage tanks cost around US\$ 170 /m^3 capacity for small tanks to US\$ 60/m^3 for large tanks [TSU: figures will need to be adjusted to 2005 US\$/m^3] (Reynolds 2000). It may be possible to refurbish gasoline tanks for ethanol storage at lower costs. Collection terminals at ports and refineries often include equipment for blending ethanol, receiving shipments via rail, truck, boat or pipeline, and loading blended product on to road tankers (Reynolds 2000).

In the US, most ethanol is transported by rail, road tanker and barge (NCEP 2007), but since 2008 batches have been sent through gasoline pipelines in Florida (KinderMorgan 2010). Capacities and costs vary for ethanol storage and delivery equipment (Table 8.4). As a point of reference, ethanol plants in the US produce 300-1200 m^3/day; demand for 1 million cars using E10 would be about 400- 800 m^3/ day; and storage facilities can hold 4000-12,000 m^3.

Table 8.4: Equipment capacity for ethanol storage and long-distance transport (RFA 2009).

	Capacity	**Cost (US$ 2005)**	**References**
Truck/trailer	25 m^3	$103,000 $141,000	(USEPA 2007) (Reynolds 2000)
Rail car	90 m^3	$85,000	(USEPA 2007)
River barge	Several units at 1200 m^3/unit	$5M for one 1,200 m^3unit	(USEPA 2007)
Ocean ship	3000-30,000 m^3		(Reynolds 2000)
Pipeline (300 mm diameter)	12,000 m^3/day	$0.34-0.85 M/km	
New terminal storage tank	3000 m^3 6000 m^3	$510,000 $860,000	(Reynolds 2000) (Reynolds 2000)
Retrofit gasoline storage tank	1200 m^3	$18,800	(USEPA 2007)
Blending equipment		$170,000-450,000	(Reynolds 2000)
Total terminal refit	6,000 m^3 capacity	$1.13 M	(Reynolds 2000)
Ethanol production plant	230-950 m^3/day		
Ethanol terminal	600 m^3 (local) 12,000 m^3 (regional)		

Tankers are often used to distribute ethanol from large regional terminals served by boat, barge or rail, to smaller local terminals that have insufficient storage to receive barge or rail deliveries.

Rail shipment is generally the most cost effective delivery system for medium and longer distance (500 to 3,000 km) to destinations without port facilities (Reynolds 2000). Because of the number of units and smaller unit volumes compared to barges, as well as the more labour intensive efforts for cargo loading, unloading and inspection, rail shipments require more input at the terminal. Unit trains for ethanol (containing up to 75 railcars) have been proposed as an alternative to pipeline development (Reynolds 2000).

Barges are used for long distance transport when biofuel production plants have access to rivers or sea. In the US for example, barges travel down the Mississippi river from Midwestern ethanol plants to ports at the Gulf of Mexico where the ethanol is stored before being transferred to ships for transport to overseas or national coastal destination terminals for blending.

Storage and transport costs are a relatively small portion of total costs. The costs of transporting large ethanol volumes over long distances for waterway (barge and ship) and rail prevail over truck transport (Reynolds 2000). Estimates range from US$ (2005) 6 to 10 /m^3 for ocean shipping; US$ 20 to 90 /m^3 for barge; US$ 10 to $40 /$m^3$ for rail and US$10 – 20 /$m^3$ for trucks used over short distances [TSU: figures will need to be adjusted to 2005 US$/$m^3$].

In Brazil, depending on the origin of the biofuel, the costs of transporting ethanol from the producing regions to export ports is around US$(2005) 35-64 /$m^3$ which also includes storage costs at the terminal (Scandiffio 2008). Ethanol pipelines are being planned to connect main rural producing centres to coastal export ports with an expected cost ranging from US$ 20-29 /m^3, 70% less than by road and 45% less than by rail (CGEE 2009).

8.2.3.6 Case study: Brazil ethanol

Successful integration of liquid biofuels with the oil distribution system began with the inception of the National Alcohol Program in 1975 when the state oil company, Petrobras, was obliged to purchase all alcohol domestically produced, blend it with gasoline, and distribute it nationwide. In 1979, vehicles suitable for use of E100 were produced and sold and Petrobras had to develop and adapt existing infrastructure to deliver this product to all regions. (Ethanol production is regionally concentrated but the fuel is available nationwide). When sugar prices competed with ethanol production, owners of E100 vehicles experienced fuel shortages.

Almost all new small road vehicles sold today are flex-fuel, capable of using bioethanol blends ranging from E20 to E100. Since 2003, the manufacture of flex-fuel engines, the biofuel distribution system and the retailing of blends have all been successful. All gasoline sold for spark-ignition engines has a blended content of 20-23% anhydrous ethanol (by volume). Over the last 30 years a country-wide ethanol storage and distribution system was implemented so that biofuel blends are available in practically all refuelling stations. Ethanol prices to the consumer have declined steadily and remain competitive with gasoline prices in late 2009 / early 2010 when oil fluctuated around US$ 80 /barrel [TSU: figure will need to be adjusted to 2005 US$/barrel].

Since 1990, excess electricity generated in sugar/ethanol plants from CHP systems using the bagasse co-product has been able to be fed into the national grid. Technological improvements, better energy management and co-generation schemes have enabled optimal use of the bagasse. Governmental programmes (PROINFA 2010), regulatory changes, and public auctions for bio-electricity contracts were also introduced to enable this electricity to be sold to local utilities or monitored and dispatched by the national system operator. The greater generation of electricity from bagassecoincides with the dry season and so complements the country's hydroelectric-based system.

In 2008 total installed capacity for bioelectricity production was 3.9 GW, around 3.7% of total electrical capacity. Ethanol production was 495 PJ, equivalent to 85% of the energy in gasoline consumed in that year (EPE 2009).

8.2.5 Autonomous systems

8.2.5.1 Characteristics

To be sustainable, and depending on whether the energy carrier is electricity, hydrogen, or liquid, gaseous or solid fuels, an energy system needs to maintain demand-supply balance over various time frames. When a system is small, the demand-supply balance problem readily emerges so that the energy system has autonomy for the balancing (an autonomous system). The integration of several RE conversion technologies, energy storage options and energy use technologies in a small-scale energy system depends on the site specific availability of RE resources and the energy demand due to geology, climate, and lifestyle. This creates several types of autonomous systems.

- *Power supply*. Different RE generators can each meet a part of an autonomous power system demand to enhance the sustainability of the system in, for example, on an off-grid island. Currently, it is usual that fossil fuel generators are also included to give security, reliability and flexibility of system operation.
- *Power supply in a developing economy*. Single or mixed types of RE generation technologies can form a hybrid power supply system in a remote area for mini-grid or stand-alone off-grid

electrification. A stand-alone hybrid power supply could improve its performance with integration of energy storage technologies (section 8.2.1.4) to overcome RE variability.

- *Buildings.* Remote rural buildings can often benefit from autonomous energy supply systems due to the RE resource usually available and the large distances from the power or gas grids. Urban domestic and commercial buildings are normally independent of integrated RE technology due to the network energy supply, though interest in buildings becoming energy generators is growing (IEA 2009).
- *Specific utilization.* In areas where the provision of commercial energy is not economically available, RE can be beneficial for supplying energy services such as water desalination, water pumping, refrigeration and drying.

8.2.5.2 Options to facilitate integration and deploy autonomous systems

An autonomous RE power system could involve the limited deployment of a single type of RE generation technology such as solar power, or incorporate a portfolio of technologies. The capacity of the RE generation can be increased by the addition of more generation units of similar type, or by adding other types of RE generation technologies to enhance operational flexibility. Fossil fuel generation to maintain the desired supply reliability and flexibility of system operation could, in the future, be displaced by increased flexibility and the integration of energy storage technologies.

In developing economies, the balance between cost and quality is critical when designing and deploying autonomous power supplies particularly in rural areas. The simplest type of remote area power system is a DC supply from stand-alone, solar PV panels to meet small lighting, ventilation, radio and television demands of one or more households. Power can be made available during the night by adding a battery or small petrol or diesel generator. A hybrid wind/solar system may have increased reliability benefits where a wind resource is available and also reduce the battery capacity needed to provide a given level of reliability. Micro-hydro schemes are common in hilly regions to give continuous supply, with storage batteries added to meet peak load demands if required.

Batteries and other energy storage technologies used to enhance the performance of small-scale power supply systems are usually expensive, so capital and operational costs should be carefully evaluated along with the level of reliability desired.

Heat demands, usually met by traditional biomass or fossil fuels, could utilise solar thermal, geothermal or modern biomass (IEA 2007) including improved designs of cooking stoves (section 8.3.2.4). Meeting cooling demands from RE such as solar adsorption technology is not yet fully commercial.

8.2.5.2.1 Technical options

For many autonomous RE systems, (with the possible exception of bioenergy CHP or run-of-river micro hydro schemes but including wind/diesel), energy storage and special energy utilization technologies are an integral part (Lone and Mufti 2008).

Simulation analyses, demonstration tests and commercial operations on the application of energy storage technologies to an autonomous system have been reported. These include demonstrations of pumped hydro systems plus wind integration in the Canary Islands (Bueno and Carta 2006) and PV plus wind with hydrogen storage in Greece (Ipsakis, Voutetakis et al. 2009). For heating or to fuel internal combustion engine driven generators, liquid fuels produced from biomass are comparatively easy to store in a container, as are gaseous fuels in tanks or under pressure.

To enhance value or improve performance, autonomous RE systems can be integrated with special energy utilization technologies that use surplus power only when available including solar stills, humidifiers/dehumidifiers, membrane distillers, reverse osmosis or electro-dialysis water desalinators (Mathioulakis, Belessiotis et al. 2007), water pumps using solar PV arrays and an AC or DC motor (Delgado and Torres, 2007), solar-powered adsorption refrigerator (Lemmini and Errougani 2007), and multi-seeds oil press (Mpagalile, Hanna et al. 2005).

Buildings could be designed to generate as much energy as they consume by installing energy efficiency technologies and on-site power generation. The Net-Zero Energy Commercial Building Initiative of the (USDOE 2008) aims to achieve marketable building designs by 2025. Low-rise buildings have good potential to become autonomous through the combination of air-tight structure, high heat insulation, energy efficient air conditioning, lighting, ventilation, water heating, and high utilization of RE technologies (8.2.5.7). Building-integrated photovoltaics (BIPV) (Bloem 2008), distributed energy systems (IEA 2009) and off-grid operation (Dalton, Lockington et al. 2008) are all now past the demonstration phase of development.

8.2.5.3 Benefits and costs of RE integration design

In autonomous energy systems, the electricity generated is usually more expensive than that from a network where grid connection is available. Integration of different kinds of RE may improve the economy and reliability of the supply (Skretas and Papadopoulos 2007). The viability of autonomous energy systems should be evaluated including the future constraints of fossil fuel supply, current technology innovation , avoidance of infrastructure construction and projected cost reductions (Nema, Nema et al. 2009).

For remote off-grid areas, it is widely recognized that electrification can contribute to rural development through increased productivity per capita; enhanced social and business services such as education, markets, drinking water and irrigation; improved security due to street lighting; decreased poverty; and improved health and environmental issues (Goldemberg 2000; Johansson and Goldemberg 2005; Takada and Charles 2006; Takada and Fracchia 2007). The use of biomass, where resources, including organic wastes, are substantial and sustainable, is inevitable to supply basic services for cooking, lighting and small-scale power generation.

In an autonomous building where several RE technologies can be integrated to provide various services, there is potential to enhance the performance of the system. In China, extensive solar thermal utilization in the building sector has brought environmental, social and economic benefits (Li, Zhang et al. 2007). In Japan, house suppliers, (such as Misawa Home Co. Ltd. and Shimizu Construction Co., Ltd.) sell net-zero energy houses which solely use electricity but compensate for their power consumption by integrated solar PV. An urban autonomous building can benefit from having a green value and non-interruptible power service.

Autonomous energy to supply remote telecommunication facilities is economically feasible in both developed and developing countries. Solar water pumping is at the commercial stage, but not always well deployed in developing countries where it is needed, such as the Algerian Sahara (Bouzidi, M. et al. 2009).

8.2.5.4 Constraints on the rate and extent of deployment

Technological constraints and planning tools. The role of RE technologies is changing from a niche market to having a major role in autonomous energy systems, thereby increasing the need for system integration. For each type of autonomous system, appropriate planning methodologies should be established (Giatrakos, Tsoutsos et al. 2009). The variety of possible RE technologies, including variable generators, makes planning more difficult. To improve planning methodology, databases could be established from RD&D as well as commercial experiences that reflect various combinations of technologies, specific site conditions, and life styles (Amigun, Sigamoney et al. 2008; Himri, Stambouli et al. 2008). In the case of biomass, sustainability criteria should be included (Igarashi, Mochidzuki et al. 2009).

Institutional social constraints and enabling environment. Major constraints can arise as a result of wide-ranging technology specifications and the difficulty of appropriate planning, designing, construction and maintenance which can lead to capital and operational cost increases and various disclaimers following a failure. Establishing standards, certifying products, integrating planning tools and developing a knowledge database could help avoid these problems (Kaldellis, Zafirakis et al. 2009), as could local capacity building and market establishment to give low capital and operational costs (Meah, Ula et al. 2008).

The deployment of RE may require accompanying policy measures (often characterized as “the enabling environment”) such as establishing institutions (e.g. energy efficiency and RE agencies), appropriate energy pricing, economic incentives (e.g. subsidies, preferential rates for loans, grants), and fiscal incentives (e.g. lower profit tax, reduction or waiver on import duty) (Chapter 11).

Implementation and operation. RE technologies (except some biomass projects) are capital-cost-intensive compared with operation-cost-intensive fossil fuel conversion technologies. Accordingly, even where an autonomous, integrated system is economically feasible, there can be need for an appropriate financial scheme to remove the barrier of large capital costs. Local employment to operate and maintain autonomous systems can be secured through appropriate training and capacity building programmes.

8.2.5.5 Case studies

8.2.5.5.1 Seawater desalination in a rural area of Baja California, Mexico

Baja California Sur, Mexico is an arid sparsely populated costal state where underground aquifers are over-exploited due to population growth, agricultural demands and booming tourism. Around 70 desalination plants use fossil fuel electricity and there are plans to construct more.

Small-scale desalination using PV is an attractive water supply option for small remote communities in the state. The most successful solar desalination system consists of a PV array, battery bank, and seawater reverse osmosis plant (PFSWRO) to produce 19 m^3/day of freshwater with a total dissolved solids content of < 250 ppm and consuming as little as 2.6 kWh/m^3 of water (Contreras, Thomson et al. 2007). PFSWRO uses an energy recovery device and integrates battery banks to enable 24 hour operation. The balance between continuous, smooth operation and cost minimisation depends on optimizing the integration of battery banks. In the future, further integration of desalination plants and rural electrification could be beneficial for provision of water and energy supplies to remote rural communities.

8.2.5.5.2 The Renewable Energy House, Bruxelles, Belgium.

The aim in refurbishing the offices and meeting facilities of this 140 year-old, 2,800 m² building, was to reduce the annual energy consumption for heating, ventilation and air conditioning by 50% compared to a reference building, and to meet the remaining energy demand for heating and cooling using solely RE sources. Key elements of the heating/cooling systems are 85 kW and 15 kW biomass wood pellet boilers; 60 m² solar thermal collectors (half being evacuated tubes and half flat plates); and four 115 m deep geothermal borehole loops connected to a 24 kW ground source heat pump (GSHP) in winter. This is used in summer for cooling, but most cooling comes from a 35 kW capacity (at 7-12°C), thermally-driven, absorption cooler driven by relatively low temperature solar heat (85°C) and a little electrical power for the control and pumping circuits (Fig. 8.22).

In winter, the heating system mainly relies on the GSHP biomass and the pellet boilers since the solar contribution is low. However, when available, solar heat reduces pellet consumption since both heat the same water storage tank. The GSHP operates on a separate circuit. In summer, since solar radiation and cooling demands usually coincide, the solar absorption cooler provides most of the cooling, (backed up on cloudy days by heat from the biomass boiler). The GSHP borehole loops absorb any excess low-grade heat and thus serve as a seasonal heat storage system (EREC 2008).

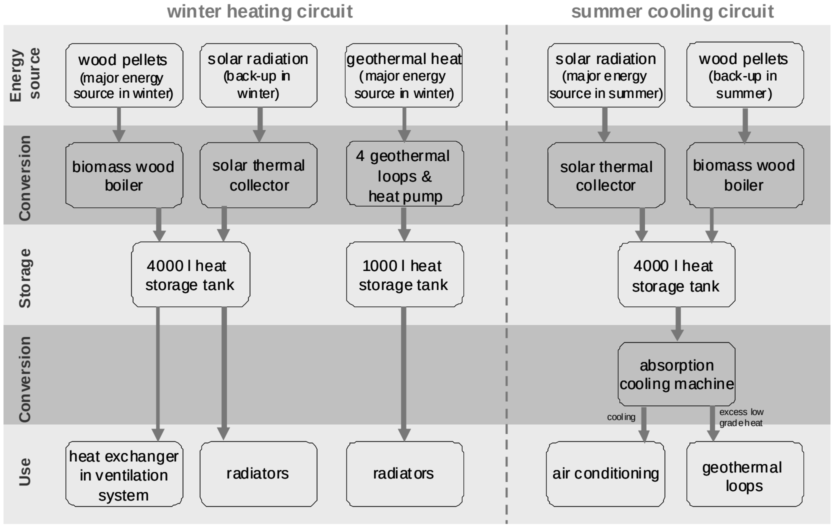

Figure 8.22: Renewable heating and cooling system in an autonomous building (EREC 2008).

8.2.5.5.3 Wind/hydrogen demonstration, Utsira, Norway

An autonomous wind/hydrogen energy demonstration system located on the island of Utsira, Norway was officially launched by Norsk Hydro (now Statoil) and Enercon (a German wind turbine manufacturer) in July 2004. The main components of the installed system are a 600 kW rated wind turbine (with cut-off set at 300 kW), water electrolyser to produce 10 Nm^3/h hydrogen, 2400 Nm^3 of hydrogen storage (at 200 bar), 55 kW hydrogen engine, and a 10 kW PEM fuel cell. The innovative system gives 2-3 days of full energy autonomy supplying 10 households on the island (Ulleberg, Nakken et al. 2010).

Operational experience and data collected from the plant for 4-5 years showed the specific energy consumption for the overall hydrogen production system (including electrolyzer, compressor, inverter, transformer, and auxiliary power) at nominal operating conditions was about 6.5 kWh/Nm^3, equivalent to an efficiency of about 45% (based on lower heat value). The efficiency of the hydrogen engine/generator system was about 25% at nominal operating conditions. Hence, the overall efficiency of the hydrogen system (AC-electricity to hydrogen to AC-electricity) assuming no storage losses was only about 10%. If the hydrogen engine is replaced by a new 50 kW PEM fuel cell, the overall hydrogen storage efficiency would increase to about 16-18%. Replacing the electrolyser by a more efficient unit (e.g. a PEM electrolyzer or a more advanced alkaline design), the overall system efficiency would increase to around 20% (Ulleberg, Nakken et al. 2010).

This low efficiency illustrates the challenge for commercial hydrogen systems. Nevertheless, the project demonstrated that it is possible to supply remote area communities with wind power using hydrogen as the energy storage medium but that further technical improvements and cost reductions need to be made before wind/hydrogen-systems can compete with commercial solutions such as a wind/diesel hybrid. Areas for improvement include the overall wind energy utilization since only 20% is currently utilized. This can best be achieved by installing more suitable and efficient load-following electrolyzers that allow for continuous and dynamic operation. Surplus wind energy could also be used to meet local heating demands, both at the plant and in the households. In addition, the hydrogen (and possibly the oxygen) could be utilized in other local applications, e.g. as a fuel for local vehicles and boats.

More compact hydrogen storage systems and more robust and less costly fuel cells need to be developed before wind/hydrogen-systems can be technically and economically viable.

8.3 Strategic elements for transition pathways

For each of the transport, buildings, industry, and primary production sectors, in order to gain greater RE deployment, strategic elements and non-technical issues need to be better understood. Preparing transition pathways for each element could enable a smooth integration of RE with the conventional energy systems to occur. Multi-benefits for the energy end-users should be the ultimate aim.

In the IPCC 4th Assessment Report -Mitigation (Metz, Davidson et al. 2007) the economic potentials for each of the transport (Chapter 5); residential and commercial buildings (Chapter 6); industry (Chapter 7); and agriculture (Chapter 8) sectors were analysed in detail (Fig. 8.23). The substitution of fossil fuels by RE sources was included in the energy supply sector (chapter 4), together with fuel switching, nuclear power and CCS (carbon dioxide capture and storage).

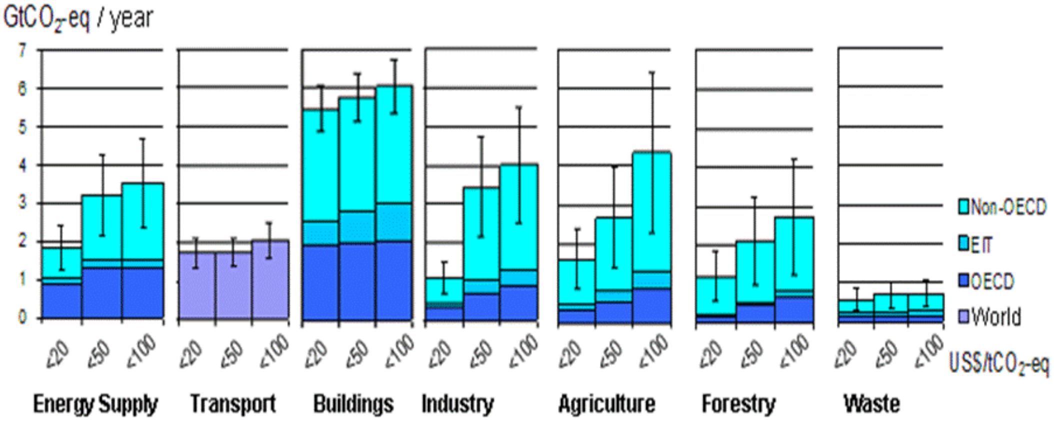

Figure 8.23: Estimated economic, mitigation potential ranges for energy supply and end-use sectors, above the assumed baseline for different regions as a function of the carbon price in 2030 and based on end-use allocations of emissions including from electricity generation.

The IPCC 4th Assessment Report was based mainly on data collected from 2004 or before as published in the latest literature at the time of writing. Since then, RE technology developments have continued to evolve and there has been increased deployment due to improved cost-competitiveness, more supporting policies, and increased public concern at the threats of energy security and climate change. In the following sections, for each sector the current status of RE use, possible pathways to enhance its increased adoption, the transition issues yet to be overcome, and future trends, are discussed. Regional variations are included, particularly for the building sector where deploying RE technologies differs markedly with the present state of urban development.

8.3.1 Transport

8.3.1.1 Sector status and strategies

The direct combustion of fossil fuels for transport consumes 19% of global primary energy use, produces approximately 23%[10] of GHG emissions and between 5-70% of air pollutant emissions depending on the pollutant and region (IEA 2009). Light duty vehicles (LDVs) account for about half of all transport energy use worldwide, with heavy duty vehicles (HDVs) 24%, aviation 11%,

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[10] 23% in 2005 on a well-to-wheel basis

shipping 10%, and rail 3% (IEA 2009). Recent studies suggest that decarbonising and improving the efficiency of the transport sector will be critically important to achieving long-term, deep cuts in carbon emissions as required for climate stabilization (IEA 2009).

Energy supply security is also a serious concern for the transport sector. Demand for mobility is growing rapidly with the number of motorized vehicles projected to triple by 2050 (IEA 2009). Globally, about 94% of transport fuels come from petroleum, a large fraction of which is imported (EIA 2009).

To help meet future goals for both energy supply security and GHG reduction, oil use will need to be radically reduced over a period of several decades. Recent scenario studies (Yang 2007; IEA 2008; NRC 2008) (McKinsey *et al*., 2008) suggest that a combination of approaches will be needed to accomplish 50-80% reductions in transport-related GHG emissions by 2050 (compared to current values) whilst meeting the projected growth in demand and diversifying the primary energy supply (IEA 2009)[11].

- *Reduction of travel demand* (in terms of less *vehicle kms travelled*) might be best achieved by encouraging greater use of car-pooling, cycling and walking, combining trips or tele-commuting. In addition, city and regional “smart growth” practices could reduce GHG emissions as much as 25% by planning cities with denser population so that people do not have to travel as far to work, shop and socialize (Johnston and [NameOtherAuthors?] 2007; PCGCC 2010).
- *Improving efficiency* (in terms of reduced *MJ per km*) can be improved by shifting to more energy efficient modes of transport, such as from LDVs to mass transit (bus or rail[12]), or from trucks to rail or ships[13] (IEA 2009). Vehicles can be made more energy efficient by reducing vehicle weight, streamlining, and improving designs of engines, transmissions and drive trains, such as hybrid electric vehicles (HEVs), turbo-charging and down-sizing. Electric drive vehicles, employing either batteries or fuel cells, can be more efficient than their internal combustion engine (ICE) counterparts, but the full well-to-wheel efficiency will depend on the source of the electricity or hydrogen (Kromer and Heywood 2007; NRC 2008). Consumer acceptance of high efficiency drive trains and lighter cars will depend on a host of factors including vehicle performance and purchase price, fuel price, and advancements in materials and safety. In the heavy duty sub-sector for freight movement, and in aviation, there is also promise of significant efficiency improvements.
- *Replacing petroleum-based fuels with low or near-zero carbon fuels*. These include renewably produced biofuels, and electricity or hydrogen produced from low carbon sources such as renewables, fossil energy with CCS, or nuclear power. Alternatives to petroleum-based fuels have had limited success thus far since the total number of alternative-fuelled passenger vehicles are currently less than 1% of the global on-road vehicle fleet (IEA 2009). Alternative fuels, including electricity for rail, typically represent about 5-6% of total transport energy use (IEA 2009). Exceptions include: Brazil, where around 50% (by energy content) of transport fuel for LDVs (IEA 2007), representing about 15% of total energy use, is from sugar cane ethanol (EIA 2009); Sweden, where imported ethanol is being encouraged; and the US where ethanol,

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[11] In IEA scenarios, vehicles become about twice as efficient by 2050 and in the “Blue Map” scenario (50% GHG reduction by 2050), conventional gasoline and diesel LDVs are largely replaced. GHG emission reductions come from a mix of improved efficiency (which accounts for at least half of the reductions) and alternative fuels (biofuels, electricity and hydrogen) making up 25-50% of total transport fuel use in 2050. Liquid biofuels are used extensively in the HDV, aviation and marine sections

[12] Assuming that mass-transit is operating at relatively high capacity.

[13] On a passenger-km basis, the transport modes with the lowest GHG intensity are rail, bus and 2-wheelers, the highest being LDVs and aviation. For freight, shipping is the lowest GHG intensity mode on a tCO_2-km basis, followed by rail, and then, by at least an order of magnitude higher, HDVs and air.

derived from corn or imported from Brazil, is currently blended with gasoline up to 10% by volume in some regions, but still only accounts for about 3% of total US transport energy use (USDOE 2009). Compressed natural gas (CNG) is widely used in LDV fleets, lead by Pakistan, Argentina, Iran, Brazil, and India (IANGV 2009). Liquefied petroleum gas (LPG) is also used in several countries. Sweden is encouraging the use of biogas for vehicles (IEA 2010)[14] and electricity also makes a material contribution to the transport sector in many countries, mostly limited to rail. The context for alternative fuels is rapidly changing and a host of policy initiatives in Europe, North America and Asia are driving towards lower carbon fuels and zero-emission vehicles.

8.3.1.2 Renewable fuels and light-duty vehicle pathways

The potential exists to make a transition in the transport sector using large quantities of RE as fuels (IEA 2009). In this section, future pathways for RE fuels and vehicle are reviewed, each with different environmental impacts, costs and benefits from a lifecycle perspective. A variety of more efficient vehicles and alternative fuels have been proposed including gasoline and diesel plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (EVs), hydrogen fuel cell electric vehicles (HFCVs), and liquid and gaseous biofuels. Possible fuel/vehicle pathways (Fig. 8.24) begin with the primary energy source, its conversion to an energy carrier (or fuel), and end-use in a vehicle power unit.

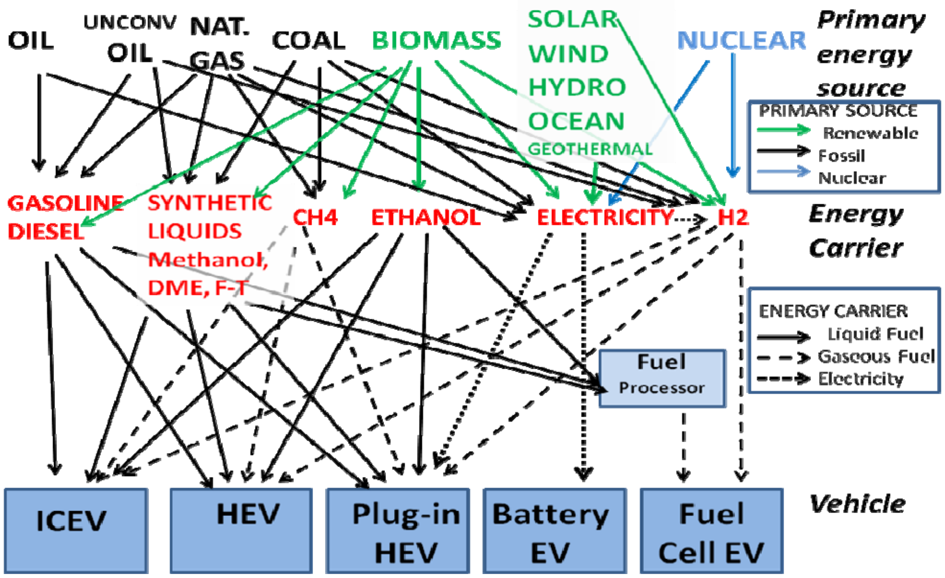

Figure 8.24: Possible fuel/vehicle pathways, from primary energy sources, through energy carrying fuels (red) to vehicle end-use options, and showing RE resources (green).

Notes: F-T= Fischer-Tropsch process. "Unconventional oil" refers to oil sands, oil shale, and heavy crudes.

Technical details of liquid and gaseous RE fuel production and delivery are given in Chapters 2 and sections 8.2.3 and 8.2.4. This section focuses on how the different RE pathways can be integrated into the present transport system. Metrics include cost, GHG emissions from well-to-wheels (WTW), (made up of "well-to-tank" emissions upstream of the vehicle plus "tank-to-wheels" vehicle-related emissions), energy use, and air pollutant emissions.

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[14] In Sweden 19% of biogas produced was used in vehicles in 2006, but this is still only about 1% of total transport energy use**.**

Primary energy use and GHG emissions vary with different fuel/vehicle options. WTW analyses (MacLean and Lave 2003; CONCAWE 2007; Bandivadekar, Bodek et al. 2008; Wang 2008) account for all the emissions including those associated with primary resource extraction, processing and transport, conversion to a useful fuel, distribution and dispensing, and vehicle use, although land use change impacts from biofuel feedstock production are often not included (Chapter 2). Air quality and energy security are other considerations for future transport pathways and sustainability issues, such as land-use, water and materials requirements, that may impose constraints. Commercialising new vehicle-drive technologies could require large amounts of scarce, hard to access mineral resources. For example, automotive fuel cells require platinum, HEV motors require high-power, lightweight magnets; EVs and HFCVs need neodymium and lanthanum; and the most likely next generation of advanced, lightweight, high-energy-density batteries require lithium. Composite sustainable fuel indicators include a variety of factors in addition to GHG emissions (Zah, Böni et al. 2007).

8.3.1.2.1 Status and prospects - vehicle technology

A variety of alternative vehicle drive trains could use RE based fuels including advanced ICE vehicles using spark-ignition or compression-ignition engines (ICEVs), HEVs, PHEVs, EVs, and HFCVs. Several recent studies have assessed the performance, technical status, and cost of different vehicle types (CONCAWE 2007; Kromer and Heywood 2007; Bandivadekar, Bodek et al. 2008; IEA 2009; Plotkin and Singh 2009). Fuel economy and incremental costs of alternative-fuelled vehicles based upon these studies have been compared (Figs. 8.25 and 8.26). Since each study employed different criteria and assumptions for vehicle design and technology status, the development timeframes varied between 2010 and 2035, and since not all vehicle/fuel pathways were covered in all studies, the results have been normalised to those for an advanced, gasoline ICEV (as one was defined in each study). The relative efficiency assumptions for different vehicle types varied among the studies, especially for less mature technologies, although the overall findings were consistent. Several trends are apparent.

- There is significant potential to improve fuel economy by adopting new drive trains and more advanced engines.
- Hybrid vehicles and adoption of electric drives give increased efficiency and improved fuel economy by 15-70% over conventional gasoline ICEVs.
- Although still under development and in demonstration phase, HFCVs may run 2 to 2.5 times more efficiently than gasoline ICEVs.
- EVs could operate up to 2.7 to 3.5 times as efficiently as gasoline ICEVs, not including electric power generation inefficiencies.
- On a total WTW fuel cycle basis, the relative efficiency improvements for HFCVs and EVs are considerably less when electricity generation and hydrogen production losses are included.
- Losses related to electricity generation, transmission and distribution range between approximately 40-80%, depending on the source of power. A similar loss range occurs for hydrogen production, depending on the energy feed, conversion technology, and distribution infrastructure.
- There is uncertainty in the fuel economy and cost projections for HFCVs and EVs, both of which are still far from high volume commercialization.
- In general, the higher the fuel economy, the higher the vehicle price (assuming size and performance are similar).

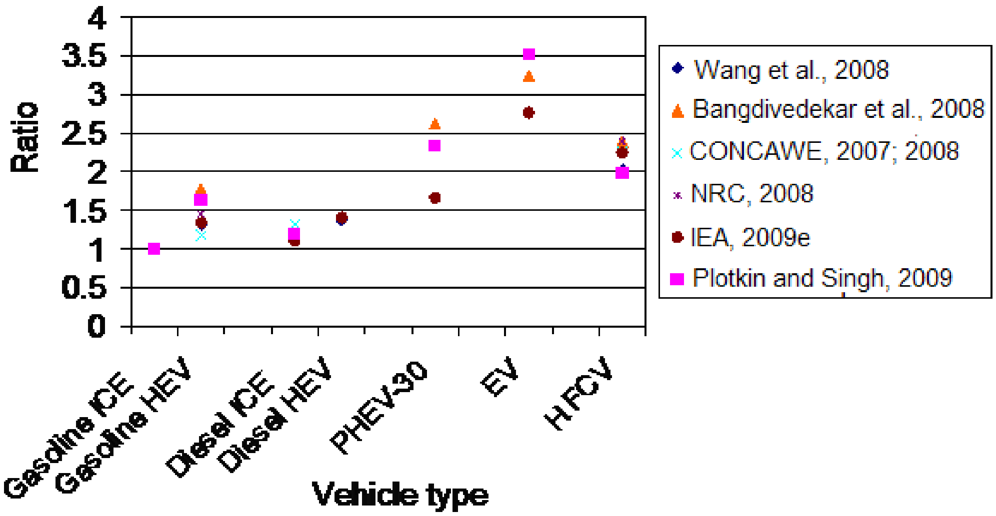

Figure 8.25: Relative fuel economies of future alternative-fuelled light duty vehicles compared to advanced spark ignition, gasoline-fuelled, ICE vehicles, based on various studies.

Note: The values represent tank-to-wheel energy use. Well-to-tank energy use should also be considered (8.3.1.2). Typical well-to-tank energy losses are 5-15% for gasoline and diesel; 60% for biofuels; 45-80% for electricity; and 40%-90% for hydrogen (Wang 2008).

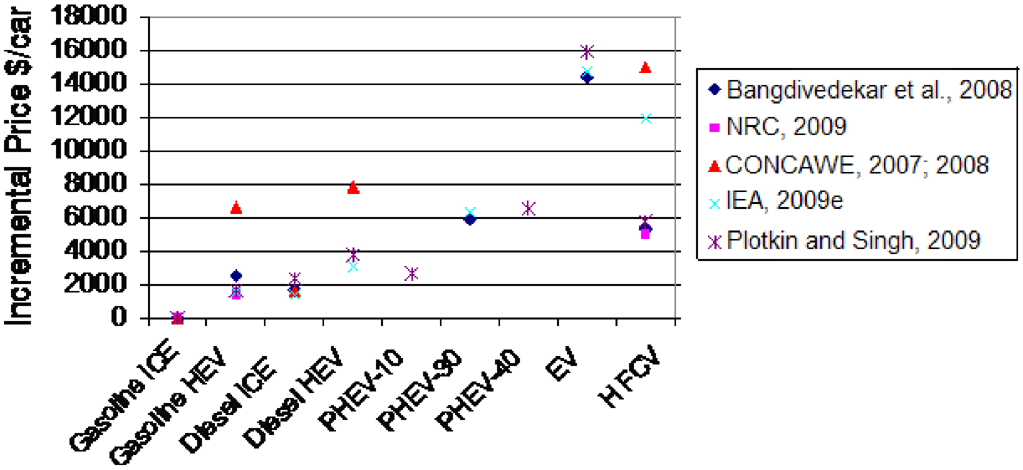

Figure 8.26: Relative incremental retail price for alternative light duty vehicles compared to advanced gasoline, spark ignition, ICE vehicles

Notes: Bandivedekar et al. (2008) gave projections for 2035. NRC (2009) assumed mature technologies with cost reductions due to experience learning and mass production post-2025. CONCAWE (2007 and 2008) were for 2010+ technologies; IEA (2009) and Plotkin and Singh (2009) were for 2030 technology projections.

Millions of vehicles capable of running on liquid biofuels or biomethane are already commercially available and in the global fleet. The cost, weight, and life of present battery technologies are the main barriers to both EVs and PHEVs but the vehicles are undergoing rapid development, spurred by recent policy initiatives worldwide. Several companies have announced plans to commercialize them within the next few years, albeit in relatively small numbers initially (tens of thousands of vehicles per year). Electric two-wheel motor-bikes and scooters are a large and fast-growing market in the developing world, especially in China with 20 million annual sales in 2007 (ICCT 2009). They have significant potential for fuel efficiency improvement and GHG reduction. HFCVs have been demonstrated, but are unlikely to be fully commercialized until at least 2015-2020 due to barriers of fuel cell durability, cost, on-board hydrogen storage and hydrogen infrastructure availability and cost. The timing for commercializing each technology is discussed below (8.3.1.4).

8.3.1.3 Transition issues for light-duty transport

To meet future energy security and GHG emission reduction goals, the transport sector will need to be fundamentally transformed (8.3.1.1). Historically, major changes in transport systems, such as building canals and railroads, paving highways, and adopting gasoline cars, have taken many decades to complete for several reasons.

- Passenger vehicles have a relatively long lifetime (15 years average in the US but longer elsewhere). Even if a new technology rapidly moved to 100% of new vehicle sales, it would take years for the vehicle stock to “turn over”. In practice, adoption of new vehicle technologies occurs slowly and can take 25 to 60 years for an innovation to be used in 35% of the on-road fleet (Kromer and Heywood 2007). For example, research into gasoline HEVs in the 1970s and 1980s led to a decision to commercialize in 1993 with the first vehicle becoming available for sale in 1997 in Japan. Over 13 years later, HEVs still represent only about 1% of new car sales and less than 0.5% of the worldwide fleet (although low oil prices during this period were maybe a factor). This slow turnover rate is also true for relatively modest technology changes such as the adoption of automatic transmissions, intermittent windscreen wipers and direct fuel injection. The timeframe for new technologies relying on batteries, fuel cells, or advanced biofuels could be even longer since they all need further RD&D investment and international standardization before they can be fully commercialized. Further cost reductions would then be needed to achieve wide customer acceptance.
- Changing fuel supply infrastructure, especially if switching on a major scale from liquids to gaseous fuels or electricity, will require a substantial amount of capital and take many decades to complete (IEA 2009; Plotkin and Singh 2009). Developing new supply chains for RE, and replacing existing fossil fuel systems, will take time and require close co-ordination among fuel suppliers, vehicle manufacturers and policy makers.

Each fuel/vehicle pathway faces its own transition challenges which can vary by region. In terms of technology readiness of fuels and vehicles, challenges include infrastructure compatibility, consumer acceptance (costs, travel range, refuelling times, safety concerns), primary resource availability for fuel production, life-cycle GHG emissions, and environmental and sustainability issues including air pollutant emissions and demand for water, land and materials.

8.3.1.3.1 Liquid biofuel pathways

Biofuels are generally compatible with ICEV technologies. In fact, many ICEVs already use liquid biofuels whereas only a small fraction have been adapted to run on gaseous fuels or hydrogen. HEVs introduced for gasoline vehicles can also use ethanol blends. However, most of the existing gasoline and diesel ICEV fleet can only operate on relatively low biofuel blends up to 10% by volume of ethanol or 5% of biodiesel, to avoid possible adverse effects of higher blends on the engine. An increasing number of flexible fuel vehicles (FFVs) in the US, Brazil, and Sweden can use higher blends of ethanol (up to 85%) or revert to gasoline.

Biomass can be converted to liquid fuels using many different routes (Chapter 2). First generation processes are commercially available and 2nd generation and more advanced processes, aiming to convert non-food, cellulosic materials and algae are under development (8.2.4). Second generation biofuels have potential for lower WTW GHG emissions than petroleum derived fuels, but these technologies are still several years from market (IEA 2008).

An advantage of some advanced liquid biofuels is their relative compatibility with the existing liquid fuel infrastructure and ease of blending with petroleum-derived fuels. Low liquid biofuels blends have similar properties to neat gasoline or diesel with similar engine performance and refuelling times. They do not require new vehicle types and can be relatively “transparent” to the consumer. Ethanol, under some circumstances, cannot be shipped through existing fuel pipelines (8.2.4) and in some countries, has limits on the concentrations that can be blended. It would likely need its own distribution and storage systems, as well as dispensing pumps for blends beyond E10. Fuel costs may therefore be the main factor determining consumer acceptance. In Brazil, for example, flex-fuel vehicle users select their fuel based on price. Reduced range and reduced fuel economy with ethanol and, to a lesser extent, biodiesel, can also be a factor in consumer acceptance.

Primary biomass resource availability can be a serious issue for biofuels. Recent studies (IEA 2009; Plotkin and Singh 2009) have assessed the national or global potential for biofuels to displace petroleum products. Environmental and land-use concerns could limit production to 20-25% of total transport energy demand. Given that certain transport sub-sectors such as aviation and marine require liquid fuels, it may be that biofuels will be used primarily for these applications, whilst electric drive train vehicles (EVs, PHEVs, or HFCVs), if successfully developed and cost effective, might dominate the LDV sector.

8.3.1.3.2 Biomethane pathways

Biogas and landfill gas (produced from organic wastes and green crops, Chapter 2) can be purified and injected into existing natural gas distribution systems (8.2.3). Spark-ignition ICEVs designed or converted to run on CNG can also be run on biomethane. Biogas would first need the CO_2 to be stripped to give greater range per storage cylinder refill, and H_2S also stripped to reduce risk of engine corrosion.

8.3.1.3.3 Hydrogen/fuel cell pathways

Hydrogen is a versatile energy carrier that can be produced in several ways (8.2.3). WTW GHG emissions vary for different hydrogen fuel/vehicle pathways, but both RE and fossil hydrogen pathways can offer reductions compared to gasoline vehicles (8.3.1.4).

Although hydrogen can be burned in a converted ICEV, more efficient HFCVs are attracting greater R&D investment by engine manufacturers. Most of the world’s major automakers have developed prototype HFCVs, and several hundred of these vehicles, including buses, are being demonstrated worldwide. HFCVs are currently very costly, in part because they are not yet mass produced and fuel cell lifetimes are not yet adequate. It is projected that the costs of FCVs will fall with further improvements resulting from R&D, economies-of-scale from mass production, and learning experience (NRC 2008).

HFCVs could match current gasoline ICEVs in terms of vehicle performance and refuelling times. The maximum range of present-day HFCV cars of about 500 km is acceptable, but hydrogen refilling availability and the high cost of both vehicle and fuel remain key barriers to consumer acceptance. Hydrogen is not yet widely distributed to consumers in the same way as electricity, natural gas, gasoline, diesel or biofuels are. Bringing hydrogen to a large numbers of vehicle owners would require building a new refuelling infrastructure over several decades (8.2.3).

Hydrogen can be produced regionally in industrial plants or locally on-site at vehicle refuelling stations or in buildings. The first steps to provide hydrogen to HFCV test fleets and demonstrate refuelling technologies in mini-networks are in place in Iceland and being planned elsewhere through projects such as the California Hydrogen Highways Network, the British Columbia Hydrogen Network, the European "HyWays" Hydrogen Roadmap, and Norway's "Projects in Europe". System level learning from these programmes is valuable and necessary, including development of safety codes and standards. In the US, a mix of low carbon resources including natural gas, coal (with CCS), biomass, and wind power could supply ample hydrogen (NRC 2008). The primary resources required to provide sufficient fuel for 100 million passenger vehicles in the US using various gasoline and hydrogen pathways have been assessed (Ogden and Yang 2009). For example, enough hydrogen could be produced from wind-powered electrolysis using about 13% of the technically available wind resource. However, the combined inefficiencies of making the hydrogen via electrolysis from primary electricity sources, then converting it back into electricity on a vehicle via a fuel cell, loses more than 60% of the original RE inputs. Electricity is used more efficiently in an EV or PHEV but hydrogen might be preferred in large vehicles requiring a long range and fast refuelling times.

Hydrogen production and delivery pathways have a significant impact on the cost to the consumer. In addition, compared to industrial uses, fuel cell grade hydrogen needs to be >99.99% pure and generally compressed to 35 to 70 MPa before dispensing. Using optimistic assumptions, hydrogen at the pump might near-term cost US$(2005) 7-12/kg excluding taxes, eventually reducing to US$(2005) 3 - 4 /kg[15] (NRC 2008; NREL 2009). Given the potential higher efficiency of fuel cell vehicles, the fuel cost per kilometre could become competitive with ICEVs in the future (Kromer and Heywood 2007; NRC 2008).

Several studies (Gielen and Simbolotti 2005; Gronich 2006; Greene, Leiby et al. 2007; NRC 2008) indicated that cost reductions were needed to "buy-down" fuel cell vehicles to market clearing levels (through technological learning and mass production) and to build the associated infrastructure over several decades that could cost hundreds of billions of dollars (8.2.3.5). The majority of this cost would be for the incremental costs of early hydrogen vehicles, with a lesser amount needed for early infrastructure. Even at high oil prices, government support policies may most likely be needed to subsidize these technologies in order to reach cost-competitive levels and gain customer acceptance.

8.3.1.3.4 Electric and hybrid vehicle pathways

While electricity generation from primary energy sources is typically only 20%-55% efficient (or about 18% - 50% once transmission and distribution losses are included), EV drive trains are relatively efficient and battery charging is a reasonably efficient way to store and use primary RE. Combined EV drive train efficiency (85%) and battery charge/discharge efficiencies (90% for electric plug-to-wheels) are in the order of 77%.

The GHG emissions and environmental benefits of EVs depend on the marginal grid mix and the source of electricity used for vehicle charging. For example, the current US grid being 45% dependent on coal, WTW emissions from EVs would not be much of an improvement over efficient gasoline vehicles (Fig. 8.27) whereas for the French electric grid, which uses significant amounts of nuclear power, WTW emissions would be relatively small (Zgheib and Clodic 2009). Various studies have developed scenarios for decarbonising the electricity grid over the next few decades (8.2.1and Chapter 10) that would result in reduced WTW emissions for EVs and PHEVs (EPRI 2007; IEA 2009). With large fractions of RE or low carbon electricity, WTW emissions for EVs could, over time, become much smaller.

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[15] 1 kilogram of hydrogen has a similar energy content to 1 US gallon or 3.78 litres of gasoline

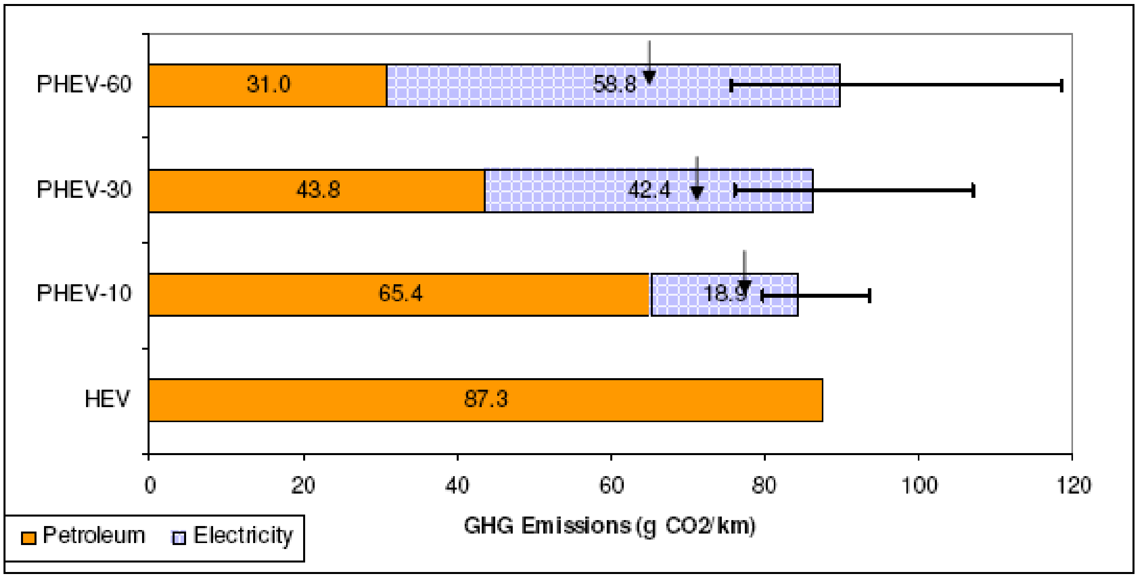

Figure 8.27: Well-to-wheels GHG emissions for gasoline-fuelled hybrid electric vehicles (HEVs) and plug-in hybrids (PHEVs) showing the various ranges when running on electricity only.

Notes: The US06 drive cycle was used to estimate vehicle emissions as CO_2/km. PHEV-10 corresponds to an all-electric range of about 16 km whereas PHEV-60 is around 100 km. Horizontal bars indicate the emission range when using electricity from natural gas to coal-fired power generation. Vertical arrows indicate emission levels from a partially decarbonized grid similar to that in California (Kromer and Heywood 2007).

EV use is currently limited to neighbourhood and niche fleet vehicles, from small go-carts to pick-ups and buses. There is also a limited number of passenger EVs still operating from original models sold by GM, Toyota, Honda and others in the 1990s and early 2000s. Limited commercialization of EVs and PHEVs is planned over the next few years in response to policy measures (Kalhammer, Kopf et al. 2007) with several automobile manufacturers making niche initial offerings. The main transition issue is to bring down the cost and improve the performance of advanced batteries. Today's lithium batteries cost 3-5 times the goal needed to compete with gasoline vehicles on a lifecycle cost basis. Demonstrated lifetimes for advanced lithium battery technologies are 3-5 years, when 10 years is required ideally for automotive applications (Nelson, Santini et al. 2009).

For RE electricity to serve growing EV markets, several innovations need to occur such as development of low-cost power supplies available at the time of recharging EVs. If night-time, off-peak recharging could be employed, new capacity would not necessarily be needed and there may be an adequate temporal match with wind or hydropower resources more than with solar PV. Energy storage may also be a way to balance vehicle electric demand with RE sources. In addition, the distribution grid would need upgrading, possibly including smart grid technologies, to handle the added load. Consumer acceptance is also a key issue. One attraction of EVs is that they could be recharged at home, avoiding trips to the refuelling station. However, home recharging would require new equipment and not all households would be able to conveniently install it, perhaps only 30-50% in the US (Kurani *et al*. 2009). So public recharging point infrastructure may need to be developed in some areas. "Level 1" charging, using a standard plug, and would take several hours, compared with the quick refill time possible with liquid or gaseous fuels. "Level 2" charging could take less time but would require a specialized higher power outlet. Even fast-charge outlets at publically accessible recharging stations might bring batteries to near full-charge only after 10-15 minutes, taking more time than refilling an ICEV. In-home overnight recharging systems might cost US$(2005)700-1300 per charger for level 1 charging and US$800-1900 for level 2 chargers [TSU: figure will need to be adjusted to 2005 US$] (USDOE 2008). An EV is likely to have a shorter range than a similar size ICEV, 200-300 km versus 500-900 km (Bandivadekar, Bodek et al. 2008).

While this range is adequate for 80% of car trips in urban/suburban areas, this factor would make long distance EV travel less practical. This could be overcome by owners of small commuter EVs using rental or community-owned HEV or PHEV vehicles for longer journeys (IEA 2009).

The added vehicle cost for PHEVs, while still significant, is less than for an EV and the range should be comparable to a gasoline HEV. One strategy is to introduce PHEVs initially while developing and scaling up battery technologies for EVs. This could help lead to more cost-competitive EVs. However, HEVs will always be cheaper to manufacture than PHEVs due to the smaller battery capacity, although advances in battery technologies could make them more competitive. Incentives such as low electricity prices relative to gasoline, carbon charges, more inexpensive low-carbon electricity, and first-cost subsidies would be needed to make PHEVs a viable option. Availability of materials for advanced batteries, notably lithium, may be a future concern. EVs have the added ancillary benefit of zero tailpipe emissions which can reduce urban air pollution. However, if the electricity is produced from an uncontrolled source (such as coal plants without proper scrubbers) one source of pollution might simply be substituted for another (Kromer and Heywood 2007; Bandivadekar, Bodek et al. 2008).

8.3.1.4 Comparisons of alternative fuel/vehicle pathways

Different entire fuel/vehicle pathways impact on WTW GHG emissions (Fig. 8.28). For conventional fuels, most of the emissions are “tank-to-wheels” and take place at the vehicles. For electricity and hydrogen, all emissions are “well-to-tank” and the vehicle itself has zero emissions. For RE biofuel pathways, carbon emissions at the vehicle are offset by carbon uptake from the atmosphere by future biomass feedstocks.

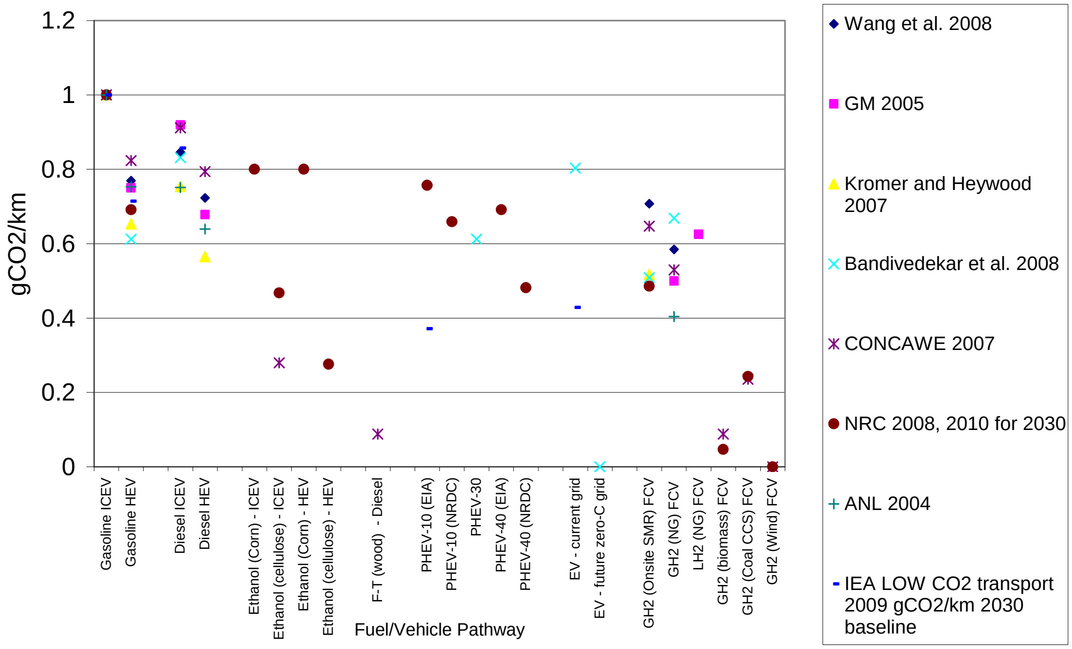

Figure 8.28: Well-to-wheels GHG emissions from several studies of alternative light duty fuel/vehicle pathways.

Note: GHG emissions are normalized to emissions from a gasoline ICEV. For all hydrogen pathways, hydrogen is stored on-board the vehicle as a compressed gas. GH2 = gaseous hydrogen delivery to station; LH2 = liquid hydrogen delivery to station.

8.3.1.5 Comparisons between technologies

Transition issues vary for biofuels, hydrogen, and electric vehicles (Table 8.5). No one option is seen to be a clear "winner" and all will take several decades to implement at the large scale.

Table 8.5: Transition issues for biofuels, hydrogen, and electricity

Technology Status	**Biofuels**	**Hydrogen**	**Electricity**
Vehicles	Millions of flex-fuel vehicles using ethanol, but conventional vehicles still limited to low concentration blends of ethanol (< 10%) or biodiesel (< 5%)	Demonstration HFCVs. Commercial HFCVs: 2015-20	Limited current use of EVs. Demonstration PHEVs, Commercial PHEVs :2010-15. Commercial EVs: 2015-2020.
Fuel production	1st generation: Ethanol from sugar and starch crops, biomethane, biodiesel. 2nd generation: ethanol / diesel/green fuels from cellulosic biomass, biowastes, bio-oils, and algae - after at least 2015.	Fossil H_2 commercial for large-scale industrial applications, but not competitive as transport fuel. Renewable H_2 generally more costly.	Commercial power available. RE electricity generally more costly.
Cost (vs. gasoline vehicles) Incremental vehicle price compared to future gasoline ICEV (US$2005)	Similar vehicle cost to gasoline.	HFCV experience price increment (2035)[16]compared to gasoline ICEV >US$ 5300	Experience price increment compared to gasoline ICEV >US$ 5900 (2035) (PHEVs)

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[16] (Bandevedakar *et al*., 2008)

Fuel cost (US$ /km)	Fuel cost per km competes, if biofuel price per unit energy ~ gasoline price per unit energy.	Fuel cost per kg for H_2 at $3-4/kg (target for mature H_2 infrastructure; may prove optimistic) used in HFCV competes with gasoline at US$ 0.40-0.53/l used in gasoline ICEV, assuming HFCV has 2x fuel economy of gasoline ICEV. Renewable H_2 at least 1.5-3x more expensive.	>US$ 14,000 (2035) (EVs)[16]. Electricity cost per km competes with gasoline cost per km for electricity costs $0.10-0.30/kWh when gasoline costs $0.3-0.9/l (assuming EV has fuel economy 3x gasoline ICEV)
Compatibility with existing infrastructure	Partly compatible with existing petroleum distribution system. Separate distribution and storage infrastructure can be needed for ethanol.	New H_2 infrastructure needed, as well as renewable H_2 production sources. Infrastructure deployment must be coordinated with vehicle market growth.	Widespread electric infrastructure in place. Need to add in-home and public chargers, RE generation sources, and upgrade transmission and distribution (especially for fast chargers).
Consumer acceptance	Fuel cost: alcohol vehicles have shorter range than gasoline. Potential cost impact on food crops and land use. Land and water issues can be a factor.	Vehicle and fuel costs. Safety of on-board gaseous H_2 storage. Fuelling station availability in early markets.	Vehicle initial cost. High electricity cost of charging on-peak. Limited range unless PHEV. Modest to long recharge time, but home recharging possible. Significantly degraded performance in extreme climates (cold winters, hot summers).
Existing and potential primary resources	Sugar, starch, oil crops. Cellulosic crops; forest, agricultural and solid wastes. Algae and other biological oils.	Fossil fuels, nuclear, all RE-potential RE resource base is large but inefficiencies and costs of converting to H_2 an issue.	Fossil fuels, nuclear, all RE – potential RE resource base is large.
GHG emissions	Depends on feedstock, pathway and land use issues. Low for fuels from waste residues, and sugarcane. Near-term can be high for corn ethanol. 2nd generation biofuels lower.	Depends on H_2 production mix. Compared to future hybrid gasoline ICEVs, WTW GHG emissions for HFCVs using H_2 from natural gas are slightly more to slightly less depending on assumptions. WTW GHG emissions can approach zero for RE pathways.	Depends on grid mix. Using coal-dominated grid mix, EVs, and PHEVs have WTW GHG emissions similar or higher than gasoline HEV. With larger fraction of RE and low carbon electricity, WTW emissions are lower.
Petroleum consumption	Low	Very low	Very low
Environmental and sustainability issues Air pollution Water use Land use Materials use	Similar to gasoline. Additional issues for ethanol due to permeation of volatile organic compounds (VOCs) through fuel tank seals. Aldehyde emissions. More than gasoline depending on feedstock and irrigation needs. Might compete with food-for cropland.	Zero emission vehicle Potentially very low but depends on pathway. Depends on pathway. Platinum in fuel cells. Neodymium and other rare earths in electric motors.	Zero emission vehicle. Potentially very low but depends on pathway. Depends on pathway. Lithium in batteries. Neodymium and other rare earths in electric motors.

Note: Costs quoted do not always include payback of incremental first vehicle costs.

8.3.1.6 Low emission propulsion and renewable options in other transport sectors

8.3.1.6.1 Heavy duty vehicles

Globally, most HDVs consist of freight trucks and long-haul tractor-trailers, which account for about 24% of transport-related energy use and a similar fraction of GHGs (IEA 2009). Other HDVs include buses and off-highway vehicles such as agriculture and construction equipment. As was the case for LDVs, there are several strategies to reduce fuel consumption and GHG emissions:

- partially switching to lower carbon fuels;
- streamlining operational logistics for handling freight and routing by using GPS routing technology, avoiding empty return trips, etc.; and
- further increasing vehicle efficiency, perhaps by up to 30-40% by 2030 (IEA 2009). This can be achieved through more advanced engines, exhaust gas energy recovery (via advanced turbo-charging or turbo-compounding), hybrid vehicles (which may include either electric or hydraulic motors), light-weighting, tyres with lower rolling resistance, improved truck-trailer integration for better aerodynamics, more efficient driving behaviour, optimized automatic gear shifting, speed reduction, and use of more efficient auxiliary power units (APUs) decoupled from the power train.

Today, about 85% of freight-truck fuel is diesel, with the remainder gasoline. Integrating biofuels into the fuel mix would be the most straight forward RE option. The IEA (IEA 2008) expects 2nd generation biofuels to become a more significant blend component in diesel fuel for trucks, possibly reaching as high as 20-30% by 2050. Due to range and resulting energy storage requirements for long-haul HDVs, use of other lower carbon alternatives such as CNG, LPG, compressed biogas, hydrogen (for either HFCVs or ICEVs), or electricity would likely be limited to urban or short-haul HDVs, such as buses, refuse trucks, and delivery trucks. LNG might also become an option for freight transport. Another potential use of low carbon H_2 or electricity might be to power on-board fuel cell APUs or charge batteries, although neither of these options is cost effective yet.

The reduction of fuel consumption and GHG emissions in HDVs may be more difficult than for LDVs due to slower vehicle turnover, faster growth in vehicle km t (VKT), less discretionary freight movement, and inherent economic drivers that continuously aim to minimize life cycle HDV costs. Because many HDVs are purchased for fleet operations, there could be an opportunity to integrate alternative fuels and vehicles by providing fleet-wide support for new fuelling infrastructure, technology maintenance and, if needed, driver training. According to the IEA's baseline scenario (IEA 2008), HDV energy use by 2050, even with improved energy efficiency of about 20%, is projected to increase by 50% as the quantity of worldwide freight moved by trucking doubles. Most of this growth will occur in non-OECD countries.

8.3.1.6.2 Aviation

Aviation energy demand accounted for about 11% of all transport energy in 2006 and could double or triple by 2050 (IEA 2009). Rapid growth of aviation is mainly driven by the increase of air traffic volumes for both passenger and freight traffic and the fact that aviation boasts the highest energy and GHG intensity of all transport modes. Efficiency improvements can play an important role in reducing aviation energy use by 30-50% in future aircraft (IEA 2009). These include improved aerodynamics, airframe weight reduction, higher engine efficiency, and improvements in operation and air traffic control management to give higher load factors, better routing, and more efficient ground operations at airports (including more gate electrification and use of low carbon-fuelled service vehicles) (TRB 2009). Although reductions in energy intensity (energy use per passenger- or per cargo tonne- kilometre) can be substantial, they will not sufficiently decouple fuel demand growth from activity growth to avoid large increases in fuel use since about 90% of fuel use and

GHG emissions occur in flight, mostly at cruising altitude (TRB 2009). Slow fleet turnover, every 30 years on average (IEA 2009; TRB 2009), will delay the penetration of advanced aircraft designs.

Aircraft will continue to rely mainly on liquid fuels due to the need for high energy density fuels in order to minimize fuel weight and volume. In addition, due to safety, the fuels need to meet more stringent requirements than for other transport modes, particularly thermal stability to assure fuel integrity at high engine temperatures and to avoid freezing or gelling at low temperatures; specific viscosity; surface tension; ignition properties; and compatibility with aircraft materials. Compared to other transport sectors, aviation has less potential for fuel switching due to these special fuel requirements. In terms of RE, various aircraft have already flown test flights using various biofuel blends, but significantly more processing is needed than for road fuels to ensure that stringent aviation fuel specifications are met. IEA scenarios range from a few percent up to 30% biofuel use in aviation by 2050 (IEA 2009).

Liquid hydrogen is another long-term option, but faces significant hurdles due to its low volumetric energy density. Fundamental aircraft design changes to accommodate cryogenic storage, and distribution infrastructure hurdles at airports. The most likely fuel alternatives, but not necessarily low carbon, are synthetic jet fuels (from natural gas, coal or biomass) since they have similar characteristics to conventional jet fuel.

8.3.1.6.3 Maritime

Marine transport, the most efficient mode for moving freight, currently consumes about 9% of total transport fuel, 90% of which is used by international shipping (IEA 2009). Ships rely mainly on heavy fuel (“bunker”) oil (HFO), but lighter marine diesel oil is also used. HFO accounts for nearly 80% of all marine fuels. The sulphate emissions that create aerosols may actually mitigate GHG impact by creating a cooling effect. However, future regulations will require lower sulphur marine fuels. An expected doubling to tripling of shipping transport by2050, coupled with ever more stringent air quality regulations aimed at reducing particulate emissions through cleaner fuels, will lead to greater GHG emissions from this sector.

Due to a fragmented industry where ship ownership and operation can occur in different countries, as well as slow fleet turnover (typical ship replacement occurs about every 30 years), energy efficiency across the shipping industry has not improved at the same rate as in the HDV and aviation sectors. Hence, there exist significant opportunities to reduce fuel consumption through a range of technical and operational efficiency measures (IEA 2009; TRB 2009) such as improvements in:

- vessel design (e.g., larger, lighter, more hydro-dynamic, lower drag hull coatings);
- engine efficiency (e.g., diesel-electric drives, waste heat recovery, engine derating);
- propulsion systems (e.g., optimized propeller design and operation, use of sails or kites);
- APUs; and
- operation (e.g., speed reduction, routing optimization, better fleet utilization, reduced ballast).

These measures could potentially reduce energy intensity by as much as 50-70% for certain ship types (IEA 2009).

The key application of RE in marine transport could be through the use of biofuels. Existing ships could run on a range of fuels, including blends of lower quality such as low cost bio-crudes (pyrolysis oil from biomass). Engines would probably need to be modified, similar to HDV road vehicles, to operate on high blend (80-100%) biofuel mixtures. Other RE and low-carbon options could include the use of on-deck hybrid solar PV and micro-wind systems to generate auxiliary power, solar thermal systems to generate hot water or space heating or cooling, and electric APU systems plugged in to a RE grid source while at port.

8.3.1.6.4 Rail

Although rail transport accounts for only a small fraction (~2% in 2005) of global transport energy use, by 2050 rail freight volume is expected to increase by up to 50% with most of this growth occurring in non-OECD countries (IEA 2009). Rail moves more freight and uses an order of magnitude less energy than trucking due to its much higher efficiency (IEA 2009). Rail transport is primarily powered by diesel fuel (almost 90% of rail energy use in 2005), with the balance of the rail network mostly electrified (IEA 2009). Growth in high-speed electric rail technology continues rapidly in Europe, Japan, and elsewhere. As with shipping, the use of high sulphur fuels has helped to mitigate net GHG emissions due to the negative radiative forcing effect of sulphates, but this trend has other negative environmental consequences and will likely decrease with stricter clean fuel regulations.

Rail sector efficiency increases of up to 20-25% are possible (IEA 2009; TRB 2009). Options include:

- upgrading locomotives to more efficient diesel engines, hybrids, and APUs;
- increasing load factors by reducing the empty weight of the rolling stock, lengthening trains, and using double-stacked containers; and
- operational improvements such as operator training, optimized logistics and reduced idling.

The two primary pathways for RE penetration in rail transport are through increased use of biodiesel and renewable “green” diesel, which may account for 2-20% of rail fuel use in 2050 (IEA 2009) and a shift towards electrification. Compared to their diesel counterparts, all-electric locomotives can improve life cycle efficiency by up to 15%, (or less if compared to a diesel hybrid-electric drive system that includes battery storage), and further reduce GHG emissions as electricity generation switches to RE and/or nuclear power. Although the use of hydrogen fuel cells may be limited due to range, energy storage, and cost issues, the challenges for installing fuel cells on locomotives appear to be fewer than for passenger HFCVs. Compared with LDVs, a rail system provides more room for H_2 storage, offers economies of scale for larger fuel cell systems, and uses the electric traction motors already in diesel-electric locomotives.

8.3.1.7 Future trends

Perhaps the most important single trend facing the transport sector is the projected high growth of vehicle numbers worldwide which is expected to triple from the 700 million LDVs today by 2050 (IEA 2008). Meeting this demand while achieving a low carbon, sustainable and secure energy supply, will require rapid technology advancements that are offered in vehicles that are accepted by the public, strong policy initiatives, monetary incentives, and the willingness of customers to pay additional costs. There is scope for RE transport fuel use to grow significantly over the next several decades, playing a major role in this transition.

In the future, a wider diversity of transport fuels and vehicle types is likely. These could vary by geographic region and transport sub-sector. For applications such as air and marine, liquid fuels are probably the only practical option. In the LDV sector, increased use of electric drive train technologies has already begun, beginning with HEVs, progressing to PHEVs and EVs and HFCVs (IEA 2008). Historically, the electric and transport sectors have been completely separate, but, through grid-connected EVs, they are likely to interact in new ways by charging battery vehicles or, possibly, “vehicle-to-grid” electricity supply (8.2.1.6) (McCarthy, Ogden et al. 2008)

Ancillary environmental concerns and energy security are important motivations for new transport systems. Sustainability issues may impose constraints on the use of alternative fuels or vehicle designs and understanding these issues will be necessary if a low carbon future transport system is to be achieved.

Meeting future goals for GHG emissions and energy security will mean displacing today's ICEVs, planes, trains, and ships with higher efficiency, lower emission models and ultimately adopting new, low- or zero- carbon fuels that can be produced cleanly and efficiently from diverse primary sources. There is considerable uncertainty in the various technology pathways, and further RD&D investment is needed for key technologies including batteries, fuel cells, hydrogen storage, and for RE and low carbon production methods for biofuels, hydrogen, and electricity. Given these uncertainties and the long timeline for change, it is important to maintain a portfolio approach that includes behavioural changes (to reduce VKT), more efficient vehicles, and a variety of low-carbon fuels. This approach will recognize that people ultimately make the vehicle purchase decisions, and that different technologies and fuel options will fit their various situations. Recent studies (IEA 2008; IEA 2009) see a major role for RE transport fuels in meeting societal goals, assuming that strict carbon limits are put in place.

8.3.2 Buildings and households

The buildings and household sector in 2007 accounted for ~116 EJ, or about 30 % of total global final energy demand. Around 40 EJ of this total was from combustion of traditional biomass for cooking and heating. By 2030, the total demand could rise to ~136 EJ (Fig. 8.2). GHG emissions from the building sector, including through electricity use, were about 8.6 Gt CO_2 in 2004 (IPCC, 2007) with scope for significant reduction potential[17] (Metz, Davidson et al. 2007; IEA 2009). The sector provides a variety of basic energy services to support the livelihoods and well-being of people living in both developed and developing countries including for:

- preparation of food for consumption and sale;
- refrigeration of food and other perishable items including medicines / vaccines;
- cooking – 95% of staple foods needing to be cooked (Practical Action, 2010);
- heating of building space in colder regions;
- heating of water for washing, distillation and desalination;
- cooling of building space, particularly in tropical regions;
- lighting for streets, commercial buildings, and households to allow night study;
- communications and entertainment including telephones, computers, TV, radio;
- mobility of people and transport of products to markets;
- social services including water pumping and purification, health treatment, and education; and
- industrial activities necessary for agriculture, agro-processing, industrial enterprises, manufacture of goods and provision of services.

Energy carriers including are converted into energy services in a variety of ways. Although it is possible to use different types of energy to provide the same service, it is also possible to select a vector for its specific characteristics that are most suitable to meet the specific requirements of the energy service to be provided (Table 8.6).

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[17] Full details of the potential for energy efficiency and RE in the building sector were provided in Chapter 6 of the IPCC 4th Assessment Report – Mitigation (Metz *et al*., 2007).

Table 8.6. Energy carriers and their suitability for providing basic energy needs.

	Solid fuels (wood, charcoal)	Liquid fuels	Gaseous fuels	Mechanical power	Electricity
Cooking	XXX	XX	XXX		XX
Space and water heating	XXX	XXX	XXX		XX
Space cooling					XXX
Lighting	X	XX	XX		XXX
Refrigeration	X	XX	XX		XXX
Communication/ entertainment					XXX
Mobility and transport	X	XXX	X	XX	X
Social services				XX	XXX
Productive uses	XX	XX	XX	XXX	XXX

X = possible but not usually preferable; XX = applicable but limited; XXX = most suitable

Energy for cooking, water heating and waste treatment is deemed to be a basic human requirement, although for many millions of people living in developing countries, these services are not always readily available. For residential and commercial buildings, energy carriers and service delivery systems vary depending on the local characteristics of a region and its wealth. Building owners and managers use energy to provide comfort for those working or living there through space heating, ventilation and cooling as well as for lighting, and powering appliances.

The present use of fossil fuels to provide heating and cooling can be replaced economically in many regions by modern biomass and enclosed stoves, ground source heat pumps, solar thermal and solar sorption systems (IEA 2007). The total global demand for RE heating (excluding traditional biomass) is around 3.5-4.5 EJ/year. Policies to encourage the greater deployment of RE heating/cooling systems are limited but several successful national and municipal approaches are in place (IEA 2007).

RE integration differs between commercial high-rise apartment buildings in mega-cities and small towns of mainly individual dwellings; between wealthy suburbs and poor urban areas; between established districts and new sub-divisions; and between farming and fishing communities in OECD countries and small village settlements in developing countries that have limited access to energy services. The following section covers these regional differences.

8.3.2.1 Urban settlements in developed countries

In OECD and other major economies, most urban buildings are connected to electricity, water, and sewage distribution schemes. Many have natural gas supplied for heating and cooking giving greater convenience for residents than using coal, biomass or oil-products to provide these services. RE resources are widespread but have low energy density by comparison with fossil fuels and RE conversion technologies can be comparatively expensive. Nevertheless, integration in buildings is expanding in order to improve residents' quality of life at the same time as realizing low carbon and secure energy supplies (IEA 2009). RE deployment in a building is often combined with the enhancement of energy efficiency as well as energy conservation via behavioural change.

8.3.2.1.1 Challenges caused by RE integration

Efforts to improve energy efficiency and utilize low carbon energy sources are largely dependent on the motivation of building owners and inhabitants. Institutional and financial measures such as energy auditing, labelling, subsidies, regulations, incentives and automatic billing systems can lead to increased deployment. The features and conditions of energy demand in an existing or new building differ with location and design. Effective and efficient methods and technical products are being developed to apply to buildings under a variety of situations.

The transition from a fossil-fuel based, centralized energy supply system into a more distributed system with increased RE (8.2.1.6) will need a drastic revision of how urban space has been traditionally planned and occupied. The required changes in land and resource use to better accommodate RE technologies in parallel with the existing energy supply is one of the major structural changes that will shape their integration.

The greater deployment of RE resources in an urban environment (IEA 2009) may require innovative use of roof and wall surfaces of city buildings. This will impact on the orientation and height of buildings to gain better access to solar radiation and wind resources without shading. Local seasonal storage of excess heat using ground source heat pumps, and access to surface ground water, may need to be considered. The opportunity is available for buildings to become energy suppliers rather than energy consumers. Building-integrated PV systems have experienced rapid growth reaching 20 GW capacity in 2009 (REN21 2006) but the present PV market of around US$(2005) 20 bn/yr could become constrained by lack of standardisation, lower production volumes and competition from PV panels when applied to buildings as retrofits (Lux 2009). Retrofits can now encompass roof-integrated systems that resemble traditional roof coverings.

Appliances in buildings could also contribute to maintaining the supply/demand balance of the energy system through demand response and energy storage (possibly including electric vehicles in future). This is an important spatial option for some cities and towns, possibly requiring adaptation of the local electricity (8.2.1) and/or heating/cooling distribution grid (8.2.2). Technological advances are required in order to speed up the integration of RE into the built environment including energy storage technologies, real time meters, demand-side management and more efficient systems that also have benefits for the power supply system. New RE technologies may need to be accompanied by innovative and progressive energy regulations and incentives to obtain their more rapid dissemination (IEA 2008). Several examples exist of successful government policies and entrepreneurial initiatives that can be replicated elsewhere.

Many buildings are leased to their occupiers, leading to the conundrum of owner/tenant benefits. Investing in energy efficiency or RE initiatives by the building owner usually benefits the tenants more than the investor, so that return on investment often has to be recouped through higher rents. Relatively high capital investments by building owners and long payback periods for technologies such as solar water heaters, or ground source heat pumps, can be a constraint, possibly overcome by government grants, utility leasing arrangements, or micro-financing schemes to access modern energy services.

8.3.2.1.2 Options to facilitate RE integration into urban supply systems

New building designs in both hot and cold regions have demonstrated that imported energy for cooling/heating can be minimised by careful design and the use of adequate insulation and thermal sinks. Building codes are steadily being improved to encourage the uptake of such technologies, and it is hoped that by around 2050, most new buildings will require little, if any, heating or cooling using imported energy.

Existing buildings can often be retrofitted to significantly reduce their energy demand for heating and cooling using energy efficient technologies such as triple glazing, cavity wall and ceiling insulation, shading, and white painted roofs. In OECD countries many building designs demonstrate these passive solar concepts well, but they remain a minority due to slow stock turnover. The lower the energy demand that the inhabitants of a building require to meet comfort standards as well as other energy services, then the more likely that RE can be employed to fully meet those demands.

Solar thermal and solar PV technologies can be integrated into building designs as components (such as roof tiles, wall facades, windows, balcony rails etc). Innovative architects are beginning to incorporate such concepts into their designs. Integration of PV panels into buildings during construction can replace the look and function of traditional building materials for roofs, windows overhangs, and walls, thereby improving the aesthetics and system reliability while reducing costs and utility transmission losses. Development of small wind turbines with low noise and little vibration can make roof-mounting more acceptable to building inhabitants and neighbours, though flickering may remain an issue in some situations.

Distributed CHP systems (biomass, solar thermal, geothermal, H_2 from electrolysis or fossil fuels) at medium and small scales (Liu and Riffat 2009), could be used on-site to produce sufficient heat and power to meet local demands with excess exported off-site to gain revenue (IEA 2009). CHP combustion/steam generation engines, gas turbines, and other conversion technologies are available at large (50 MW_e) and small (5 kW_e) scales with on-going research into fuel cells and micro-CHP systems (Leilei *et al.*, 2009). [Authors: Source does not appear in reference list]

Greater integration of RE into the built environment is directly dependent on how urban planning, architectural design, engineering and a combination of technologies could be integrated. Tools and methods to assess and support strategic decisions for planning new building construction and retrofits are available (Doukas, Nychtis et al. 2008). For subsequent stages, other methods, including computer simulations, are necessary to project the outcomes of a strategy (Dimoudi and Kostarela 2008; Larsen, Filippin et al. 2008).

8.3.2.1.3 Efficiency and passive RE integration

Air conditioning is one of the largest energy uses in buildings, mainly for space heating in high latitudes and cooling in low latitudes. A well designed and insulated building requires little imported energy and various kinds of building materials and construction methods are available. To reduce heating demand these include vacuum insulation panels, multi-foil insulation, insulation paint, vacuum glazing, and triple glazed windows, and for cooling, automatic shading and electro-chromatic glazing systems. Substantial design progress has been made in high performance heat pump air conditioners utilising atmospheric or ground heat. For single-residential, multi-residential, or commercial air-tight buildings, high energy demands for forced ventilation can be reduced through appropriate selection and hybridization of PV generation, solar chimneys and wind cowls (Antvorskov 2007).

Improved efficiency appliances for lighting, cooking, water heating, high thermal insulation refrigeration, liquid crystal displays (LCD), stand-by power modes etc. continue to be sought by R&D, and many RE technologies are also under development for use in residential and commercial buildings (Fig. 8.29). Smart appliances that use low energy and operate automatically at off-peak times for use with future intelligent electricity networks (IEA 2009), are reaching the market.

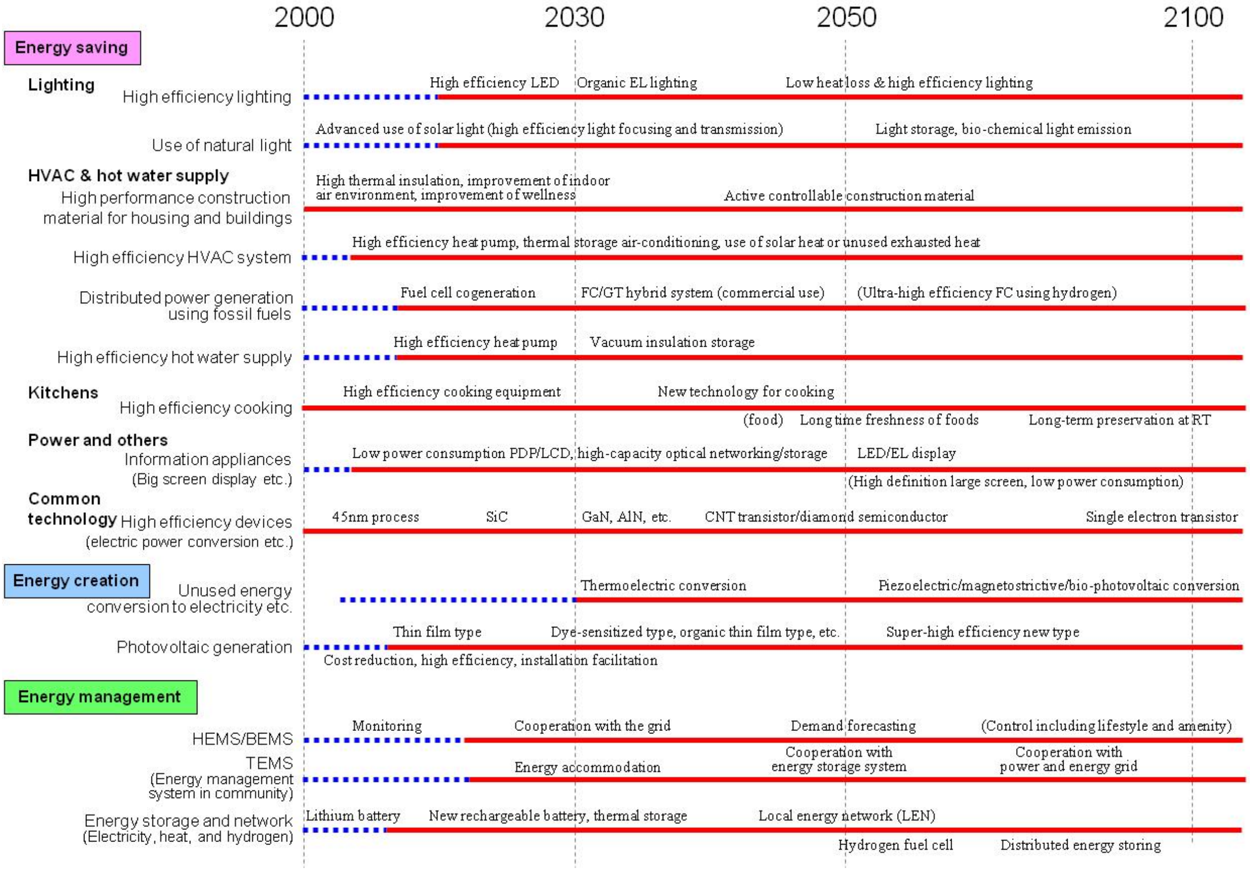


Figure 8.29: Technology development pathways for future energy efficiency and RE technologies for use in residential and commercial buildings (METI 2005).

8.3.2.1.4 Energy management technology

An energy manager of a building is usually responsible for multiple objectives including comfort, energy efficiency, environmental impacts and the integration of RE, all for minimal cost. In commercial buildings, various building energy management systems and controls have been developed to balance these multiple objectives (Dounis and Caraiscos 2009). Measuring and monitoring both energy use and the building environment are usually required (Wei, Yong et al. 2009). Monitoring techniques have been deployed in multi-family buildings with home energy management standard technologies produced to control and actuate appliances.

Advanced electricity meters, with bi-directional communication capability and related information infrastructure technology, are expected to be widely deployed to gain the benefits of demand response in combination with interfacing intelligent technology for appliances, distributed generation and energy storage (NETL 2008) (8.2.1.6).

8.3.2.1.5 Policies and regulations

Regardless of the type of RE technology, policies including building codes and minimum air emission standards are needed to help overcome barriers (including education and training of engineers, architects and installers), and to encourage rapid deployment in both new and existing buildings. Urban planning regulations may need modification to encourage rather than hinder deployment (IEA 2009). For example, regulations to protect the solar envelope for PV and solar thermal installations and prevent shading from newly planted trees and new building construction need to be developed, along with easing the process to obtain a resource or building consent within pre-determined guidelines.

8.3.2.1.6 Case studies

An analysis (WBCSD 2009) depicted the pathway for energy efficiency of single-family homes in France and an office building in Japan.

Single-family homes in France. Energy consumption is usually dominated by space heating being around two thirds of the total demand (Fig. 8.30). Solar PV and solar thermal were the major potential RE sources for these buildings and energy efficiency offers potential by reducing space heating needs through insulation, air tightness, improvements in domestic hot water and lighting.

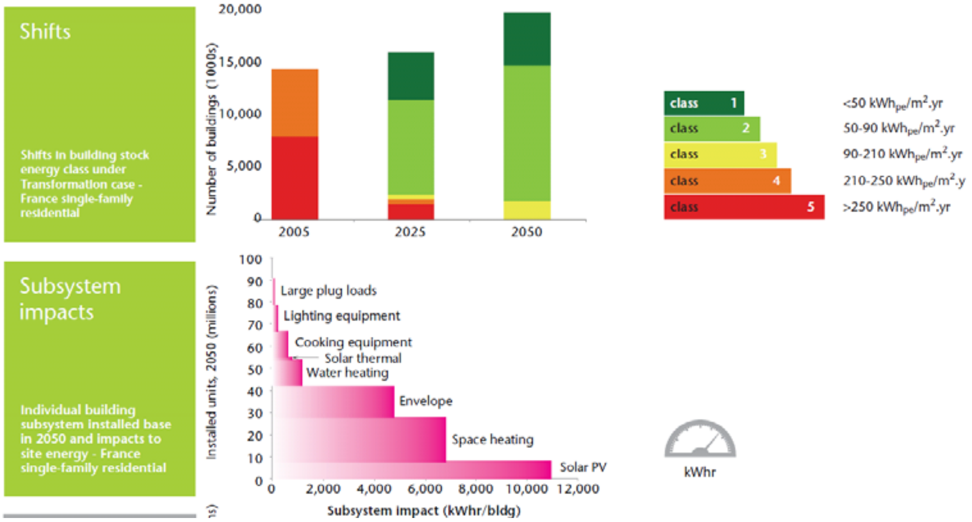


Figure 8.30: Possible trends in building stock energy classes from 2005 to 2050 and projected installations of energy saving technologies and integrated solar thermal and solar PV by 2050 for single-family homes in France (WBCSD 2009).

Office buildings in Japan: Heating and cooling equipment have the highest potential to reduce energy demand followed by lighting (Fig. 8.31). PV is the major RE source projected to be used in 2050, especially for low-rise buildings.

Figure 8.31: Possible trends in building stock energy classes from 2005 to 2050 and projected installations by 2050 of energy saving technologies and solar PV in office buildings in Japan (WBCSD 2009).

Distributed energy management technology for buildings is now under development, incorporating latest IT technologies to effectively control domestic peak demand and use energy storage equipment and DG systems in or around buildings (Cheung 2010). Buildings that have been passive energy consumers could become energy producers and building managers could become co-operators of an energy network (USDOE 2008).

Assuming low stock turnover of buildings of around 1% per year in developed countries, retrofitting of existing buildings will play a significant role for energy efficiency and RE integration (Ravetz 2008; Roberts 2008). Among many activities to pursue optimum retrofitting to gain 100% energy supply for heating, cooling & electricity, the “Renewable Energy House” in Bruxelles is a good example (8.2.5.5) (EREC 2008). Another example of retrofitting is residential buildings in China’s northern region where exterior windows, roofs, and heating system were retrofitted and the importance of metering of energy use and management is based on actual data (Zhao, Zhu et al. 2009).

8.3.2.2 Urban settlements in developing countries

Urban energy consumption patterns of the more wealthy members of society in many developing countries resemble those of developed countries (8.3.2.1). For the urban poor, commercial energy sources rely mainly on traditional biomass, particularly that sourced from animal dung and vegetation located close to urban consumption centres. The inefficiency of the whole supply chain, together with indoor air pollution problems, affect a large proportion of the urban population, particularly the many women who still rely on fuelwood or charcoal for their basic cooking and heating needs. In sub-Saharan Africa and elsewhere, many urban areas continue to experience a transition from fuelwood to charcoal which is impacting negatively on deforestation, given the low energy conversion efficiency of traditional kilns used in the carbonization process.

In many urban areas of developing countries, including in China, solar water heaters are considered to be a good RE option. Large-scale implementation of solar water heating can benefit both the customer and the utility. For a utility that uses centralised load switching to manage electric water-heater load, the impact of solar water heaters is limited to energy savings. For utilities that do not, then the installation of a large number of solar water heaters may have the additional benefit of reducing peak demand on the grid. In high sunshine regions, maximum solar water-heater output corresponds with peak summer electrical demand for cooling, and there is a capacity benefit from load displacement of electric water heaters. Emission reductions can result, especially where the solar water heating displaces the marginal and most-polluting generating plant used to produce peak-load power. A market niche for solar water heaters remains, particularly in the service sector such as hotels and lodges as well as in middle and high income households. Regulations and incentives could be necessary to reach a critical mass in many regions and hence gain larger dissemination.

8.3.2.2.1 Challenges and options

The major challenge is to reverse inefficient biomass consumption pattern by providing access to modern energy services while increasing the share of sustainable RE sources. In some urban areas, grid electricity is available although often unreliable and limited to basic needs. It is unlikely that decentralized RE will secure significant penetration in the next two decades. The introduction of liquid or gaseous RE fuels to replace solid biomass for cooking could play a critical role whilst improving the health of millions of people. In some regions LPG has displaced charcoal, though this is a costly option for the majority of poor people and only a few countries have achieved significant penetration. LPG, if subsidised, can become a high burden on a state budget. Its use benefits mainly middle and high income people as well as businesses. Replacing LPG by DME (di-methyl ether) produced from biomass, shows some potential. The scale of biofuel production that would be needed to meet cooking fuel demand is less than that for meeting transport fuel demand (8.2.4; 8.3.1).

A further challenge is to ensure that biomass as used extensively for fuel by many urban and rural communities in developing countries is supplied from sustainably produced forests. Many land areas close to urban areas have already been depleted of trees. In Senegal as a result, charcoal for use in urban areas is supplied from forests in excess of 400 km away, leading not only to high prices but also to relatively high GHG emissions as a result of inefficient carbonisation technologies and road transport.

Biomass will probably remain a valuable fuel in many urban centres in poor developing countries. To ensure the sustainability of biomass resources, a holistic approach encompassing supply (plantations, natural forest management) and demand (fuel switching, efficient equipment such as improved stoves and kilns) is required (Fig. 8.32). This approach could be accompanied by fiscal policies (for instance differential taxation) to provide financial incentives for biomass only being supplied from sustainable sources.

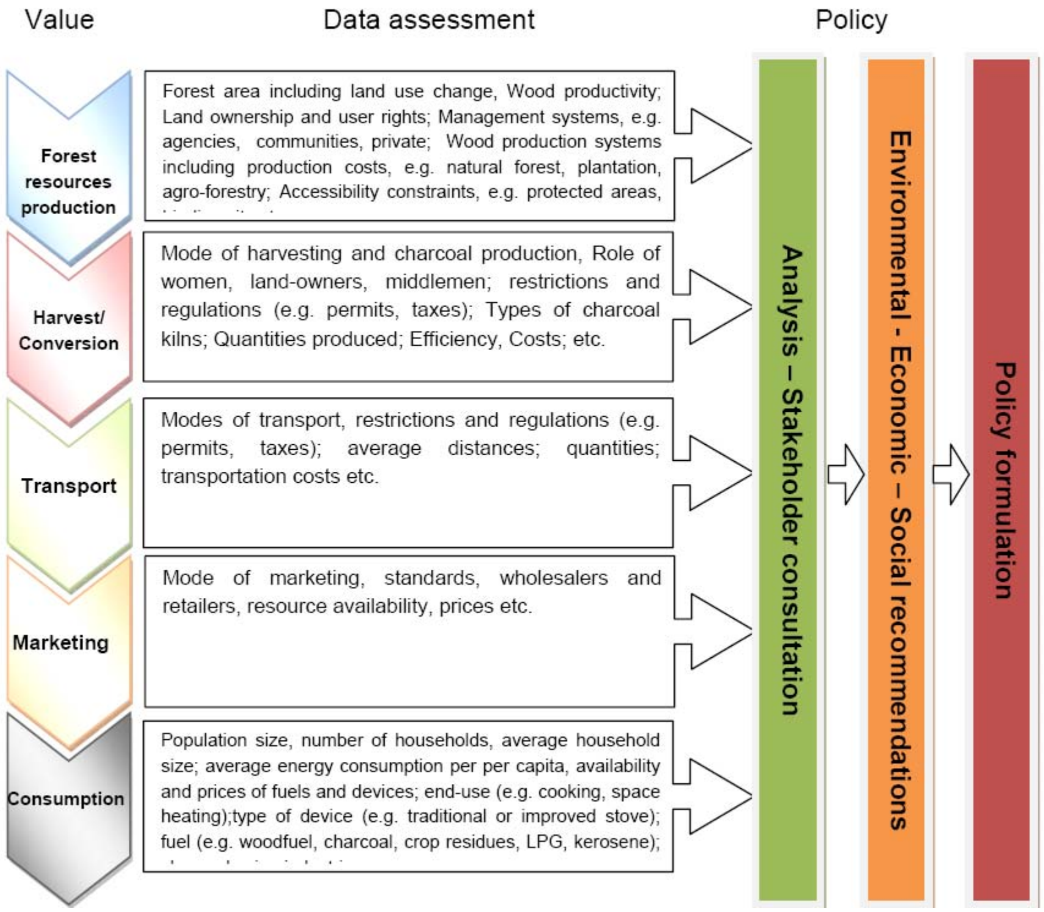


Figure 8.32: A holistic approach to sustainable RE supply using chain analysis of woody biomass supplied for energy purposes (Khennas, Sepp et al. 2009). [TSU: Figure will need to be redrawn to assure that all text is visible in data assessment boxes]

8.3.2.2.2 Case Studies

Peri-urban settlements in Brazil. The fast urbanization process in many developing countries has created peri-urban areas near to central metropolitan areas. In Brazil, all major cities and about one third of all municipalities have a large fraction of their population living in peri-urban areas that frequently lack proper services and basic urban waterworks, sanitation and electricity distribution infrastructure (IBGE 2008). Dwellings constructions are, for the most part, precarious, fragile and temporary and energy planning is complex. Where a distribution grid is available, it often does not comply with the standards of the utility, there being illegal connections and no meters. This can provide an opportunity to create new RE technologies. Depending on the type of settlement, a combination of small-scale energy technologies suitable for rural communities or urban dwellings could be employed where they can be financed (Fig. 8.33). These include treadle and wind pumps, solar pumps, improved stoves, biodiesel as a fuel for stationary engines, solar water heaters, wind turbines, biomass gasifiers and solar PV systems.

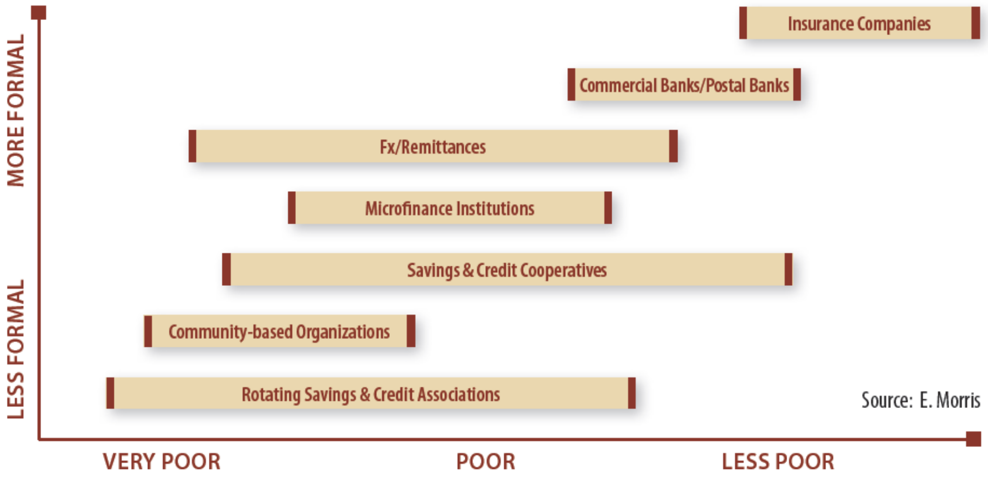


Figure 8.33: Financing options to provide energy services for the poor (based on experience in Burkina Faso, Kenya, Nepal and Tanzania) (UNDP 2009).

Access to energy services is not necessarily the main problem of the majority of the urban and peri-urban poor, but rather the ability to afford the services. Therefore, greater penetration of RE technologies will need to be accompanied by comprehensive energy policies and tariffs so as to enable these households to make use of RE.

Access to modern energy services is a challenge for many local governments and energy utilities. Brazil's electricity utilities invest about US$(2005) 80M annually in low-income, energy efficiency programmes, about half of their compulsory investments in end-use programmes under current regulations. A number of complex issues still need to be tackled including enforcing legal regulations, developing more creative and technical solutions to treat theft and fraud in services, and the improving the economic situation of poor populations living in a peri-urban setting.

Low-income energy efficiency and solar water heating programmes have been promoted. A number of programmes have replaced inefficient light bulbs and refrigerators, improved local distribution networks and maintained individual connections (including re-wiring of domestic installations). Modern and state-of-the-art technologies are leap-frogging in some peri-urban districts, including remote metering, real-time demand monitoring of households, more efficient transformers, new cabling systems and improved materials (ICA 2009).

A pilot case study in one "favela" in São Paulo reported the reduction of household electricity consumption from 250 kWh/month to 151 kWh/month and an internal rate of return on investment of 276% with a payback of only 1.36 years. The financial analysis assumed a reduction in commercial and technical losses and increased revenues for the utility due to a reduction in arrears and non-payments (ICA 2009).

Multi-family housing in China. Over 90% of the population in Chinese urban areas live in multi-family apartment buildings. The major energy reduction potential is in space heating consumption, water heating and lighting (Fig 8.34). Solar thermal is the major RE source utilized. Sub-metering, apartment-level controls within the building, and billing of individual apartments are key to small-scale RE deployment possibilities.

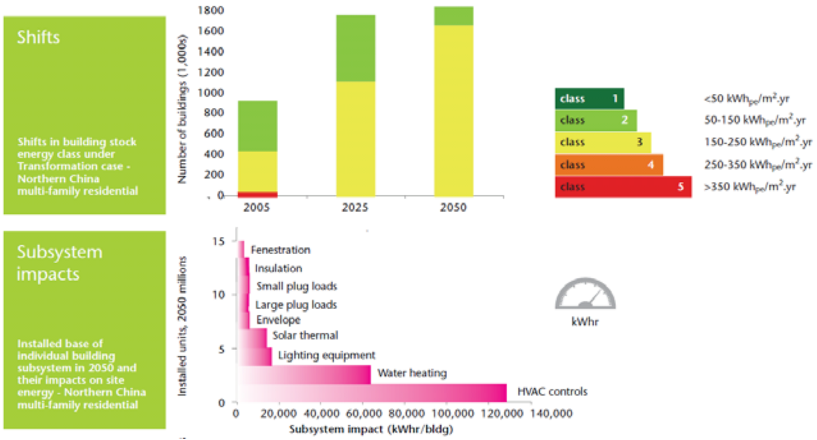


Figure 8.34: Possible trends in building stock energy classes from 2005 to 2050 and projected installations by 2050 of energy saving technologies and solar water heaters in multi-family houses in China (WBCSD 2009).

8.3.2.3 Rural settlements in developed countries

The energy consumption pattern in rural areas of developed countries does not differ a great deal from urban areas where good infrastructure exists. Modern forms of energy include electricity, natural gas, LPG and coal, however there is scope for more RE, particularly local, sustainably produced biomass for space heating.

8.3.2.3.1 Challenges of RE integration

Local RE sources can be captured to meet local energy demand but also any surplus energy can be exported and hence contribute to meeting the national demand. Finance and lack of awareness by landowners are among the key barriers to reaching this objective. Although financing might be available for some schemes (Fig. 8.33), obtaining up-front investment can be a hindrance to mobilising RE on a large scale. Institutional barriers, such as obtaining planning permission, often increase delays in implementing RE schemes, thus raising the transaction costs of integration.

8.3.2.3.2 Options to facilitate RE integration

Distribution companies with old, low voltage line networks near capacity can benefit from new distributed generation systems being installed near the demand to delay costly line-upgrading (see Case study, 8.3.4.5). Advanced bioenergy technologies for CHP systems can have a significant impact on the energy supply in countries such as Sweden and US where, as a result of increased biomass demand, the rate of afforestation has increased (Mabee and Saddler 2007). The following case study illustrates opportunities for RE deployment.

8.3.2.3.3 Case Study

Sustainable energy partnership and penetration of RE in rural England. The county of Cornwall, covering the rural peninsula in the south-west region of England, is pioneering partnerships for the delivery of energy initiatives. Because of its peripheral location, the region has limited access to natural gas pipelines but has sufficient solar, wind, marine, small hydro and biomass resources to meet the county's energy demand. In 2004, the Cornwall Sustainable Energy Partnership (CSEP) published the UK's first sub-regional sustainable energy strategy (EC 2004). The strategy's 32 point action plan aimed to support the use of natural resources, deliver local, national and international RE targets, incorporate greater energy efficiency and RE in buildings, and reduce carbon emissions (CSEP 2004). The "Energy in Buildings" group of the CSEP is the lead delivery partnership for this local area agreement (LAA).

Two years after the CSEP began, the installed capacity of RE technologies in domestic and community buildings tripled as a result of 6-fold increase in the number of RE systems installed in domestic and community buildings throughout Cornwall. As part of the LAA delivery plan, CSEP provided free technical and funding advice to developers, architects, housing associations, community groups etc. It facilitated distributed micro-generation installations in a number of social and private sector housing developments. The strategy commits the partnership to doubling Cornwall's current RE generating capacity to achieve a sub-regional target of at least 93 MW_e installed capacity by 2010.

8.3.2.4 Rural settlements in developing countries

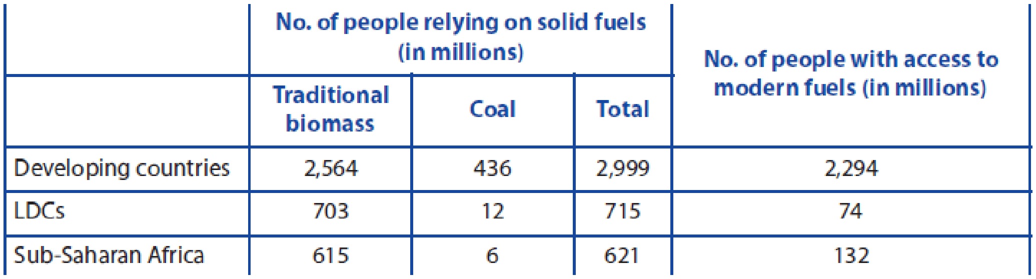
In several sub-Saharan Africa and many other developing countries, traditional biomass accounts for more than 75 % of primary energy. Rural households rely mainly on non-commercial crop residues, fuelwood and animal dung for their basic energy needs for cooking and heating. Unlike urban areas, the biomass can be collected locally, generally by women, from nearby woodlands and savannah lands. Although the daily time devoted to this chore has been increasing in some regions as the local biomass resources become diminished in a non-sustainable fashion, the illusion of a free commodity coupled with severe poverty makes it difficult to substitute firewood with modern energy forms or even to improve energy efficiency for cooking. Providing local plantations to be harvested sustainably (instead of from scavenging) is one solution, but not always easy to accomplish due to land ownership complexities and other social issues.

In 2005, 570 million cooking stoves used in rural areas had replaced very inefficient open fires, of which 220 million were improved stove designs (REN21 2006). Lighting demands can be met by kerosene lamps, torches and candles, all of which are expensive options. Only a tiny fraction of rural households in developing countries have access to modern energy services which is a major constraint to eradicating poverty and improving health, education, and social and economic development.

8.3.2.4.1 Challenges of RE integration

Around 2.6 billion people depend on traditional biomass (Table 8.7) including 89% of the population of sub-Saharan Africa. Around 1.6 billion people, mainly in rural areas, do not have access to electricity (Vijay, McDade et al. 2005). Resulting environmental impacts and future supply strategies vary depending on whether a region is rural, urban or peri-urban, and the key challenge for members of rural communities is to move up the energy ladder (Fig. 8.35)

Table 8.7: Number of people relying on solid and modern fuels (e.g. LPG, kerosene, biogas) for cooking in developing countries, least developed countries (LDCs) and sub-Saharan Africa (SSA) (UNDP 2009).



	No. of people relying on solid fuels (in millions)			No. of people with access to modern fuels (in millions)
	Traditional biomass	Coal	Total	
Developing countries	2,564	436	2,999	2,294
LDCs	703	12	715	74
Sub-Saharan Africa	615	6	621	132

Note: Based on UNDP classification of DC and LDCs, there are 50 LDCs and 45 SSA countries with 31 countries belonging to both categories.

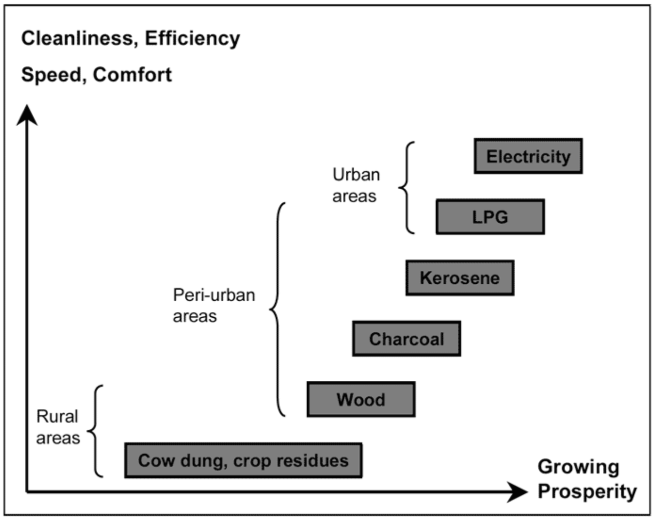


Figure 8.35: The “energy ladder” indicates how growing prosperity results from improved energy quality and energy availability (Mahamane, Lawali et al. 2009).

Some energy-poor may obtain electricity from the grid in the next few decades in some regions as extension of the distribution network reaches more peri-urban people currently without access to modern energy services. Obtaining sufficient funding for purchasing the power could be challenging, even if energy consumption remains limited to basic needs such as lighting, radio, and mobile phone recharging. If innovative finance mechanisms can be put in place (UNDP 2009), then the energy poor may better utilize local RE technologies as the least cost option available.

8.3.2.4.2 Options to facilitate RE integration

Although rural income is generally lower than urban income, there could be a market for RE for wealthier rural people, entrepreneurs and social institutions (churches, mosques). For example solar PV, micro-hydro power, and biogas could be developed locally on a sustainable basis to service rural communities, institutions and businesses who can afford to invest in such appropriate technologies. For the majority of rural people however, innovative and affordable delivery mechanisms need to be developed such as concessions coupled with subsidies and public private partnerships to increase energy access.

8.3.2.4.3 Case Study

RE in the Democratic Republic of Congo. The Congo Basin has the second largest tropical rainforest area in the world after the Amazon. The level of deforestation in absolute values is particularly high, particularly in the Democratic Republic of Congo (DRC) which is the largest and most populated country of the Congo Basin (Table 8.8). Paradoxically, despite the large hydro potential in the region, the rural electrification rate is extremely low at less than 1% of population per year (Fig. 8.36). The prospects to develop the micro- and mini- hydro potential of the region are therefore high which would dramatically increase the rural electrification rate and ultimately improve the livelihood of the energy poor rural people. In DR Congo alone, some 325 potential hydro schemes have been identified for which preliminary data have been gathered (Khennas, Sepp et al. 2009). The implementation of such a programme would dramatically increase the supply of RE for rural people to meet their needs for basic energy services and could also contribute to limiting deforestation around the villages.

Table 8.8: Annual deforestation rates in the Congo Basin countries between 1990 and 2000.

	Forest area[1] (*1000 ha)	**Gross deforestation[2] (% /year)**	**Net deforestation[2] (% /year)**
Cameroon	19 639	0.14	0.14
Equatorial Guinea	1 900	0.10	Not available
Gabon	22 069	0.09	0.09
Central African Republic	6 250	0.19	0.06
Republic of the Congo	22 263	0.07	0.02
DR Congo	108 359	0.21	0.20
Total Congo Basin	**180 480**	**0.19**	**0.10**

(1)(CBFP 2006) (2)(de Wasseige, Devers et al. 2009)

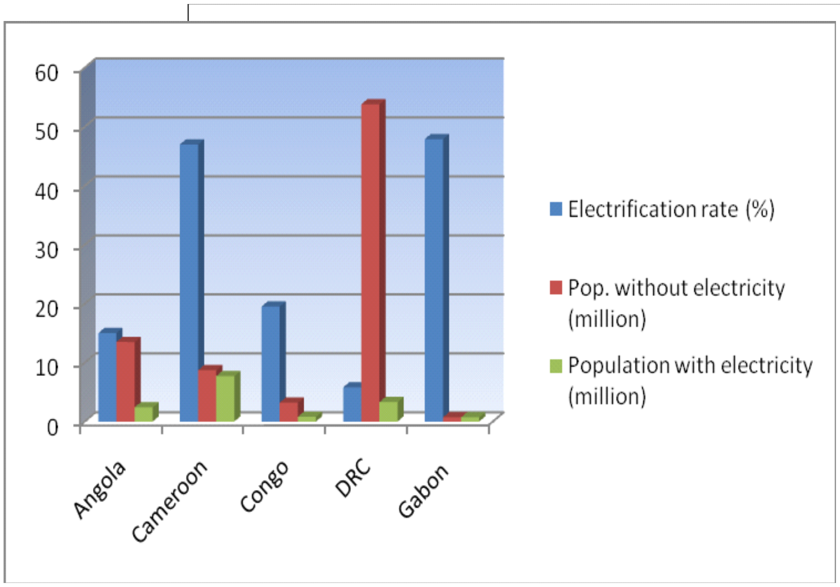


Figure 8.36: Electricity access in selected countries of the Congo Basin in 2005 (IEA 2006).

8.3.3 Industry

8.3.3.1 Introduction

Manufacturing industries account for about one-third of global energy use although the share differs markedly between individual countries. The industrial sector is highly diverse, ranging from very large, energy-intensive basic material industries to small and medium sized enterprises with light manufacturing. Perhaps 85% of industrial sector energy use is by energy-intensive industries: iron and steel, non-ferrous metals, chemicals and fertilizers, petroleum refining, minerals, and pulp and paper (Bernstein, Roy et al. 2007). The production of these industrial goods has grown strongly in the past 30-40 years and is projected to continue growing.

The sources of industry CO_2 emissions are direct and indirect use of fossil fuels, non-energy uses of fossil fuels in chemicals processing and production, and non-fossil sources such as CO_2 from calcium carbonate (CaCO3) in cement manufacturing. In most countries CO_2 accounts for more than 90% of industrial GHG emissions (Metz, Davidson et al. 2007). Direct and indirect CO_2 emissions in 2006 were 7.2 and 3.4 Gt respectively, together being equivalent to almost 40% of world energy and process CO_2 emissions (IEA 2009).

Carbon dioxide emissions from industry can be reduced by:

- energy efficiency measures to reduce internal energy use and, in some cases, make energy sources generated on-site available for sale (as waste heat, electricity and fuels);
- materials recycling to eliminate the energy-intensive primary conversion steps for many materials;
- RE integration and feedstock substitution to reduce the use of fossil fuels; and
- CCS of emissions from both fossil and biomass fuels.

All these measures are relevant for the issue of integrating RE into present and future energy systems. In addition, industry can provide demand-response facilities that are likely to achieve greater prominence in future electricity systems with more variable supply. The main opportunities for RE integration in industry include:

- Direct use of biomass derived fuels and residues for on-site biofuels, heat and CHP production and use (Ch. 2);
- Indirect use of RE through increased use of RE-based electricity, including electro-thermal processes;
- Indirect use of RE through other purchased RE-based energy carriers, e.g., liquid fuels, biogas, heat and hydrogen (section 8.2.3);
- Direct use of solar thermal energy for process heat and steam demands (Ch 3);
- Direct use of geothermal for process heat and steam demands (Ch 4).

Other RE sources may also find industrial applications (e.g., ocean energy for desalination, Ch 6). There are no severe technical limits to the increased direct and indirect use of RE in industry in the future. But integration in the short term may be limited by factors such as space constraints or demands for high reliability and continuous operation.

The current direct use of RE in industry is dominated by biomass in the pulp and paper, sugar and ethanol industries where biomass by-products are important sources of co-generated heat and electricity mainly used for the process. Biomass is also an important fuel for many SMEs such as brick-making, notably in developing countries. There is a growing interest in utilising waste and by-products for energy in, for example, the food industry through anaerobic digestion for biogas production. Waste and wastewater policies are important drivers for biogas production (Lantz, Svensson et al. 2007). Thus, industry is not only a potential user of RE but also a potential supplier of RE as a co-product. With the exception of biomass based industries the literature on RE in industry is relatively limited compared to the literature on RE in other sectors.

8.3.3.2 Energy-intensive industries

The largest contributions of CO_2 emissions in 2006 came from iron and steel (29%), cement (25%) and chemicals and petrochemicals (17%) (IEA 2009). The pulp and paper industry accounted for only about 2% of industrial CO_2 emissions but uses large amounts of biomass for process energy.

Iron and steel. Production of iron and steel involves ore preparation, coke making, and iron making in blast furnaces and basic oxygen furnaces to reduce the iron ore to iron. Primary energy inputs are 13 to 14 GJ/t from coal. Natural gas for direct reduction of iron-ore is also an established technology. Using electric-arc furnaces to recycle scrap steel, these energy-intensive steps can be by-passed and primary energy use reduced to around 4 - 6 GJ/t. However, the amount of scrap steel is limited and the increasing demand for primary steel is mainly met from iron ore.

Biomass, in the form of charcoal, was for a long time the main energy source for the iron and steel industry until coal and coke took over in the 1800s. During the production of charcoal, roughly one third of the wood energy content is converted to charcoal, the rest being released as gases but higher efficiencies are attainable (Rossilo-Calle, Bajay et al. 2000). Charcoal can provide the reducing agent in the production of iron in blast furnaces but coke has the advantage of higher heating value, purity and mechanical strength. Present day steel mills mostly rely entirely on fossil fuels and electricity and charcoal has not been able to compete, the exception being a few blast furnaces in Brazil.

Options for increasing the use of RE in the iron and steel industry in the near term include switching to renewable electricity in electric-arc furnaces and substituting coal and coke with charcoal, subject to resource and sustainability constraints. Switching to renewable methane is also an option. Research on electricity and hydrogen-based processes for reducing iron shows potential in the long term but CCS linked with coke combustion may be a less expensive option.

Cement. Production of cement involves extraction and grinding of limestone and heating to temperatures well above 950°C. Decomposition of calcium carbonate into calcium oxide takes place in a rotary kiln, driving off CO_2 in the process of producing the cement clinker. CO_2 emissions from this reaction account for slightly more than half of the total direct emissions with the remainder coming from combustion of fossil fuels. Hence, even a complete switch to RE fuels would reduce emissions by less than half.

The cement process is not particularly sensitive to the type of fuel but sufficiently high flame-temperatures are needed to heat the materials. Different types of waste, including used tyres, wood and plastics are already co-combusted in cement kilns. A variety of biomass-derived fuels can be used to displace fossil fuels. Large reductions of CO_2 emissions from carbonate-based feedstock are not possible without CCS, but emissions could also be reduced by using non-carbonate based feedstock (Phair 2006).

Chemicals and petrochemicals. This sector is large and highly diverse. High volume chemical manufacture of olefins and aromatics, methanol, and ammonia, account for more than 70% of total energy use in this sector (IEA 2008). The main feedstocks are oil, natural gas and coal, for providing the building blocks of products as well as for energy (Ren and Patel 2009). Chemicals such as ethanol and methanol may be considered both as fuels and as platform chemicals for products.

Steam-cracking is a key process step in the production of olefins and aromatics and various biomass fuels and waste could be used for steam production. Methanol production is mostly based on natural gas but it can also be produced from biomass or by reacting CO_2 with hydrogen of renewable origin.

The potential for shifting to renewable feedstocks in the chemicals sector is large (Hatti-Kaul, Törnvall et al. 2007). Many of the first man-made chemicals were derived from biomass through, for example, using ethanol as a platform chemical, before the shift was made to petrochemistry. A shift back to bio-based chemicals involves four principal approaches:

- Feedstock can be converted using industrial biotechnology processes such as fermentation or enzymatic conversions;
- Thermo-chemical conversion of biomass for the production of a range of chemicals, including methanol;
- Naturally occurring polymers and other compounds can be extracted by various means;
- Green biotechnology and plant breeding can be used to modify crops in non-food production.

Ammonia production in the fertilizer industry is an energy-intensive process which involves reacting hydrogen and nitrogen at high pressure. The energy embedded in fertilizer consumption represents about 1% of global energy demand (Ramirez and Worrell 2006). The nitrogen is obtained from air and the source of hydrogen is typically natural gas but also coal gasification, refinery gases and heavy oil products. Ammonia production gives a CO_2-rich stream and lends itself to CCS. Hydrogen from RE sources could also be used for the reaction and other nitrogen fixation processes are possible, including biological nitrogen fixation.

Forestry. The forest industry, including harvesting operations, saw mills, pulp and paper mills, and wood processing industries, handles large amounts of biomass. Residues and by-products to provide energy for internal use as well as for export are occurring all along the value chain. The internal use of biomass energy as a by-product means that the CO_2 intensity of the energy intensive pulp and paper industry is relatively low.

There are many different pulping processes but the two main routes are mechanical and chemical. With electricity-intensive mechanical pulping, wood chips are processed in large grinders and nearly all the wood ends up in the pulp which is used for paper such as newsprint. Heat is recovered from the mechanical pulping process and the steam produced is used for drying the paper and other processes. Chemical pulping is used to produce stronger high quality fibres and involves dissolving the lignin in a chemical cooking process. About half of the wood ends up in the spent pulping liquor that is concentrated in evaporators. The resulting black liquor is combusted in chemical recovery boilers and the bark component can also be combusted in separate boilers. The high pressure steam produced is used for CHP generation, enough to meet all the steam and electricity needs of a modern pulp mill.

Continuous incremental improvements in energy end-use efficiency, higher steam pressure in boilers, condensing steam turbines, etc., are reducing the need for purchased energy in the pulp and paper industry and can free up a portion of fuels, heat and electricity to be sold as co-products (Axegård, Backlund et al. 2002). Changing from the traditional recovery boiler to black liquor gasification in chemical pulping would increase the efficiency of energy recovery and facilitate higher electricity-to-heat ratios in the CHP system or the use of syngas for fuels production (see Case studies below) The main options for direct integration of RE is to replace fossil fuels in boilers, produce biogas from wastewater with high organic content, and switch from oil and gas to biomass, for example by using bark powder in lime kilns that produce calcium oxide for the preparation of pulping liquor.

Overall, possible pathways for increased use of RE vary between different industrial sub-sectors. Biomass can be co-fired with, or completely replace, fossil fuels in boilers, kilns and furnaces and there are alternatives for replacing petro-chemicals through switching to bio-based chemicals and materials. However, due to the scale of operations, access to sufficient volumes of biomass may be a constraint. Direct use of solar technologies is constrained for the same reason. For many energy-intensive processes an important future option is indirect integration of RE through switching to electricity and hydrogen. Electricity is also the main energy input for producing aluminium using the electro-chemical Hall-Héroult process. Assuming that CCS becomes an important element in future energy systems this will also be an option for energy-intensive industries, irrespective of whether the fuels used are of fossil or renewable origin.

The broad range of options for producing carbon neutral electricity and its versatility of use implies that electro-thermal processes could become more important in the future for replacing fuels in low (<200°C) and medium (200-400°C) temperature processes including drying, heating, curing, and melting. Plasma technologies can deliver heat at several thousand degrees Celsius and replace fuels in high temperature applications. Electro-thermal processes include heat pumps, electric boilers, electric ovens, resistive heating, electric arcs, plasma, induction, radio frequency and micro-waves, infrared and ultraviolet radiation, laser and electron beams (EPRI 2009). These technologies are presently used where they offer distinct advantages (such as primary energy savings, higher productivity or product quality), or where there are no viable alternatives (such as for electric-arc furnaces and aluminium smelters). Deployment has been limited since direct combustion of fossil fuels is generally less expensive than electricity. However, relative prices may change considerably under climate policies placing a value on carbon emissions.

Energy-intensive industries are typically capital intensive and the resulting long capital asset cycles constitute one of the main transition issues in this sector. Cyclical markets and periods of low profit margins are common in energy-intensive industries, and management focus is usually on cutting costs and sweating assets rather than on making investments and taking risks with new technologies. In existing plants, retrofit options may be constrained by, e.g., space limitations, risk aversion, and reliability requirements. Green-field investments mainly take place in developing countries where enabling energy and climate policies are less common than in developed countries. However, energy-intensive industries are also generally given favourable treatment in developed countries that have ambitious climate policies since they are subject to international competition and resulting risks of carbon leakage. Exemptions from energy and carbon tax, or free allocation of emission permits in trading schemes, are prevalent. But industries using biomass, such as the pulp and paper industry, can also benefit from and respond to RE policy (Ericsson, Nilsson et al. 2010). Sectoral approaches are considered in international climate policy in order to reduce carbon leakage risks and facilitate technology transfer and financing of mitigation measures (Schmidt, Helme et al. 2008).

8.3.3.2.1 Case studies

Black liquor gasification for bio-DME production. Black liquor gasification as an alternative to chemical recovery boilers is a technology that has been subject to R&D for more than 20 years and has also been demonstrated in a few pilot plants. The syngas produced (mainly CO and H_2) can be used with high efficiency in combined cycles for CHP or for the production of biofuels via, for example, the Fischer-Tropsch process (section 8.2.4). A pilot plant, the first one with pressurised gasification, for producing DME (di-methyl ether) is expected to begin production in Piteå, Sweden, in August 2010 with a capacity of about 4t/day. The plant, with financial support from the Swedish Government and the European Commission, involves companies Chemrec, Haldor Topsoe, Volvo, Preem, Total, Delphi and ETC. Compared to gasification of solid biomass, one advantage of black liquor is that it is easier to feed to a pressurised gasifier. Depending on the overall plant energy balance and layout there are often process integration advantages and potential for significant increases in energy efficiency. Energy which is tapped off for liquid or gaseous biofuels production (including DME) can be compensated for by using lower quality biomass for meeting pulp and paper process energy demands. In addition to DME production, the project also involves four filling stations and 14 DME trucks to study the viability of bio-DME as a fuel for heavy trucks.

Demand response in industry Industrial peak load shifting as a form of load management is an important measure to facilitate a greater uptake of variable RE generation in power systems (section 8.2.1). It can also reduce the need for high marginal cost generation, offer low cost system balancing and decrease grid reinforcement investment. The concept is already widely used to secure enough reserve- and peaking-capacity in many countries and is expected to become more important in the future. Existing programmes have mainly focused on industrial users that can shed relatively large loads through rescheduling, machinery interruption, thermal energy storage, cool stores, reducing demand response times, interruptible electric boilers, etc. Typically, industries are contracted to reduce or shut down load, sometimes remotely by the transmission system operator, according to pre-defined rules and against various means of financial compensation. For industry, reduced production and risks of process equipment failure associated with demand response are important considerations. Estimates of the potential depend on the level of industrial manageable power demand. According to one study the potential for demand response in the energy-intensive industries of Finland is 1280 MW, equivalent to 9% of total peak demand (Torriti, Hassan et al. 2010).

8.3.3.3 Other non-energy intensive industry

Non-energy intensive industries, although numerous, account for a smaller share of total energy use than energy-intensive industries but, are more flexible and offer greater opportunities for the integration of RE. They include food processing, textiles, light manufacturing of appliances and electronics, automotive assembly plants, wood processing, etc. Much of the energy demand in these industries is for installations similar to energy use in commercial buildings such as lighting, space heating, cooling and ventilation and office equipment. Most industrial heating and cooling demands are for moderate temperature ranges which facilitate the application of solar thermal energy, geothermal energy and solar-powered cooling systems with absorption chillers (IEA 2007; Schnitzer, Brunner et al. 2007). Solar thermal collector capacity in operation world wide in 2007 was almost 150 GW but less than 1% is in industrial applications (IEA-SHC 2010).

Process energy use is typically for low and medium temperature heating, cooling, washing, cooking pumping and air-handling, coating, drying and dehydration, curing, grinding, preheating, concentration, pasteurization and sterilization, and some chemical reactions. In addition, a range of mechanical operations use electric motors and compressed air to power tools and other equipment. Plants range in size from very small enterprises to large-scale assembly plants and sugar mills.

Many companies use hot water and steam for processes at temperatures between 50 and 120°C. When fossil fuels are used, installations that provide the heat are mostly run at temperatures between 120 and 180°C to enable the use of smaller heat exchangers and heating networks, since heat exchanger areas can be smaller with higher temperatures in process heat supply. Solar energy will therefore possibly focus more on engineering designs for operating at lower temperatures in order to optimise the whole system. For temperatures < 80°C, thermal collectors are on the market, but there is limited experience for applications that require temperatures up to 250°C (Schnitzer, Brunner et al. 2007). Such higher temperatures are possible using heat pumps or, in appropriate areas, concentrating solar thermal systems

Industrial electro-technologies can save primary energy by using electricity. Industrial CO_2 emissions can be reduced even if there are no primary energy savings, assuming electricity from RE resources replaces or saves fossil fuel-based thermal generation. Examples include freeze concentration instead of the thermal process of evaporation; dielectric heating (radio frequency and microwave heating) for drying; polymerisation; and powder coatings with infra-red ovens for curing instead of solvent-based coatings and conventional convection ovens (Eurelectric 2004). Other advantages include quick process start up, better process control, and higher productivity (EPRI 2009). The conventional wisdom that high quality (high exergy) electricity should not be used for low quality (low exergy) thermal applications may be challenged in a future decarbonised electricity system.

RE is most widely used in the food and fibre processing industries where on-site biomass residues are commonly used to meet internal energy needs, exported for use elsewhere, or constitute a waste disposal problem. Bio-based industries often provide opportunity for utilising residues that are normally left after harvest of the feedstock or generated on-site during processing. For cane-based sugar and ethanol production, the mills are typically self-sufficient or net sellers of energy from using the waste bagasse as fuel. Historically bagasse (the fibre remaining after crushing sugar cane for juice extraction), was combusted inefficiently to dispose of it whilst producing just enough heat and power for use on-site. For ethanol plants in Brazil the surplus electricity sold to the grid is expected to increase from about 9 to 135 kWh/t of cane between 2005/2006 and 2020 as a result of increasing steam pressure and higher rates of residue recovery (Macedo, Seabra et al. 2008).

In other food and fibre processing industries, wastewater with high organic content could be used for biogas production but currently is poorly utilized. In many developing countries, substantial amounts of crop residues in the form of husks, straw and shells from nuts, coffee, coconuts, rice, etc. can be used for heat and power generation. These residues are low cost and often used as fuel to supply heat for local industries together with fuelwood and charcoal. In developed countries, waste policies are an important factor driving the increased utilisation of biomass residues for energy.

Bio-based industries such as pulp and paper and the sugar/ethanol industries, as well as other process industries, generate waste heat that can be used in other industries and in district heating systems. Industrial ecology and symbiosis are relatively new concepts used to denote such inter-firm exchanges of energy, water, by-products etc. although these are not new phenomena. Greenhouses and fish-farming are also potential users of low-grade heat. An inventory of the Swedish forest industry found several examples of such inter-firm exchanges, but typically between different entities within the same company group (Wolf and Petersson 2007). The potential for increased indirect use of RE in such innovative way is difficult to estimate.

Dehydration of agricultural and other products is an important application of solar energy. In many developing countries the traditional method of dehydration in open air may result in food contamination, nutritional deterioration and large product losses. Solar dryer technologies that improve product quality and reduce drying times have been demonstrated. Examples include a solar tunnel dryer for hot chilli (Hossain and Bala 2007) and a solar dryer with thermal storage and biomass backup heater for pineapple (Madhlopa and Ngwalo 2007).

Geothermal energy could meet many process heat demands in industry at temperatures, or elevated by heat pumps to higher temperatures. Almost 500 MW of geothermal capacity, equivalent to about 4 % of worldwide direct applications of geothermal energy, is currently used for industrial process heat (Lund 2005). Current utilisation is only about 10 PJ with applications in dairies, laundries, leather tanning, beverages, and a paper mill in New Zealand. The potential is very large (see Chapter 4) and high capacity factors relative to solar thermal energy make it an attractive alternative for industry.

The potential for increasing the direct use of RE in industry is poorly understood due to the complexity and diversity of industry, and varying geographical and climatic conditions. Aggregate mitigation cost estimates cannot be made for similar reasons. Improved utilisation of processing residues in biomass-based industries and substituting for fossil fuels offer near-term opportunities. Solar thermal technologies are promising but further development of collectors, thermal storage, back-up systems and process adaptation and integration is needed. Increased use of energy carriers such as electricity and natural gas, that are clean and convenient at the point of end-use, is a general trend in industry. Indirect integration using electricity generated from RE sources, and facilitated through electro-technologies, may therefore have a large impact in the near and long-term. Direct use of RE in industry has difficulty competing at present due to the relatively low fossil fuel prices and low- or zero-energy and carbon taxes for industry. RE support policies in different countries tend to focus more on the energy, transport and building sectors than on industry and consequently potentials are relatively un-charted.

8.3.3.3.1 Case studies

Sugar industry and CHP. Limited grid access and low prices offered by monopoly-buyers of electricity and independent power producers have provided disincentives for many industries to increase overall energy efficiency and electricity-to-heat ratios in CHP production. Process electricity consumption in sugar and sugar/ethanol mills for example is typically in the range of 20-30/ kWh per tonne of fresh cane. Most mills have been designed to be self-sufficient in heat and electricity using mainly bagasse as a fuel in low pressure boilers. With high pressure boilers and condensing extraction steam turbines, more than 100 kWh/t can be produced for export. However sugar/ethanol mills provide opportunity for integrating a much higher level of biomass for energy in industry. The sugarcane tops and leaves are normally burned before harvest or left in the field after harvest. These could also be collected and brought to the mill to increase the potential export of electricity to more than 150 kWh/t. This could be further increased to over 300 kWh/t using gasification technology and combined cycles or supercritical steam cycles (Larson et al., 2001). Integrating the utilisation of biomass residues with sugar/ethanol mills and feedstock logistics offer cost and other advantages over separate handling and conversion of the residues.

Solar industrial process heat for industry. There is good potential to use solar heat for industrial processes. In 2003, the net industrial heat demand in Europe was estimated to be 8.7 EJ and the electricity demand was 4.4 EJ (Werner 2006). Heat demands were estimated in 2003 at low, medium and high temperature levels for several industries in EU 25 plus four accession countries, and three European Free Trade Association countries (Fig. 8.37). (The figure was created from German industry experiences that were applied to the IEA database for the target area). Industrial process heat accounted for around 28% of total primary energy consumption with more than half of this demand for temperatures below 400°C. This could be a suitable application for solar thermal energy (Vannoni, Battisti et al. 2008).

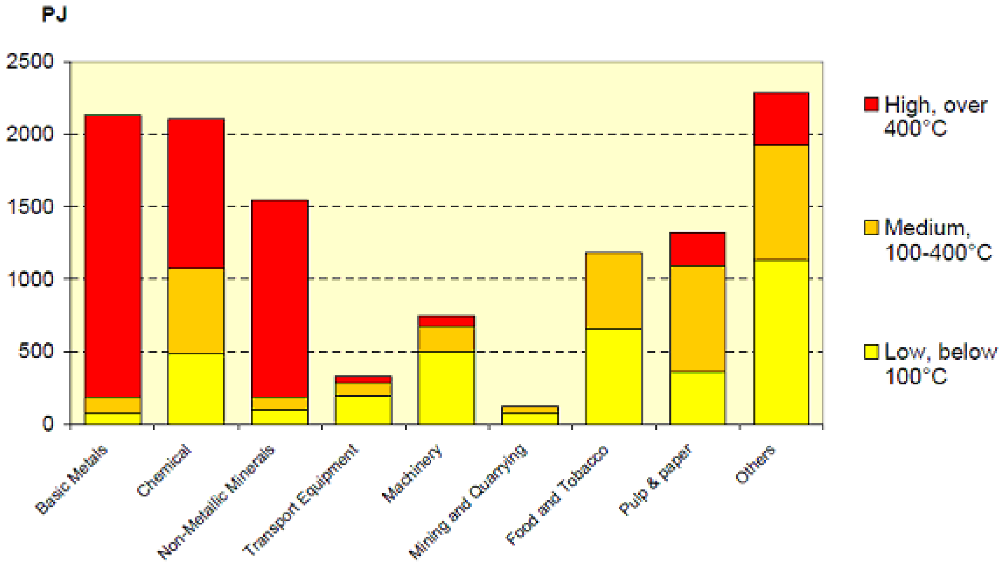


Figure 8.37: Industrial heat demands by temperature quality and by manufacturing sector for 32 European countries (Werner 2006).

Solar thermal energy technologies can be used to supply industrial heat including concentrating solar thermal systems that can produce steam directly in the collector. A pilot plant installed in Ennepetal, Germany in February 2007, the P3 project, aims to demonstrate direct steam generation in small parabolic trough collectors for industrial applications (Hennecke, Hirsch et al. 2008). The principal options for the integration of solar steam (Fig. 8.38) are:

- solar augmentation of the drying process;
- direct solar steam supply to individual consumers in the new production line; and
- solar steam integration into the existing steam distribution network. In this configuration the solar steam can feed directly into the production line by means of an over-pressure valve (>4 bar). The feed water to the solar steam generator is provided from the industrial steam system. Condensate from the solar system can be returned by the condensate line of the existing system. The feed water pump for the solar field is controlled by temperature measurement in the steam drum that is operated at a constant pressure of about 4.3 bar.

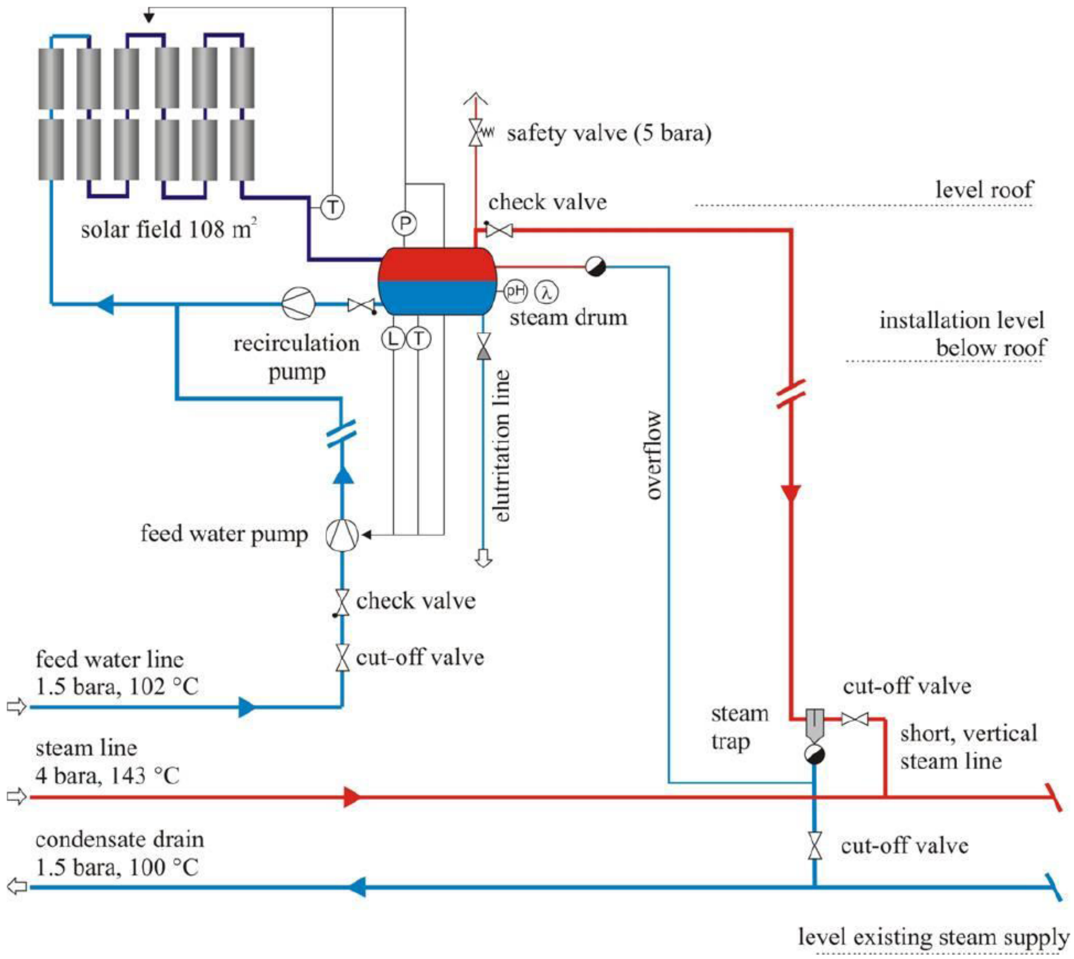


Figure 8.38: Layout of a direct solar steam integration system to be integrated at the ALANOD factory, Ennepetal, Germany (Hennecke, Hirsch et al. 2008).

8.3.4 Agriculture, forestry and fishing

There is complex relationship between primary production, energy inputs, water and land use including soil carbon, biodiversity, landscape and recreation. Large regional differences occur due to climate, seasons, weather patterns, terrain, soil types, precipitation, cultural practices, land use history and ownership, and farm management methods (extensive subsistence and low input (organic) farming or intensive, high input, industrialised farming).

Subsistence farming and fishing rely largely on human energy and animal power with traditional biomass from crop residues and fuelwood used for drying and heating applications (section 8.3.1.2). In contrast industrialised agriculture, forest and fishing industries depend on significant fossil fuel energy inputs that are either combusted:

- directly for heating, drying and to power boats, tractors and machinery, or
- indirectly to manufacture fertilisers and agri-chemicals; produce and transport imported feed; construct buildings and fences; and generate electricity for water pumping, lighting, cooling and operating fixed equipment.

Intensive agriculture as undertaken in USA typically uses on-farm twice as much energy directly as indirectly (Schnepf 2004), though this varies with the enterprise type. For some food products such as potatoes, the total energy inputs can exceed the food energy value of the harvested crop (as shown by a negative energy ratio of energy output/energy input) (Haj Seyed Hadi 2006). However this varies depending on the local farm management, the boundaries used and assumptions made, hence a positive energy ratio for potatoes has also been reported in Iran (Mohammadi, Tabatabaeefar et al. 2008).

In OECD countries, energy demand for the agriculture sector is typically around 5% of total consumer energy. Energy efficiency measures are being implemented and future opportunities exist to reduce fertiliser and agri-chemical inputs by using precision farming application methods (USDA 2009), improved manufacturing techniques and organic farming systems.

Primary producers can have a dual role as an energy user and as a supplier of energy carriers produced as co-products (Table 8.9)[18]. Landowners also have access to local RE resources including wind, solar radiation, potential and kinetic energy in rivers and streams and geothermal heat depending on land use, terrain and location.

Currently land use and land use change (agriculture and forests) accounts for around 30% of total greenhouse gas emissions (Metz, Davidson et al. 2007). CO_2 arises from fossil fuel energy inputs but most GHGs stem from deforestation, methane from ruminant digestion and paddy fields, and nitrous oxides from wastes and nitrogenous fertiliser use. Competition for land use to provide food, fibre, animal feed, recreation, biodiversity conservation forests, as well as energy crops is growing. Water use constraints, sustainable production and energy developments including biofuel production are under close scrutiny (Park 2008).

Rich multi-national corporate organisations and food importing countries such as Saudi Arabia, South Korea, Kuwait and Qatar have negotiated investments with governments of poor countries for between 15 to 20 M ha of land from 2006 to 2009. Their aim is to grow, manage and export food such as wheat, rice and maize, but also to produce crops for biofuel exports (Von Braun and Meizen-Dick 2009). Deals being quoted include China securing the right to grow palm oil for biofuel on 2.8M ha in the Democratic Republic of the Congo and also negotiating 2M ha in Zambia, South Korea investing in Madagascar, and Sun Biofuels UK, a private company, growing jatropha plantations for biodiesel oil in Ethiopia and Mozambique. Investments can either cause exploitation of the existing rural communities (WWICS 2010) or provide benefits when the advantages are equally shared, such as Brazilian sugar ethanol companies investing in Ghana (REW 2008).

A code of good conduct to share benefits, abide by national trade policies and respect customary rights of the family farm unit is being considered.

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[18] Note this section covers only on-farm and in-forest production and processing activities including harvest and post-harvest operations up to the farm gate. Food, fibre processing operations are covered in the Industry section 8.3.3.

Table 8.9: Primary production from industrial scale enterprises showing energy demand, energy use intensity (GJ/ha of land or buildings), RE carriers produced mainly for use on-farm and their potential for export across the farm boundary.

Type of enterprise	Direct energy inputs	Energy use intensity	Potential renewable energy carriers	Energy export potential
Dairying	Electricity for milking facility, pumping of water and manure, refrigeration. Diesel for tractor. Diesel or electricity for irrigation.	High. Medium. High if for irrigation.	Manure for biogas. Heat from milk cooling. Solar water heating. Solar PV.	Limited as most used on-site.
Pastoral grazing animals (e.g. sheep, beef, deer, goat, llama)	Electricity for shearing. Diesel.	Very low but higher if irrigated. Low or medium if some pasture conserved.	Hill sites for wind turbines. Hydro power options. Solar systems on buildings. Green crops for biogas.	Wind power. Biogas CHP (combined heat and power).
Beef-lot, intensive production	Electricity for lighting, cooling, water pumping. Diesel for tractor.	Medium. High for harvesting feed.	Manure for biogas CHP. Solar PV and/or solar thermal if roof space available.	Limited as used on-site.
Pigs	Electricity for lighting, heating, cleaning.	High if housed indoors. Medium if kept outdoors.	Manure for biogas. Solar if roof space available.	Limited as used on-site.
Poultry	Electricity for lighting, heating, cleaning.	High if housed indoors. Low if free-ranging.	Combustion of litter for CHP. Solar systems.	High. Several multi-MW power plants operating in UK, US.
Arable (e.g. wheat, maize, rapeseed, palm oil, cotton, sugarcane, rice etc.).	Diesel. Electricity for storage facilities, conveyor motors, irrigation. Gas or LPG for drying.	Very high for machinery. Medium if rainfed. High if irrigated. Low and seasonal.	Crop residues for heat, power and possibly biofuels. Energy crops. Hydro power if streams suitable.	High where energy crops are purpose-grown.
Vegetables large scale (potatoes, onions, carrots, etc.)	Diesel. Electricity for grading, conveying irrigation, cooling.	High for machinery. High if irrigated and for post-harvest chillers.	Dry residues for combustion. Wet residues for biogas.	Limited if used on site.
Market garden - vegetables small scale (mixture)	Diesel for machinery. Electricity for washing, grading.	Medium. Low for post-harvest. Medium if cool-stores.	Some residues and rejects for biogas but usually too small a resource for on-site use.	Low.

Nursery cropping	Diesel for machinery. Heat for protected houses.	Low. Medium.	Some residues and rejects for combustion.	Low.
Greenhouse production	Electricity for ventilation, lighting. Gas, oil, or biomass for heat.	High where heated. Medium if unheated.	Small volumes of residues and rejects for combustion.	Low.
Orchard (pip fruit, olives, bananas, pineapple etc.)	Diesel for machinery. Electricity for grading, drip irrigation, cool-store etc.	Medium. Medium if irrigated and post-harvest storage.	Prunings for heat. Reject fruit for biogas.	Low.
Forest plantations (eucalyptus, spruce, pine, palm oil, etc)	Diesel for planting, pruning and harvesting.	Low.	Forest residues. Short rotation forest crops. Spent oil palm bunches.	High – large volumes of biomass for CHP or possibly for biofuels.
Fishing – large trawlers off-shore	Marine diesel/fuel oil. Electricity for refrigeration.	High.	(Reject fish dumped at sea).	None.
Fish farm – near-shore or on-shore.	Diesel for boats for servicing. Electricity for refrigeration.	Low or medium if facilities off-shore. Medium.	Fish wastes for biogas and oil. Ocean energy.	Low. Electricity from ocean energy possible in future.
Fishing – small boats near-shore.	Diesel/gasoline. Electricity for ice or refrigeration.	Low. Low.	Fish wastes for biogas and oil.	Low.

8.3.4.1 Status and strategies

The integration of land use with the development of RE projects for electricity generation is well established. For example, wind farms constructed on pasture and crop lands provide multi-purpose land use and additional revenue to the landowner since only 2 to 3% of the total land area is taken out of agricultural production for access roads, turbine foundations and control centre buildings. Similar opportunities exist for small and large hydropower projects (although social disbenefits for local residents can also exist – see Chapter 9). Many sites in Europe and elsewhere that used to house water mills could be utilised for run-of-river micro-hydro power generation schemes and low head turbines have been developed for operating in low gradient water distribution channels to power irrigation pumps (EECA 2008).

Solar thermal systems have been commonly used for water heating but solar sorption technologies for air-conditioning, refrigeration, ice making, and post-harvest chilling of fresh products remain at the development stage (Fan, Luo et al. 2007). Geothermal heat has been used for various thermal applications including for heating greenhouses, heating water for fish and prawn farming (Lund 2002), desiccation of fruit and vegetables, heating animal livestock houses and drying timber.

Biomass resources produced in forests and on farms are commonly used to meet local agricultural and rural community energy demands. Although many examples exist, developing a bioenergy project can be challenging in terms of securing biomass feedstock for the long term, ensuring it is sustainably produced, storing it for all-year-round use with minimal losses, transporting it cost-effectively due to its relatively low energy density compared with fossil fuels, recycling nutrients and obtaining planning consents (IEA 2007).

Anaerobic digestion of animal manures, food and fibre processing wastes, or green crops to produce biogas is a well understood technology (Chapter 2). Gas storage is costly, so matching supply with demand is a challenge for the system designer. The odourless, digested solid residues can be used for soil conditioning and nutrient replenishment. Fish processing residues can also be utilised, though they tend to be dried and ground for animal feed or fertilisers. On-farm use of biogas for heat, or CHP using gas engines, is common practice. A less common application is as a transport fuel similar to compressed natural gas (CNG).

Dry crop residues produced during processing are in effect delivered free-on-site. Rice husks, coconut shells etc. are easily stored and commonly combusted at the small scale for heat generation or at a larger scale for CHP. Bagasse (fibrous residues from sugarcane), at around 50% moisture content (wet basis), has traditionally been combusted inefficiently to provide sufficient heat and power to supply the refinery but mainly to avoid a costly disposal problem. Privatisation of the electricity industry in many countries has enabled sugar plant owners to invest in more efficient CHP plants that generate excess power for export. Partly drying the bagasse with available heat to give more efficient combustion, and with reduced air pollutant emissions, could be warranted (Shanmukharadhya and Sudhakar 2007).

Cereal straw or forest residues have to be collected and transported as a separate operation following the harvest of the primary product (grain or timber). Due to the additional costs involved, techniques for integrated harvesting of these co-products have been developed such as whole crop harvesting with later separation, or whole tree extraction to a landing where the tree is processed into various products (Heikkilä, Laitila et al. 2006).

8.3.4.2 Pathways for renewable energy adoption

Much cultivated land could simultaneously be used for RE supply, in many cases best utilising the energy on the property to displace imported energy needed to run the enterprise (Table 8.9). Fish enterprises may be able to utilise local waves or ocean currents for power generation opportunities in the future (Chapter 6). Market drivers for RE power generation on rural land, coastlines and waterways include electrification of rural areas, energy security and the avoidance of transmission line capacity upgrading where loads are increasing.

Little surplus land is available for bringing into cultivation in most countries and further deforestation is not an acceptable option. Therefore to meet the growing demands for primary products including biomass, increasing productivity of existing arable, pastoral and plantation forest lands by improving management and selecting higher yielding varieties is one option. (Changing diets to eat less animal products is another). Through these actions, average yields of staple crops have continued to increase over the past few decades (Fig. 8.39) though with variations between regions. This trend could continue over the next few decades, with genetically modified crops possibly having a positive influence. Conversely, global warming trends have possibly already offset some of the productivity gains expected from technological advances (Lobell and Field 2007).

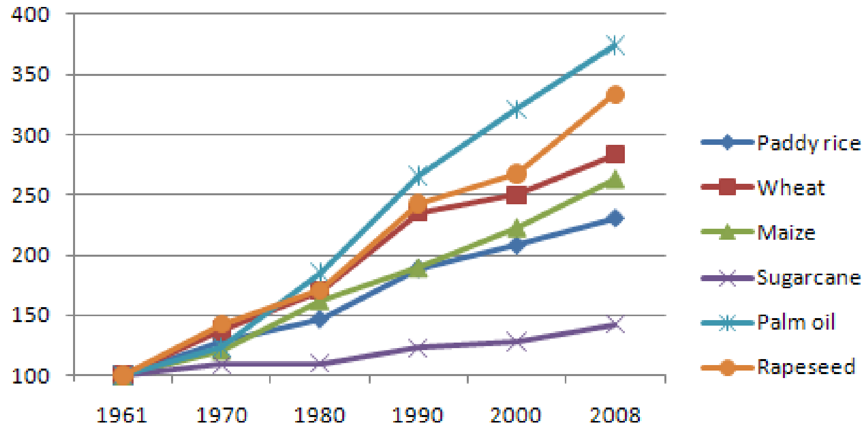


Figure 8.39: Increased productivity per hectare for a range of crops over the past few decades compared with base year 1961 (FAO 2009).

8.3.4.3 Transition issues

The primary production sector is making a slow transition to reducing its dependence on energy inputs as well as to better using its naturally endowed, RE sources. Multi-uses of land for agriculture and energy purposes is increasing but the share of the total potential being utilised at present is miniscule. Barriers to greater deployment include high capital costs, lack of available financing, remoteness from energy demand (including access to electricity and gas grids), competition for land use, transport constraints, water supply limitations, and lack of skills and knowledge by landowners.

8.3.4.4 Future trends

Distributed energy systems based on RE technologies are beginning to gain support in cities (IEA 2009) but also have large potential in rural areas. The concept could also be applied to produce mini-power distribution grids in rural communities in developing countries where electricity services are not yet available.

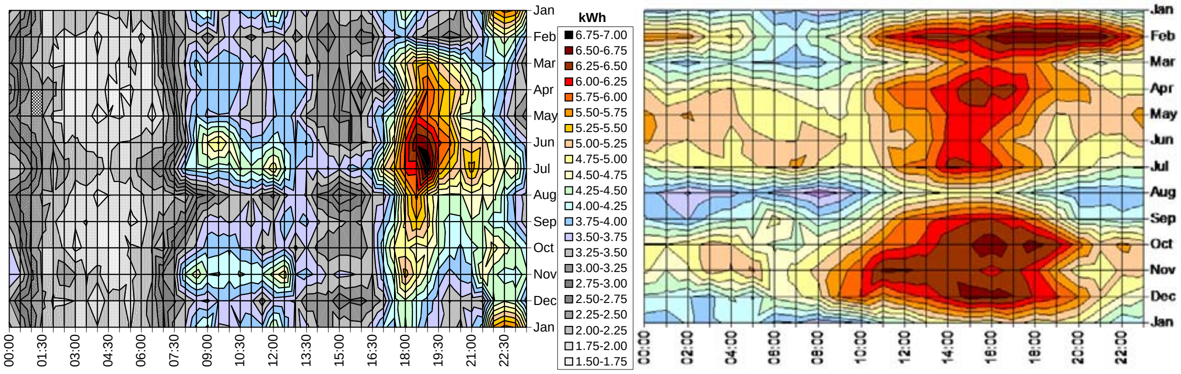
A future opportunity for the agricultural sector is the concept of carbon sequestration in the soil as “bio-char” (Lehmann 2007). When produced via gasification or pyrolysis using the controlled oxygen combustion of sustainably produced biomass, incorporation of the residual char into arable soils is claimed to enhance future plant growth and the carbon is removed from the atmosphere (Verheijen, Diafas et al. 2010). Further RD&D is required to assess soil suitability, impacts on crops yields, methods of pulverisation and integration but the future integration potential, once proven, could be significant

8.3.4.5 Case study

Distributed generation in a rural community. Distributed energy systems for rural communities can provide climate change mitigation benefits, lead to sustainable development, give increased security of supply and provide revenue to landowners. A small demonstration project at Totara Valley, New Zealand aims to:

- demonstrate a methodology for local energy resources to be easily identified and utilised to meet local demands for heat and power in order to provide economic and social benefits;
- identify new business opportunities for power distribution companies and circumvent the commercial challenge of having to supply their more remote customers; and
- solve the technical problems of supplying heat and power to multi-users from several small generation sites within a given locality using RE resources wherever feasible.

Electricity meters at strategic locations measured demands of the appliances used in the woolsheds, houses, workshops, freezer sheds etc. (Murray 2005) and enabled a series of electricity profiles to be produced showing both seasonal and daily variations (Figure 8.40). The wind speed and solar radiation resources were monitored and a method developed to show seasonal and daily variations.



(a) (b)

Figure 8.40: Average seasonal and daily electricity demand for the Totara Valley community households in kWh consumption per 30 minute periods (a) with annual and daily wind data (b) showing a reasonable match with the demand (Murray 2005).

A 2.2kW wind turbine was installed on the best hill site, but due to the cost of 1.5km of copper cabling being around 2005 US$ 13,000 it is used to power an electrolyser (Sudol 2009) with the hydrogen produced piped down to a fuel cell with storage and transfer losses of only around 1%. A 1kW Pelton micro-hydro turbine was installed. Since wind and solar are variable and not all properties have a reliable stream with micro-hydro potential, matching power supply with continually varying demand is difficult and often requires some form of storage if not being grid-connected as in this example. Suitable controls and smart metering systems will help integrate various generation technologies between users and the local grid, and enable metering of both imported and exported power to be achieved (Gardiner, Pilbrow et al. 2008).

A power distribution company could have a strong business interest in becoming a joint venture partner in such a scheme, to buy and sell electricity but also to sell or lease the power generation equipment to the community members. A related study from the line company perspective (Jayamaha 2003), modelled different scales of communities in detail (Figure 8.41) to show benefits arise from having larger communities.

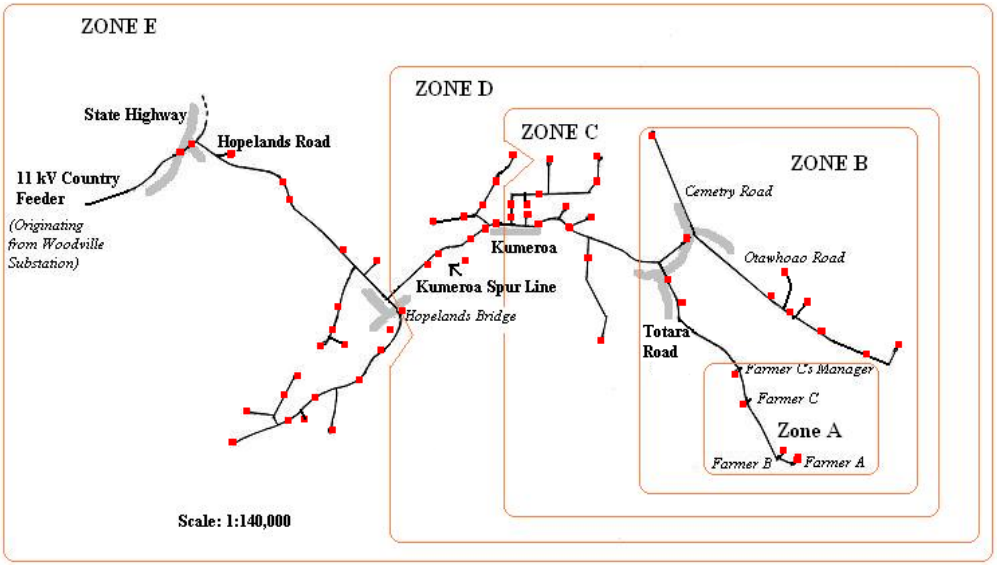


Figure 8.41: The power distribution feeder reaching Totara Valley (Zone A) is the end of the line. House and other building clusters with power loads are shown as red squares. The larger the scale of community using their local RE resources (Zones A, B, C, D or E), the greater economic benefits of the system (Jayamaha 2003).

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 9

Renewable Energy in the Context of Sustainable Development

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	LAs:	John Christensen, Junichi Fujino, Monirul Mirza, Hugh Rudnick, August Schlaepfer, Andrey B Shmakin			
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Yellow highlighted – original chapter text to which comments are referenced

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Chapter 9 has been allocated a total of 68 pages in the SRREN. The actual chapter length (excluding references & cover page) is 72 pages including the Appendix, a total of 4 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened in terms of text and/or figures and tables.

All monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to US$ for the base year 2005

Chapter 9: Renewable Energy in the Context of Sustainable Development

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EXECUTIVE SUMMARY

Development is a concept frequently associated with economic growth, still in many cases disregarding income distribution, physical limits from the environment and the external costs of impacts caused by some and borne by others. Climate change is one of these most relevant impacts, with externalities present at global level.

Sustainable Development (SD) is a relatively recent concept, aiming to consider such impacts. There are several definitions of SD, but probably the most important came up in 1987, with an influential report published by the United Nations, entitled “Our Common Future” (or “The Brundtland Report”). In this publication, sustainable development is a principle to be pursued, in order to meet the needs of the present without compromising the ability of future generations to meet their own needs. The report recognized that poverty is one of the main causes of environmental degradation and that equitable economic development is a key to addressing environmental problems.

Energy for sustainable development has three major pillars: (1) more efficient use of energy, especially at the point of end-use, (2) increased utilization of renewable energy, and (3) accelerated development and deployment of new and more efficient energy technologies. The questions of renewable and sustainable energy have their roots in two distinct issues: while renewability is a response to concerns about the depletion of primary energy sources (such as fossil fuels), sustainability is a response to environmental degradation of the planet and leaving a legacy to future generations of a reduced quality of life. Both issues now figure prominently on the political agendas of all levels of government and international relations.

Much of the discourses on SD have historically focused on economic and environmental dimensions of renewable energy technologies and their implementation. Social and institutional dimensions have not received the same degree of attention. With growing interest in the two-way relationship between SD and renewable energy, the latter two dimensions need to be given the same level of importance. The use of renewable energy technologies can significantly reduce GHG emissions and some technologies have ancillary or co-benefits that will reduce local pollution and improve health benefits.

The reverse relationship whereby development that is sustainable can create conditions in which mitigation through the use of renewables can be effectively pursued is equally important and needs to be highlighted in future development pathways. Most development pathways already focus on SD goals such as poverty alleviation, water and food security, access to energy, reliable infrastructure, etc. How to make these pathways more sustainable such that GHG emissions are reduced is critically important for permitting an increased role for renewable energy technologies.

Access to, and affordability of, modern forms of energy, especially electricity for all purposes and clean fuels for cooking, heating, lighting and transportation to the billions of people without them today and in the future is a major challenge in itself. Wide disparities within and among developing countries contribute to social instability and affect basic human development. Making the joint achievement of promoting access while simultaneously making a transition to a cleaner and secure energy future is a challenging task.

Energy services can play a variety of direct and indirect roles in helping to achieve the millennium development goals - MDGs. They can halve extreme poverty (e.g. providing more jobs), reduce hunger (through improved agriculture, for example), increase access to safe drinking water, allow lighting that permits home study, increase security, among others. Moreover, efficient use of energy sources and good management can help to achieve sustainable use of natural resources and reduce deforestation (UNDP, 2004).

Renewable energy technologies are ones that consume primary energy resources that are not subject to depletion. Renewable energy resources have also some problematic but often solvable technical and economic challenges, like not fully accessible, sometimes temporally and regionally variable and not cost competitive. In addition to the direct SD implications of renewable energy, it is important to assess their life-cycle impacts. The latter can significantly influence the selection choice among competing renewable technologies.

From the policy perspective, the main attractions of renewable energy are their security of supply, and the fact that they are environmentally relatively benign compared to fossil fuels. Most forms of renewable energy, such as hydro, wind, solar and biomass, are available within the borders of one country and are not subject to disruption by international political events. (Reword using Tom's paragraph)

9.1 Introduction

Development is a concept frequently associated with economic growth, still in many cases disregarding income distribution, physical limits from the environment and the external costs of impacts caused by some and borne by others. Climate change is one of these most relevant impacts, with externalities present at global level.

Sustainable Development (SD) is a relatively recent concept, aiming to consider such impacts. There are several definitions of SD, but probably the most important came up in 1987, with an influential report published by the United Nations, entitled "Our Common Future" (or "The Brundtland Report"). In this publication, sustainable development is a principle to be pursued, in order to meet the needs of the present without compromising the ability of future generations to meet their own needs. The report recognized that poverty is one of the main causes of environmental degradation and that equitable economic development is a key to addressing environmental problems. The report also emphasized the issue of the legacy that the present generation is leaving for future generations.

The concept of sustainable development (SD) has its roots in the idea of a sustainable society (Brown, 1981) and in the management of renewable and non-renewable resources. The World Commission on Environment and Development adopted the concept and launched sustainability into political, public and academic discourses. The concept was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bojo, Maler, and Unemo, 1992; WCED, 1987).

While there are many definitions of sustainable development, the international sustainability discourse is helping to establish some commonly held principles of sustainable development. These include, for instance, the welfare of future generations, the maintenance of essential biophysical life support systems, ecosystem wellbeing, more universal participation in development processes and decision-making, and the achievement of an acceptable standard of human well-being (WCED, 1987; Meadowcroft, 1997; Swart, Robinson, and Cohen, 2003; MA, 2005).

Since the early 1960´s, the SD concept has grown out of concerns about a declining quality of the environment coupled with increasing needs for resources as populations expand and living standards rise. Early initiatives focused more on individual attributes of the environment, including water quality, air quality, management of hazardous substances and cultural resources. Some of the outcomes from the initiatives included a complex array of regulations intended to manage and improve development, a movement toward recycling of consumable resources and an emphasis on renewable energy as a substitute for energy production that consumed resources (Frey and Linke, 2002). While the initiatives taken regionally had many positive effects, it soon became evident that there were global environmental issues that needed to be addressed as well.

A significant event to the SD movement was the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil, in 1992, when the United Nations Framework Convention on Climate Change (UNFCCC) was proposed, seeking to stabilize atmospheric concentrations of greenhouse gases at considered safe levels. In 1997, the 3rd Conference of the Parties (COP) to the UNFCCC resulted in the Kyoto Protocol, a multilateral environmental agreement (MEA) aiming to curb worldwide emissions.

The discussion of sustainable development in the IPCC process has evolved since the First Assessment Report which focused on the technology and cost-effectiveness of mitigation activities, to the Second Assessment Report (SAR) that included issues related to equity and to environmental (Hourcade et al., 2001) and social considerations (IPCC, 1996). The Third Assessment Report (TAR) further broadened the treatment of SD by addressing issues related to global sustainability and the Fourth Assessment (AR4) included chapters on SD in both WG II and III reports with a focus on a review of both climate-first and development-first literature. The SRREN report will also serve as a good starting point for the Fifth Assessment (AR5) report.

In light of this background, every chapter of this WGIII SRREN focuses to some extent on its links to sustainable development practices. Chapter 1 introduces the concept, Chapters 2 to 7 cover the environmental and other implications of bioenergy, direct solar energy, geothermal, hydropower, ocean and wind energy, and Chapters 8, 10, and 11 focus on integration, costs and benefits, and policy respectively.

This chapter focuses on aspects of sustainable development that are not covered in depth in the other chapters, and as an integrative chapter it compares and reports the SD impacts of multiple technologies. The impacts include environmental and socio-economic aspects for many of which only qualitative information is available. The chapter begins by highlighting the two-way relationship between SD and renewable energy in Section 9.1. The discussion focuses on the interaction between SD and renewable energy in Section 9.2, on impacts of renewables on the socio-environment aspects in Section 9.3, and on socio-economic aspects in Section 9.4. Section 9.5 describes the implications of sustainable development pathways on renewables and finally Section 9.6 focuses on selected policy implications.

9.1.1 The Two-way Relationship between Sustainable Development and Renewables

Economic and social development has always depended on energy services for comfort (e.g., space heating and cooling), convenience (e.g., food storage and cooking), mobility (e.g., motive power), and productivity (e.g., power for operating tools). Throughout most of human history, these services have been provided by renewable energy sources such as biomass, hydropower, wind, and passive solar energy because they were the only alternatives at hand; but over the past several centuries industrial economies and societies have transformed landscapes and the quality of life by exploiting non-renewable fossil energy sources or other non-traditional sources such as nuclear energy.

In most respects, consumers of energy services are focused on whether those essential services are abundant, reliable, and affordable – not on where the energy comes from. In many industrial societies, in fact, energy is viewed not as a commodity but as an entitlement (Aronson, 1984), and governments are considered responsible for meeting this fundamental human need, along with health, education, opportunity for self development, food, shelter, and safety. When more energy services are considered essential for sustainable development, getting more energy can be a higher priority than carbon emissions or other indirect effects associated with choices among energy sources. In other words, whether the energy source is renewable or not is not always the most important issue under a development perspective.

Central issues for renewable energy in the modern context include all three of the dimensions of energy services for development:

- Abundance. Among currently available renewable energy technologies large-hydro has shown significant penetration in many regions. However, in many other regions where current renewable energy niches in either electricity production or transportation fuels are low, increasing them to significantly higher levels is a profound challenge to scalability because of the magnitude of the needs. Clearly, Brazil stands out as a sizeable economy built to a considerable degree on hydropower, plus significant attention to biofuels but realistic near-term trajectories toward that kind of energy mix for other large countries remain elusive. Meanwhile, some smaller countries and regions are becoming laboratories for pursuing more ambitious goals, such as Denmark's goal of increasing its share of wind power as an electricity source.

- Reliability. Many renewable energy sources are based on continual energy sources, such as water flow or plant growth, but some are based on intermittent energy sources, such as solar radiation or wind. Where the sources are intermittent, the only ways that they can meet continuing needs for energy services are by energy storage, improved grid integration and management, and/or by using other energy sources as supplements, each of which tends to increase costs and reduce net benefits.
- Affordability. Energy costs are a complex issue for renewable energy. At a local scale, in many cases renewable energy options offer a prospect of reduced energy costs. In applications such as rural lighting, solar lanterns that replace kerosene lamps are cost effective particularly where kerosene is subsidized. But for larger-scale energy needs for development, fossil energy sources – or intermediate sources dependent on them -- are considerably less expensive at present (except for select hydro and wind power sources). Achieving grid parity through rapid reduction in costs of renewable technologies is a oft-noted aim in many regions that are pursuing targeted goals for RE penetration.

Renewable energy applications are essential to deliver genuine results on Millennium Development Goals and all five World Summit on Sustainable Development 2002 (WSSD) components:

- water: sustaining communities and industry without waste or pollution;
- energy: generated from clean, renewable sources;
- health: ensuring clean water, air and sanitation;
- agriculture: renewable base with sustainable forms of irrigation;
- biodiversity: elimination of habitat destruction, such as energy poverty induced deforestation practices, or water depletion and contamination in fossil and nuclear power generation.

Making development more sustainable recognizes that there are many ways in which societies balance the economic, social, environmental, and institutional aspects, including climate change, dimensions of sustainable development. It also admits the possibility of conflict and trade-offs between measures that advance one aspect of sustainable development while harming another (Munasinghe, 2000). For a development path to be sustainable over a long period, however, wealth, resources, and opportunity must be shared so that all citizens have access to minimum standards of security, human rights, and social benefits, such as food, health, education, shelter, and opportunity for self-development (Reed, 1996).

The earlier chapters (mainly Chapters 2-7) provide an overview of the impacts of the implementation of many renewable technologies and practices that are being or may be deployed at various scales in the world. In this chapter, the information from the sectoral chapters is summarised and supplemented with findings from the sustainable development literature.

Synergies with local sustainable development goals, conditions for their successful implementation, and tradeoffs where the climate mitigation and local sustainable development may be at odds with each other are discussed. In addition, the implications of policy instruments on sustainable development goals are described in Section 9.5 and 9.6. As documented in the sectoral chapters, renewables options often have positive effects on aspects of sustainability, but may not always be sustainable with respect to all three dimensions of SD -- economic, environmental and social. In some cases the positive effects on sustainability are more indirect, because they are the results of side-effects of reducing GHG-emissions such as through the use of biofuels. Therefore, it is not always possible to assess the net outcome of the various effects.

The sustainable development benefits of renewable energy options will vary across sectors and regions. Tables 2 and 3 describe the positive and negative impacts of renewables, fossil fuels ands nuclear energy technologies on a variety of selected SD indicators. Appendix A provides more detailed information on the content in these tables. Generally, options that improve productivity of resource use, whether it is energy, water, or land, yield positive benefits across all three dimensions of sustainable development. More efficient and environmentally friendly use of bio energy can enhance productivity and promote social harmony and gender equity by reducing strain on humans and the natural environment. Other categories of options have a more uncertain impact and depend on the wider socioeconomic context within which the option is being implemented. A finite amount of land area is available for bioenergy crops, for instance, which limits the amount of fuel that can be produced and the carbon emissions that can be offset.

In the sectoral discussion below we focus on the three aspects of sustainable development – environmental, and economic and social (Section 9.3). Environmental impacts include those occurring in local areas on air, water, and land, including the loss of biodiversity, human health and the built environment. Virtually all forms of renewable energy supply demand land and/or water resources, and cause some level of environmental damage. The emission of greenhouse gases (GHG) is often directly related to the emissions of other pollutants, either airborne, e.g. particulates from burning biomass which causes local or indoor air pollution, or waterborne, e.g., from leaching of nitrates from fertilizer application in intensive bioenergy cropping.

Economic implications include costs and overall welfare. Sectoral costs of various mitigation policies have been widely studied and a range of cost estimates are reported for each sector at both the global and country-specific levels in the sectoral chapters and in Chapter 10. Yet mitigation costs are just one part of the broader economic impacts of SD. Other impacts include growth and distribution of income, employment and availability of jobs, government fiscal budgets, and competitiveness of the economy or sector within a globalizing market. The social dimension includes issues such as gender equality, governance, equitable income distribution, housing and education opportunity, health impacts, and corruption. Most renewable energy options will impact one or more of these issues, and both benefits and tradeoffs are likely.

In addition to the above renewable energy impacts on sustainable development, the implications of the pursuit of SD pathways on renewable energy are equally important. The pursuit of rural development in all countries for example has been accelerated through the process of electrification. In the modern era, renewable energy sources such as the use of solar lanterns as a substitute for kerosene-fuelled lamps offers a low-pollution technology with significant health benefits. Similarly the increased demand for water can be facilitated through the use of biogas-driven electric pumps.

Climate change is one of the most important global environmental challenge facing humanity with implications for food production, natural ecosystems, fresh water supply, and health. It is projected to lead to temperature increases as high as 6 degrees C by 2100 (IPCC and SRES, 2000) [TSU: reference will be corrected] and cause changes in regional and severity of precipitation patterns, sea level rise and flooding, regional temperature increases, and wind storms. Since all the renewable energy sources are directly connected to one or more of the above natural parameters, their energy output will be affected either through an impact on the infrastructure and energy source, or through a change in operating parameters. The impact of sea level rise on hydro power sources and biomass is probably the most studied among the renewable sources because of the impact on land and water is easier to estimate than the change in wind patterns and regimes.

While renewable energy sources may be affected by climate change impacts they can also be used as adaptation strategies. Micro grids using PV technologies for instance can serve as a means of electricity in cyclone shelters and after hurricanes and earthquakes.

9.1.2 Energy Indicators of Sustainable Development

To make implementation more sustainable, indicators can help to monitor progress towards sustainable development, and identify where improvements need to be made. There are many different ways to classify indicators of sustainable development (Sathaye et al., 2007). In 1995 United Nations Department of Economic and Social Affairs (UNDESA) began working to produce an overall set of indicators for sustainable development and concluded with a package of 58 indicators, of which only 3 energy related: annual energy consumption per capita, intensity of energy use and share of consumption of renewable energy resources. At the 2002 WSSD, the International Atomic Energy Agency (IAEA) presented a partnership initiative, in cooperation with UNDESA, the International Energy Agency (IEA), the Statistical Office of the European Communities (Eurostat) and the European Environment Agency (EEA), defining a set of 30 energy indicators and corresponding guidelines and methodologies to be used worldwide by countries in tracking their progress toward nationally defined sustainable energy development goals. These are based on seven themes that include equity, health, use and production patterns, security, air, water and land themes. Most of the social and environmental trends can be clearly identified as being desirable or undesirable, but it is not possible to provide a black-and-white evaluation of the economic ones. The development of sustainability criteria requires the analysis of local conditions and, for the formulation of what is to be considered sustainable, the involvement of local stakeholders. According to the field of activities, different organizations have developed sustainability criteria and tools, e.g. International Labour Organization (ILO) for acceptable labor conditions, the WWF for ecological aspects, the Worldbank for financial results; the OECD and the UN for development policymaking and information (Lewandowski and Faaij, 2006).

Measurement and reporting of indicators is thus a critical aspect of the implementation of sound renewable energy technologies. Measurement not only gauges but also spurs the implementation of sustainable development and can have a pervasive effect on decision-making (Meadows, 1998; Bossel, 1999). In the subsequent sections, we make use of some of the relevant indicators provided by the IAEA in reporting the relative sustainable development synergies and tradeoffs of various renewable energy options.

9.1.3 Barriers and Opportunities

There are several key barriers that prevent the more rapid introduction of renewable energy technologies into the energy market. These include (1) high first cost of renewable technologies, (2) lack of accounting of externalities of conventional generation, (3) lack of data and information about resources, (4) challenge of integrating renewable energy technologies into the electricity grid, (5) susbsidies for conventional supplies, and (6) lack of storage facilities. These barriers are already noted and discussed in previous chapters. In addition, there are several SD barriers that limit the introduction and scale of RE technologies. These include (1) access to land resources, (2) population displacement, (3) water pollution, (4) ecosystem and biodiversity, (5) human health, (6) built environment and (7) inadequate capacity to build and monitor performance of renewables.

These barriers have limited the introduction or expansion of RE technologies in many countries (Appendix A). Land use for bioenergy may compete with food supply, and geothermal generation can lead to land subsidence. Displacement of population from large-hydro reservoirs is limiting the expansion of this source of power. Water usage for crops and fertilizer nitrate pollution from bioenergy sources has been documented as an important issue (see Section 9.3.4). Indoor pollution from biomass use, nuisance effects from wind mills, and toxic waste from manufacturing PV, potential infrastructure damage due to inundation act as additional barriers to RE expansion. There are also strong concerns such as gender equity in rural areas in developing countries, which have largely been ignored to date but may act as a barrier in the future. As in the case of non-SD barriers there are many ways to overcome or minimize the SD barriers as well.

Ultimately capacity building is a key barrier to the rapid transfer of technologies across and within countries. Lack of capacity to set RE policies and design and implement programs delays and sometimes negates implementation of renewable technologies. Within countries, lack of maintenance in rural areas prevents adoption or limits the scale up of commercially available technologies.

9.2 Interactions between sustainable development and renewable energies

9.2.1 Sustainable Development Links to Renewable Energy Options

Some of the most relevant SD goals are described in Appendix A: poverty reduction; water security; sanitation; food security; energy security; energy access; energy affordability; infrastructure; governance; land use and rural development. Compared to conventional fossil fuels, nuclear energy and large hydros – which have overall highly concentrated and capital-intensive production, transformation and distribution chains - renewables have an important role in rural development. Relatively simple systems such as solar panels, improved cookstoves or micro hydro plants can provide the necessary lighting, heat or electricity to pump water, prepare food, refrigerate vaccines and medicines, and allow education during the night period. Local pollution and health benefits are improved.

There is a need to substitute human energy for modern energy systems that will reduce drudgery and increase wellbeing. Energy poverty is a perennial problem in many developing countries. Modern energy systems are generally considered as a key input for socio-economic development and reduction of poverty (Barnett, 1999). The availability of energy services affect women and men differently (Clancy, Operaocha, and Ulrike, 2004). Women tend to shoulder the disproportionate burden of the current fuel crisis. Women expend long hours on laborious household chores due to the lack of efficient energy systems. Cooking with firewood, cow dung, agricultural residue, twigs or old plastic buckets make up desperate choices in the absence of efficient and clean sources of energy. Women and their children tend to suffer ill health as a result of cooking in confined spaces and resulting from the adverse effects of polluting fuels. The opportunity costs of trekking long distances in the search of fuelwood and spending long hours on food processing is often done at the expense of leisure or income generating activities.

Renewable energy technologies such as wind pumps can enhance agricultural practice and increase food security thus improving the socio-economic status of women and men, but particularly women who constitute the bulk of the active agricultural labour force in developing countries. Renewable technologies and effective energy interventions in rural areas can help widen energy access in agricultural activities since the bulk of agricultural production is energy-dependent. One reason for the inability of agriculture to lift rural populations out of the poverty trap is lack of access to efficient forms of energy since energy power is essential in every aspect of the food chain and agricultural development (water pumping, irrigation, cultivation of seedbeds, post-harvesting food processing, etc.). However whilst the potential value of renewable to reduce current drudgery particularly amongst social groups such as women is well known – the real benefits accrued from using renewable are not evenly distributed. Biogas systems have in some cases increased women's load because of the daily need for water and dung addition which often needs to be headloaded. (Denton, 2002). Attempts need to be made to address such constraints including those faced with the use of solar cookers in some parts of Africa (Gitonga, 1999). For women to benefit even more from renewable energy technologies, more efforts need to be made on a pricing level to allow women to expand their energy choice and thus have the purchasing power to cater for a range of energy services that meet their needs.

In some cases, there are also impacts associated with these technologies and they– as shown in Appendix A – also may have limited number of years of use if grid electricity arrives at a cheaper price in the future. These multiple benefits of the increased use of renewable energy technologies, which in general are coupled with efficient end use devices, are environmental protection; reduction of indoor pollution; promotion of energy security through decentralization and source diversification; job creation and income generating activities through the use of local resources; improving the quality of waste management systems (like landfills for gas); reduction on the dependence of oil imports; relieving pressure on the balance of payments.

The 2002 WSSD´s Johannesburg Plan of Implementation reflects a growing interest in renewables and addresses as well the problems of social exclusion and poverty eradication. A large number of people in the rural areas in developing countries have no access to commercial energy due to the lack of purchasing power or for other reasons. In order to survive, these people depend on non-commercial sources of energy, mainly fuelwood, manure and agricultural waste that can be obtained at a negligible monetary cost. In many of these countries, non-commercial energy corresponds to a significant share of the total primary energy consumption.

9.2.2 Past and present roles of renewable energy for development

Developing countries have in their energy matrices a very significant share of biomass, of which a fair part may be notoriously neither renewable nor “sustainable” since it comes from deforestation. About 2 billion people in the world rely on fuelwood and other primitive solid fuels for their basic needs. If each person were to use kerosene, 50 kg a year would be necessary, which would represent 100 Mtoe of oil or about 3 per cent of the world’s consumption of this fuel (Goldemberg, 2002). Clearly, this does not represent a resource limitation.

An intrinsic characteristic of a dual society in developing countries is the fact that the elite and the poor differ fundamentally in their energy uses. The elite try to mimic the lifestyle prevailing in industrialized countries and have similar luxury-oriented energy standards. In contrast, the poor are more concerned on obtaining enough energy for cooking and for other essential activities. For the poor, development means satisfying basic human needs, including access to employment, food, health services, education, housing, running water, sewage treatment, etc. The lack of access to these services by most people is a fertile ground for political unrest and hopelessness that leads to emigration to industrialized countries in search of a better future.

A large part of the energy for agriculture, transportation and domestic activities in poorer developing countries comes from the muscular effort of human beings and from draught animals. Other sources include biomass in the form of fuelwood, animal and agricultural waste. Fuelwood is actually the dominant source of energy in rural areas, especially for cooking. In rural areas, women and children usually pick up wood sticks as fuel to cook instead of buying wood. A basic level is the fulfilment of basic human needs, which may vary with climate, culture, region, period of time, age and gender. There is not a single level of basic needs, but a hierarchy of them. There are needs that have to be supplied for survival, such as a minimum of food, of dwelling and protection against fatal illnesses. The satisfaction of a greater level of needs such as basic education makes ‘productive survival’ possible. Even higher levels of needs such as trips and leisure emerge when people try to improve their quality of life beyond ‘productive survival’. Obviously, the needs perceived as basic vary according to the conditions of life in any society.

Negative aspects include environmental impacts, such as resources depletion, inputs usage (e.g. water), contaminating emissions (to air, water, soils), toxic wastes and risks of accidents. Another topic is the competition with food for land, a controversial issue due to its relation to biodiversity protection, to the distribution of goods and different aspects of international trade. Also to mention are geopolitical disputes and international security (case of weapon proliferation). Impact assessment implies consideration to life cycle approaches that are described in Section 9.3, where different boundaries and functional units may consider indirect impacts. Cost analyses also differ, according to the considered parameters (such as discount rate or indirect costs).

9.2.3 Human settlement and energy access

Historically, access to energy sources has had a significant effect on human settlement patterns. For instance, the world's population map reflects the importance of the seas for ocean transport, along with the importance of rivers for both transport and local hydropower for milling and industrial production. In the fossil fuel era, areas accessible to coal and oil sources (and to the wealth that they enabled) had comparative advantages for regional and urban growth, and in some cases this feeds opposition to major changes in energy sources.

A different dimension of this issue, however, is access to energy services in places where people already live, rather than where they may choose to locate. In this regard, the current issues tend to divide between concerns about energy access in rural settlements and in urban settlements:

- <u>Rural settlements</u>. Rural electrification to promote development (and reduce pressures for rural to urban migration) has been a development priority for many decades. In most cases, the preferred approach has been to combine local renewable resource endowments (such as solar radiation or biomass) with institutional innovations. For instance, a notable early success was the successful deployment of solar cells in rural villages in the Dominican Republic in the 1980s, led by Richard Hanson and Enersol Associates (Hanson, 1988; Waddle and Perlack, 1992). Some initiatives such as the UNEP Global Clean Energy Network and the Global Village Energy Partnership reinforced the need for sustained attention to rural energy (World Bank, 1996). For cooking and heating, systems such as improved stoves are ways of utilizing solid biomass with more efficiency and less pollution (MacCarty et al., 2008).

- <u>Urban settlements</u>. In many urban areas in developing countries, the major energy access issues are (a) the lack of reliability of electricity supply and (b) air pollution associated with local industrial, transportation, and energy production, which affect rich and poor alike. But even where it is generally available, the poor often lack ready, affordable access to electricity, as urban electricity supply institutions emphasize supplies to relatively large customers who can pay. In many cases, especially the poor use traditional renewable energy sources such as wood or charcoal for cooking and heating and passive solar energy for food preservation as the only affordable options, but urban wood and charcoal consumption often poses threats to the sustainability of regional biomass energy supply capacities when it is obtained at the expenses of deforestation (Naughton-Treves, Kammen, and Chapmand, 2007; Girard, 2002).

Box 9.1. The importance of access to energy

Access to modern forms of energy, especially electricity for all purposes and clean fuels for cooking, heating and lighting to the 2 billion people without them -- and the additional 3 billion people projected to increase world population by 2020 -- is a major challenge in itself. Wide disparities within and among developing countries contribute to social instability and affects basic human development. Making the joint achievement of promoting access while simultaneously making a transition to a cleaner and secure energy future is a challenging task. Key policy areas to be addressed include the impact of energy reform programmes (including private sector investment) on the poor, the excessive focus on upstream investment and large-scale fossil energy supply projects, the lack of appropriate institutional structures to support international energy and development programmes, research and development not being sufficiently relevant to policy, and the lack of funding to support major infrastructure investments. Energy sector reform, particularly in the electricity sector, has become a priority of the multilateral institutions involved in energy and development, and is having a profound impact on access (**Johansson** and Turkenburg, 2004; **Spalding-Fecher**, Winkler, and Mwakasonda, 2005).

Energy services can play a variety of direct and indirect roles in helping to achieve the millennium development goals (MDGs), in order to halve extreme poverty; to reduce hunger and improve access to safe drinking water; to reduce child and maternal mortality and to reduce diseases; to achieve universal primary education and to promote gender equality and empowerment of women and to ensure environmental sustainability. Access to energy services facilitates economic development – micro-enterprise, livelihood activities beyond daylight hours, locally-owned businesses, which will create employment – and assists in bridging the “digital divide”. Energy services can improve access to pumped drinking water – clean water and cooked food reduce hunger (95 % of food needs cooking). Energy is a key component of a functioning health system, for example, operating theatres, refrigeration of vaccines and other medicines, lighting, sterile equipment and transport to health clinics. Energy services reduce the time spent by women and children (especially girls) on basic survival activities (gathering firewood, fetching water, cooking, etc.). Lighting permits home study, increases security and enables the use of educational media and communications in schools (including information and communication technologies, or ICTs). Improved energy services help to reduce emissions, protecting the local and global environment. Moreover, efficient use of energy sources and good management can help to achieve sustainable use of natural resources and reduce deforestation (Goldemberg, 2002).

9.2.4 The scale of action and prospects for closing the development gap

Where renewable energy can be developed and implemented at a relatively small scale and accessible technological level, it may offer potentials for relatively rapid improvement in social and economic well-being through sound government policies. Compared with large-scale electricity generation or liquid fuel production, for example, renewable energy sources can open up opportunities for local innovation (e.g., (Kamkwamba and Mealer, 2009)) and enable local technology production and business development/job creation (e.g., (Lovins, 2002); + refs to China’s growth in solar energy). Moreover, renewable energy technology deployment can deliver improvements quickly when it is coupled with effective local institutions. For instance, the 2009 Zayed Future Energy Prize was awarded to Dipal Chandra Barua, Director of Grameen Shakti, for that institution’s successes in bringing solar PV electricity and biogas to rural populations in

Bangladesh, linked with local micro-credit programs (www.gshakti.org). [TSU: info on websites needs to be provided in footnotes]

A cautionary note, however, is that local energy resource-technology actions can in some cases have cumulative effects at larger scales that some stakeholders consider undesirable, such as effects of local bioenergy developments on biosphere protection

9.2.5 Energy security as an aspect of sustainable development

Where reliability of energy services is important to sustainable development, which is nearly always the case, economic and social threats to that reliability particularly from external sources – including threats of sudden spikes in energy prices – are an important concern. Many developing regions, for example, still recall the effects of the oil crisis of the 1970s on their development, their well-being, and even their landscapes as biomass cover disappeared for tens of kilometres around cities, and more recent reports suggest that developing countries have become more vulnerable to external shocks than at that time (World Bank, 2008). One of the most attractive features of increasing the use of local renewable energy sources, especially if local populations either control or share in the control of the use of those sources, is that it decreases risks that external factors may introduce disruptive supply shortages or price increases, often very suddenly.

9.3 Social, Environmental and Economic Impacts: Global and Regional Assessment [TSU: this has been changed from the original title 'Environmental impacts: global and regional assessment' and needs to be approved by IPCC Plenary]

9.3.1 Introduction: An overview of social, environmental and economic impacts

Development and exploitation of renewable energy has become increasingly important in the past three decades. In recent years, greenhouse gas abatement policies and the need for climate change mitigation and meeting increasing energy requirements have led to a rise in the development of renewable energy sources. In this section, we report on the social, environmental, and economic impacts of renewable energy sources. The following Table 1 provides a qualitative summary of the information available on the use of resources and the impact of different renewable technologies on the social and environmental impacts. For comparison purposes, conventional fossil fuel and nuclear technologies are also included. The subsequent Table 2 provides a similar summary of the social and economic impacts. The material presented in Table 1 is described in more detail in subsequent Sub-sections 9.3.2 to 9.3.7 in which environmental impacts of renewable energy sources on land, water, air, ecosystems and biodiversity, human health and built environment are discussed.

Since the economic impacts are also covered in earlier chapters and in the cost chapter (Chapter 10), this chapter does not provide their detailed description. The information in both Tables 1 and 2 is derived from the larger table in Appendix A.

9.3.1.1 Environmental and Social Impacts (Table 1)

Renewable energy technologies are relatively cleaner in terms of GHG emissions and environmental pollution than fossil energy sources. Apart from hydropower, windpower (White, 2007) and bioenergy (Blanco-Canqui and Lal, 2009; Liska et al., 2009; Luo, van der Voet, and Huppes, 2009), literature on the impacts of other renewables such as direct solar, geothermal and ocean energy sources on environment is rather limited.

Both positive and adverse environmental and social impacts exist for each of the RE technologies. There are options to mitigate their adverse impacts, making such technologies sustainable and preferable in comparison with conventional energy sources.

RE technologies have many ***similar*** positive environmental and social impacts that make them attractive compared to their fossil and nuclear counterparts. However, the adverse environmental and social issues that affect their deployment and limit development opportunities are more ***technology-specific*** and in some cases ***site specific.*** There are mitigative options for the adverse impacts and their implementation can improve and in many cases ensure sustainability of the technologies. Details of the most significant environmental and social impact topics, positive and negative, are shown in Table 1.

Land use and population*:* Renewable energy technologies offer a way to improve the use of degraded or desert lands that otherwise may have few productive uses. In addition, small RE power plant sites can coexist with minimal side effects on farming, forestry, and other land uses. RE offer decentralized options, reducing the impacts on land use from ducts and transmission lines.

There are several adverse impacts and conflicts with RE land use especially on lands that are being currently used for food crop production. In addition, there are risks such as land subsidence or soil contamination near geothermal plants, population displacement through the setting up of hydro reservoirs and competition with fishing in oceans.

Air and Water: Most RE technologies have little or no direct local and global atmospheric emissions, which serves as a strong mitigation mandate. Exceptions include release of methane from hydro reservoirs and biomass burning, in crops or in poorly controlled industrial processes. Even so, such releases are less toxic compared to those from poorly controlled fossil fuel combustion or even with nuclear material accidents. Small bioenergy, solar PV, hydro and other RE plants serve as a valuable resource for local (rural) ground water extraction and supply of basic energy services to communities. Wind farms offer a way to amortize strong winds.

Similar to fossil fuel sources, however, many types of RE technologies can adversely affect water sources. The need for cooling RE power plants in water-short arid areas, risk of water contamination through geothermal generation, thermal pollution, water quality degradation and health impacts from hydro reservoirs, swell/waves and tidal/ocean currents are established examples of water impacts.

Ecosystem and Biodiversity: RE plants offer limited benefit to ecosystem and biodiversity – if not considered global warming. Shaded solar reflectors may improve micro-climate and ocean energy sources may increase biodiversity in some locations. On the other hand, loss of biodiversity and disruption of ecosystem structure is a major concern mainly for bioenergy and hydropower. Impacts due to monoculture originating from bioenergy sources, loss of biodiversity and obstacle to fish migration through hydro units, ecological modification of barrages, bird and bat fatalities due to wind farms are classic examples of such problems. Recent projects utilizing modern technologies, following adequate guidelines and providing due environmental compensation have mitigated significantly these adverse effects.

Human Health: Human health can benefit through low and less toxic emissions from renewable energy sources. Steady and clean water supply from reservoirs serve as recreational and entertaining facilities, as well as for fishing and irrigation. By the same token, uncontrolled bioenergy combustion can increase indoor and outdoor air pollution, manufacturing and disposal of PV modules can generate toxic waste, hydro reservoirs can spread vector borne diseases and noise at wind farms can be a nuisance.

Built Environment: Not unlike fossil and nuclear plants, RE infrastructure provides socio-economic benefits to local communities through creation of jobs and facilitation of local development. Ocean energy provides additional benefit through protection of coastal erosion. Changes in bioenergy plant landscape, induced local seismicity near geothermal plants, risks from dam bursts or wind tower breakdown, as well as changing conditions at ocean discharge sites are illustrations of concerns about the built environment.

Bioenergy has a high potential for reducing greenhouse gas emissions, what helps benefiting ecosystem and biodiversity and overall human well-being due to reduced global warming and extreme weather events. There are many adverse impacts and conflicts with land uses (especially lands that are being currently used for food crop production), extensive water requirement, potential for introducing invasive species, loss of biodiversity from extensive monocultures and some health impacts associated to local air pollution or contamination with agrochemicals.

Mitigative measures include: adequate land use planning (ecozoning) associated to ecosystems conservation/restoration, crop intensification increasing productivity, large scale development and uses of second generation biofuel and expanding feedstock cultivation to marginal and idle lands; improving water application efficiency and development of less water hungry feedstock varieties can reduce water demand.

Solar energy is being used for soil disinfection. Replacing fossil fuels, it can contribute to avoid considerable amount of greenhouse gas emissions and to improve air quality. Its uses in desalinization process in coastal areas and ground water pumping in remote rural areas can contribute to fresh water supply. Large solar thermal plants require significant land areas. Minimal quantities of air pollution can occur during manufacturing, maintenance and demolition phases. Some health hazards can occur from the materials used for PV modules and as well as from handling of the batteries. As in other types of thermal plants, CSP power require significant amount of water for cooling purposes.

Regular recycling of PV modules can limit concerns about electronic waste; land usage concerns can be minimized by relying on otherwise-unused land, already-disturbed land, or by integrating solar energy with buildings. Dry cooling technology can be used to limit water needs for CSP power plants.

Geothermal plants occupy small area. Emissions from such plants are seldom none to negligible. They are clean in terms of health impacts. Hot mineral water is used for spa and has health benefits. Adverse impacts include: land subsidence and related damages to infrastructure, occasional release of pollutants to water and air and health hazards from hydrogen sulphide. Local public consultations, following up environmental regulations and environmental impact assessment as well as designing/implementing remedial measures can mitigate environmental and social impacts.

Hydropower projects generate benefits through energy generation, providing irrigation water, supplying water for domestic uses, mitigating flood hazards and recreational benefits. Dams in desert areas also allow the creation of fisheries. It is also relatively cleaner than fossil fuels regarding greenhouse gas emissions. For hydropower especially the large ones environmental concerns often focus on the loss of biological diversity due to inundation, loss of natural fish and other species habitats, infrastructure loss, altered hydrological regimes, downstream erosion and sedimentation in the reservoir, whereas social concerns include population displacement and altered recreational opportunities. In many cases, fish habitat can restored by constructing fish ladders or elevators, careful site selection and programs of specimens capture/relocation can reduce loss of ecosystem and biological diversity. Direct involvement of affected human populations in the project planning process can help reduce social concerns. Sustainability guidelines for dams have improved over time and compliance to these is better accepted nowadays by environmental protection groups.

Ocean energy is mostly safe for the air quality. For ocean energy, potential impacts vary by technology, but include ecological modification, impacts on fish and marine mammals, sediment re-distribution in the coast, pollution hazards, visual effects and competition with other possible uses of the ocean. Ocean energy developments may benefit to some degree from earlier experience with other forms of RE (e.g., being proactive in monitoring and early mitigation of potential effects) and integrated marine spatial planning is being introduced to address competition and environmental effects.

Wind energy turbines occupy less space and can co-exist with ecosystems. It requires very and small quantity of water and has the least impact on water resources. The technology does not produce any emissions during operation. Important environmental concerns include bird and bat fatalities, social concerns include visibility, noise impacts, nuisance effects, and impacts radar signals. Bird and bat fatalities can be reduced by deploying improved designed turbines, solid tubular towers etc. Large scale offshore projects reduce significantly such impacts and allow exploring vast potentials in a very sustainable way.

Table 9.1. Environmental and Social Benefits (+) and Concerns (-) Associated with Renewable and Conventional Energy Sources

From/ on		Bioenergy	Direct Solar	Geothermal	Hydropower	Ocean Energy	Wind Energy	Nuclear	Fossil Fuels
Land Use and Population	+	positively intensified land uses (e.g. degraded land)	decentralized energy allowing better land use (e.g. degraded or desert)	decentralized energy allowing better land use	stored water for irrigation and other uses (fisheries, domestic use, recreation)	decentralized energy allowing better land use	decentralized electricity co-existing with farming, forestry, etc.	Low land use from power plants	some fuels (LPG, kerosene) allow decentralized energy avoiding deforestation
	-	competition with food supply; threats to small landowners	land use (mostly urban) for large installations	risks of land subsidence and/or soil contamination	population displacement / impacts on cultural heritage	competition for areas (e.g., fishing and navigation)	competition for areas, landscape alterations	accidents may affect large areas; mining; decommissioning sites	land occupation and degradation (e.g. mining),
Air and Water	+	decentralized electricity for water extraction and supply; lower GHG emissions	no direct atmospheric emissions; water pumping from PV electricity	no direct atmospheric emissions	low GHG emissions in most cases; impounded water can be used for irrigation, fisheries and domestic uses	no direct atmospheric emissions	no direct emissions; improved water pumping, amortization of strong winds	no direct atmospheric emissions under normal operation	
	-	water usage for crops; fertilizers nitrate pollution; risk of fires; GHG emissions from land clearing	(limited) life cycle pollution; water for cooling CSP plants in arid areas	water usage by power plants in arid areas; risk of water contamination	risks of water quality degradation and associated health impacts; potential high methane emissions in some cases	swell/waves & tidal/ocean currents: possible effects on pollution	nuisances from noise	risks of leakages and accidents releasing toxic material	significant atmospheric emissions (GHG, other pollutants); risks of water spills, leakages, accidents, fires
Ecosystem and Biodiversity	+	possible integration between crops and with bio-corridors/ conservation units	no harm and some benefits (reflectors shade improving micro-climate)	-	-	increase of biodiversity for some constructions	-	no or little impact under normal operation	-
	-	Biodiversity loss; impacts from monoculture, burning practices and habitat land clearing and landscape diversity; invasive species; use of agrochemicals	risks from large scale projects (disruption of ecosystem structure); CSP may affect birds	water contamination effects	loss of biodiversity from inundation, new hydrological regimes; obstacle to fish migration and introduction of alien species	ecological modification from barrages	bird and bat fatalities, impacts from noise	short to long-term effects in case of contamination	loss of biodiversity from pollution and spills; change of vegetation and wildlife in mining and waste-fields
Human Health	+	lower and less toxic air pollutant emissions improving human health	virtually no pollution	cleaner air and improved public health; hot water for spa resorts	virtually no air pollution; water supply from reservoirs can contribute to improved health	virtually no pollution	virtually no pollution	virtually no pollution	-
	-	indoor pollution from traditional biomass burning; health effects from crop burning practices (e.g. sugarcane)	toxic waste from manufacturing and disposal of PV modules	some risks of contaminations	risk of spreading vector borne diseases in tropical areas; odor in isolated cases	-	nuisance effects (e.g., noise)	very significant impacts from potential accidents	effects from pollution (occupational, local, regional, global); significant impacts from potential accidents
Built Environment	+	high level of socio-economic benefits from new infrastructure (e.g. jobs, local development.)	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure; wave power protects coast from erosion	socio-economic benefits from new infrastructure; (some) turbines attractiveness e	socio-economic benefits from new infrastructure	socio-economic benefits from new infrastructure
	-	changes in landscape, negative visual aspects		induced local seismicity (EGS hydrofracturing); impact on scenic quality and use of natural areas	existing infrastructure damage due to inundation; risks from dam bursts; impacts from induced occupation	changing conditions at discharge sites (OTEC/osmotic power); irreversibility (tidal barrages)	impacts of wind turbines on radar systems; visibility of wind turbines	changes in landscape; necessary escape routes	large mining and processing structures; risks of accidents; impacts from induced occupation

9.3.1.2 Economic and Social Impacts (Table 2)

Investment Costs: Investment costs for all renewable technologies are uniformly higher than those for fossil power plants while they are comparable to those of nuclear plants (Appendix A). With addition of carbon capture and storage investment cost of fossil fuel units becomes comparable to those of renewable energy sources (IEA /OECD/NEA, 2010). Investment costs of wind energy and large hydro plants are in the same range and are typically lower than those for bioenergy, central solar plants, and geothermal units. There is significant future investment potential for direct solar and large and small hydropower. At the same time there are re-emerging investment opportunities for nuclear power due to its heavy promotion to combat climate change.

While the high first cost of RE plants may offer investors a possibility for larger returns, they also pose a barrier to their rapid deployment (Table 2). Achieving grid parity is an important goal that will affect the long term penetration of RE technologies. Barriers such as limited application in new bioenergy plant design of lessons learned from earlier units, subsidized solar systems falling into disrepair, no commercial markets yet for ocean plants, and high investment for offshore wind technologies will limit the rapid deployment of such plants.

Energy Generation/Supply Costs: The levelized cost of electricity supply from the list of RE and other technologies varies but is in the same range for both types of technologies from $50 to $120 per kWh (Appendix A). The costs are somewhat lower for hydrothermal and nuclear plants; the latter because of subsidies to the investment costs of these units. Costs tend to be higher for central solar and offshore wind technologies from $100 to $240 per kWh. PV plants incur the highest costs among this group of technologies.

The cost of new transmission and upgrades to the distribution system will be important factors when integrating increasing amounts of renewable electricity. Transmission improvements can bring new resources into the electricity system, provide geographical diversity in the generation base, and allow improved access to regional wholesale electricity markets. The structure of renewable portfolio standards, tax policies (production and/or investment tax credits), and other policy initiatives directed at renewable electricity (NAP, 2010).

Future potential for several RE technology sources appears to be very promising. Further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring the costs of power generation from biomass down to attractive cost levels in many regions. Solar plants are becoming more competitive as costs are declining; 2030 costs are projected to be 60% lower. Further, operational costs of geothermal sources vary considerably from one project to another due to size, quality of the geothermal fluids, etc., but still they are far more predictable in comparison with power plants of traditional fossil fuel energy. In the evaluation of life-cycle costs, hydro often has the best performance, with annual operating costs being a fraction of the capital investment and the energy pay-back ratio being extremely favorable because of the longevity of the power plant components. The significant risks of high cost of accidents in nuclear plants and fossil fuel extraction outweigh the RE risks that tend to be more diverse and not as punitive.

Income and Livelihood: For RE technologies since the energy for operation of the technology is derived from natural sources there is very limited use of direct manpower for O&M purposes. Bioenergy is one exception where regular biomass sources need to be harvested and placed in a conversion unit. Design and construction of most RE facilities thus yields short-term income and livelihood opportunities. The use of small off-grid power sources (solar, hydro or biomass for example) offers an opportunity for rural users to make more productive use of their night time hours, which can enhance income and also provide higher comfort level and better livelihood.

Another benefit is derived from tax payments; land rents and use of local services that can help vitalize the economy of rural areas. This benefit is also plausible from conventional power plants.

Employment: RE sources typically constitute a significant source of employment that is higher than offered by conventional technologies (Appendix A). The number of job opportunities ranges from 0.17 job-years/GWh for wind technologies up to 0.27 for hydro units. Solar PV is an exception because of its high cost and it needs 0.87 job-years/GWh (**Wei,** Patadia, and Kammen 2010). These values include construction, installation and manufacturing and O&M and fuel extraction and processing jobs. These values are significantly higher than those reported for fossil (0.11 job-years/GWh) and nuclear (0.14 job-years/GWh) technologies. Energy efficiency too shows much higher values at 0.38. In addition, certain energy sources, hydro and ocean power for example, can become a source of eco-tourism and attraction in its own right, providing jobs in tourism and services.

Gender Equity: Among RE technologies, bioenergy (particularly its use in rural areas) is the one that most affects gender equity. Improved biomass systems such as efficient cook stoves enhance lifestyles and lighten domestic workload and reduce the time women spend in collecting fuel wood and other biomass sources. At the same time, development of biofuels may present equity- and gender-related risks concerning issues such as labour conditions on plantations, access to land, constraints faced by smallholders and the disadvantaged position of women. Similarly, small direct solar and hydro units can enhance lifestyles and decentralized energy use can provide more gender friendly jobs. In comparison, fossil fuel sources that substitute for household biomass use effectively promote gender neutrality. Exception is primitive use of coal that can cause significant indoor air pollution that affects mainly women, children and the elderly.

Table 9.2. Economic and Social Benefits (+) and Concerns (-) Associated with Renewable and Conventional Energy Sources

From/ on		Bioenergy	Direct Solar	Geothermal	Hydropower	Ocean Energy	Wind Energy	Nuclear	Fossil Fuels
Income and Livelihood	+	Increase in income in ag-forestry sector Production of biofuel feedstock offers income generating opportunities in developing countries	Rural off-grid solar offers income and livelihood opportunities Construction of all facilities yields short-term income and livelihood opportunities	Construction of facilities yields short-term income and livelihood opportunities	Small hydro schemes provide long-term support for both income and livelihood of remote rural areas, especially hilly regions.	Construction of facilities yields short-term income and livelihood opportunities	Tax payments, land rents, and use of local services can help revitalize the economy of rural communities	Construction of facilities yields income and livelihood opportunities	Construction of facilities yields income and livelihood opportunities
	-							High accidental risk potential	Negative impact on livelihood in selected areas.
Energy Generation /Supply Cost	+	Costs of new transmission and upgrades to distribution system can be important factors when integrating renewable electricity since locations of its resources need not match those of conventional fossil resources.					Can be competitive with fossil generation; wind energy is produced with near-zero marginal cost	Competitive but subsidized	Competitive but subsidized in many locations; Fluctuating prices of oil supply
		Significant potential to reduce costs of biomass supply, production of perennial cropping, and power plants	Becoming more competitive as costs are declining; 2030 costs projected to be 60% lower	Variation in O&M costs due to size and quality of geothermal fluids, however, predictable compared with fossil fuel plants	Often the best life-cycle costs; low O&M costs; extremely favourable energy payback ratio because of longevity of plant components				
	-	High prices of bioenergy products act as a constraint	Current supply costs still very high			Capex costs determined from prototypes but don't reflect market costs	High cost of off-shore wind technologies	Risks of significant costs for accident treatment	Risks of high cost for offshore drilling and coal mining accidents
Investment	+	Potential for large and small scale investment	Large investment potential	Large investment potential in Asia (Indonesia)	Considerable investment potential for still expanding large and small hydro projects		The installed capital cost of on-shore wind projects dropped until 2004 while turbine size grew significantly	Re-emerging investment opportunities due to heavy promotion to slow climate change	Largely established and mature generation and supply technologies
	-	Limited application in new plant design of lessons learned	High first cost barriers; issues with subsidized systems falling into disrepair	Capital intensive due to exploration and drilling costs	High first cost a barrier plus long design and construction lead times	Difficult to accurately assess investment viability due to no commercial markets	High investment for off-shore wind plants	Uncertain investment needs for long-term disposal of nuclear wastes	Investment risk due to uncertainty in remaining oil and gas reserves
Employment	+	Increased job opportunities, particularly in rural areas.	Jobs created in rural and urban areas.	Local workforce can get better employment opportunities.		Ocean power station can become a source of eco-tourism providing jobs	Worldwide, direct employment in the wind industry is estimated at approximately 500,000		-
	-								
Gender Equity	+	Efficient cookstoves can enhance lifestyles and lighten domestic workload. Large biomass can provide jobs on a gender friendly basis. Decreased fuelwood use reduces the collection time for women .	Improved systems enhance lifestyles. Decentralized energy has potential to provide more gender friendly jobs.		Small hydro is partially relevant for women.				Usually gender neutral; kerosene/LPG substitutes for biomass may promote gender neutrality.
	-	Biofuel feedstock production may present equity- and gender-related risks such as labour conditions on plantations, access to land, constraints on smallholders and disadvantaged position of women.							Primitive use of coal can cause domestic health impacts, affecting mainly women, children and the elderly.

9.3.2 Land

Land uses and associated impacts are important for any renewable energy technologies. Bioenergy from crops is an important source of renewable energy and large-scale land uses are occurring in many areas of the world. Although bioenergy production from perennial biomass crops has many potential benefits, land conversion to grow these crops may reduce, displace, and certainly change other important products and services of the existing land such as food production and biodiversity services (Lovett et al., 2009; van der Velde, Bouraoui, and Aloe, 2009; Searchinger et al., 2008).

Generally large land areas are not required to produce solar energy for small scale domestic uses. Solar energy systems, with the exception of very large solar thermal electric plants, whether it is a hot water system or photovoltaic system, do not occupy any dedicated urban land as they are either placed on roofs or they incorporate/replace existing building cladding systems (Geun and Steemers, 2008). Geothermal power plants occupy relatively small land. The ocean thermal energy conversion (OTEC) technology requires small surface area; if located in a platform, only land is required for the cable and connecting to the station. Dams and reservoirs for hydropower generation especially the large ones require substantial land areas. Despite the benefits –energy generation, irrigation, flood control, water supplies for domestic consumptions, fisheries and recreational benefits, dams are also associated with loss of forests, agricultural land, and grasslands in upstream watershed areas due to inundation of the reservoir area (Tefera and Sterk, 2008). The wind power plants, compared to several other types of power production, occupy less space, as farming, ranching, forestry and other types of activities can co-exist with them (see chapter 7.6.3.1). In many cases, wind power plants can be located in un-used spaces (mountain passes, elevated plateaus, etc.). The leasing of land for wind turbines can benefit landowners in the form of increased income and land values. But in some cases, wind power development may create conflicts among the land owners and other people living in the neighbourhood. For off-shore installations, limited conflicts could arise with navigation, but usually only shallow waters are used for the wind power generation off-shore.

Population displacement is an important issue associated with land uses for hydropower production. Dams play a role in alteration of traditional resource management practices and often cause displacement of population and impoverishment of people due to livelihood losses (Tefera and Sterk, 2008). The displaced people usually move to available areas within the watershed and take up agricultural activities on steep slopes and flood-prone areas. The process of migration and agricultural activities on new lands, in combination with normal population growth, can cause significant and harmful land use changes and exacerbate the rate of environmental degradation within the watershed area (Tefera and Sterk, 2008).

Not only will the land use competition between bioenergy crops and food crops affect the prices and expand croplands, but it will likely result in an overall decrease in the average yield of crops as well (Gillingham, Smith, and Sands, 2007). Both types of crops will be grown first in the most profitable and higher quality lands to obtain the highest yield. With growing demand of food and energy, the expansion will take place to lower quality lands. This may have implications in terms of increasing land and crop prices as well as reduction of yields due to utilization of lower quality lands (Gillingham, Smith, and Sands, 2007). This particular kind of impact does not occur for other renewable technologies unless they occupy large agricultural lands.

Solar energy is being used for soil disinfection. Steam soil disinfection is a highly efficient method and a safe alternative to use of chemicals. The method uses steam generated directly from solar energy by means of parabolic trough collectors (PTC) to disinfect contaminated soil. It has a short processing time and it does not leave toxic residues behind (Camilo et al., 2007).

Extraction of geothermal fluids can reduce the pressure in underground reservoirs and can cause land subsidence. In the Wairākei (New Zealand), the centre of the subsidence bowl is sinking at a rate of almost half a metre every year which is the largest subsidence on record (Stewart, 2007). As the ground sinks it also moves sideways and tilts towards the centre. This puts a strain on bores and pipelines, may damage buildings and roads, and can alter surface drainage patterns. Local earthquakes can be expected in the areas of steam/water extraction (Giardini, 2009).

There are options for reducing the impacts of large scale land uses for bio-energy and hydropower generation or in other words facilitating sustainable development: (1) intensive use of land for energy will improve agriculture and technology transfer will occur for conventional agricultural activities; (2) wide scale development and uses of second generation bio-fuels would reduce pressure on lands for feedstock production; (3) perennial biomass crops could be planted on more marginal and idle lands. Although most of the trials have so far been conducted on experimental sites, the economics simply dictate that, if bioenergy crops are in demand, they will expand to as much land as needed, and also try to obtain the highest yields possible. However, there should be a balance between food and biofuel production. One response to the potential competition between energy and food crops is to target degraded as well as grazing lands rather than prime, cropland for bioenergy production, while prime, higher quality croplands are left for food production. A possible benefit of this could be that cultivating energy crops on degraded lands would restore soil organic matter and nutrient content, stabilize erosion, balance moisture conditions, and thus contribute to overall improvement of the land; and (4) for hydropower, carefully selected sites can reduce impacts on forest lands as well as reduce the risk of population displacement. Resettlement is a mitigation measure now being practiced widely during dam/reservoir construction.

9.3.3 Air

The renewable energy technologies have a potential of reducing greenhouse gas emissions and improving air quality. The ***bioenergy*** resources make them a greenhouse-gas-free source of energy that could contribute to a more environmentally-friendly and sustainable energy system. Biomass fuels can be used in high efficiency combustion systems as a substitute for fossil fuels and can result in improving air quality and decreasing greenhouse gas emissions into the atmosphere (Fan, Freedman, and Gao, 2007). When measure over the entire production chain, the production of some biofuels, such as sugar-base ethanol, results in significant reductions in carbon dioxide emissions compare to conventional gasoline. However, in practice some bioenergy chains may cause relatively high nitrous oxide emissions from soil and need a lot of auxiliary energy for refining which can weaken the GHG balance considerably. Further, some bioenergy chains cause in initial phase large GHG emissions through land clearing for bioenergy crops (Searchinger et al., 2008; Achten et al., 2007; Pacca and Moreira, 2009). This concern can be addressed by cultivating perennial crops in marginal, degraded or abandoned lands with reduced tillage and leaving behind crop residues (Jessup, 2009; Lal, 2009; Tilman et al., 2009).

Besides CO2, using bioenergy leads to smaller emissions of SO2 compared with the use of coal. Biomass such as municipal organic waste contains small quantity of sulphur and SO2 which can be released into the atmosphere through the combustion process for biogas manufacturing. Note that emissions of SO2, CO, and NOx from biogas are considered trivial (Fan, Freedman, and Gao, 2007) thus resulting in cleaner air and health benefits such as reduced respiratory complaints (Sims, 2004). In the future, biomass can provide a source of hydrogen for fuel cells, heat for environmentally sound, small scale, distributed generation systems, and gaseous biofuels for micro-turbines.

Solar energy can contribute to avoid considerable amount of GHG emissions. Unlike conventional fossil fuels which produce large amounts of GHG gases, solar energy produces almost zero emissions (Kalogirou, 2008).

Hydropower is considered a green technology, as it has very few greenhouse gas emissions compared with other large-scale fossil energy options (US EPA, 2007). According to US Environmental Protection Agency, hydropower's air emissions are negligible because no fuels are burned. However, if a large amount of vegetation exists alongside the riverbed when a dam is built, this vegetation can decay in the created reservoir, causing the build-up and release of methane gas – a potent greenhouse gas during the first years after impoundment (US EPA, 2007). Despite this however, hydropower is still considered a green and clean technology and can be a significant contributor to address air pollution and climate change as it offsets greenhouse gas emissions and air pollutants from fossil fuel power plants (Government of Canada).

Uses of solar energy can significantly improve indoor air qualities (Palanivelraja and Manirathinem, 2009). However, minimal quantities of air pollution could possibly occur from the manufacture, normal maintenance operations, and demolition of solar energy systems. The great majority of the components of solar energy systems are recyclable, thus posing minor burden on the environment (Kalogirou, 2008). Generation of hydropower allows for the power demand to be met without producing heated water, air emissions, ash, or radioactive waste (Kaygusuz, 2009). Hydropower does not produce air pollutants that cause acid rain and smog and polluting or toxic waste by-products (US EPA, 2007).

Generally, emissions from the ***geothermal*** power plants are none (binary cycle plants) to negligible as compared to fossil fuel powered plants. However, some geothermal plants can discharge pollutants (arsenic, hydrogen sulphide, methane, ammonia, radon, etc.) to the atmosphere that need special attention. Mostly, the pollutant gases are denser than air and can collect in pits, depressions or confined spaces. They pose potential hazards for working at geothermal stations or bore fields and human settlements. In the USA, official requirements for the removal of hydrogen sulphide from geothermal emissions are already established (US DOE, 2009), and it should be monitored at any geothermal plant. The carbon dioxide emission of conventional geothermal power plants is not negligible too (see Chapter 4).

The ***ocean*** energy production is mostly safe for the air quality; in fact, it eventually makes the air cleaner due to possibility to decrease the fossil fuel energy production. For OTEC technology, no solid wastes and no emissions of conventional air pollutants are reported (Cohen et al., 1982).

The ***wind*** energy production, once again, is one of the most environment-friendly technologies, except for making the wind farm equipment. The wind energy plant itself does not produce any emissions to the air. Some studies point out to possibility of influencing the local climate (wind regime, turbulence, etc.) behind the turbines, but these effects are not significant (Lu, McElroy, and Kiviluoma, 2009).

9.3.4 Water

All renewable energy development processes require water and therefore, they have implications in terms of quantity and quality. The ***bioenergy*** crop production is highly dependent on water and water demand in future would increase for this purpose (Stone et al., 2010; Varis, 2007). It has been estimated that somewhere between 3900 and 12,000 km^3 per year will be needed for production of biomass– a figure that already excludes those food crop residues that could also be used (Lundqvist et al., 2007). If 15 percent of this water were to be contributed by irrigation, the demand for blue water would rise by another 1200-3500 km^3 per year. ***Solar*** energy technology requires water during production process of hardware and some water may be required time to time for cleaning of them after installations. Parabolic trough and central tower systems using conventional steam plant to generate electricity require the use of cooling water. This could place a significant strain on water resources in arid areas (Tsoutsos, Frantzeskaki, and Gekas, 2005). ***Hydropower*** generation requires impoundment of water of large quantity and such action can cause impacts in downstream areas depending on the ecological water requirement of the downstream stretch of the channel and water requirements for other economic sectors. Desalination technology has been used in many large cities all across the world to satisfy growing water needs and this industry continues to grow especially in arid regions with limited water availability. ***Solar*** energy can be combined with desalination technology to generate a sustainable source of freshwater as well as a source of energy (Ettouney and Rizzuti, 2007). For small scale applications, Meah, (Meah, Fletcher, and Ula, 2008), found ground water pumping using solar PV systems cost effective in the drought hit rural Wyoming State, USA.

Solar energy has been proven effective for water treatment methods such as chlorination and bacterial disinfection. Small amount of electricity is generated from solar cells for drinking water chlorination (Appleyard, 2008). Moreover, solar energy can effectively be used in to disinfect biologically contaminated water. Using the thermal power of solar energy and heating water to a disinfecting temperature level as well as exposing the water to ultraviolet radiation result in inactivation of micro-organisms and elimination of coliform-group bacteria (Saitoh and El-Ghetany, 2001).

During production of bioenergy feedstock, the quality of surface water and groundwater is being impacted through nitrate pollution from the applied fertilizers in the bioenergy crop fields (Lovett et al., 2009). Except for the normal use, in the ***solar*** thermal system, there may be the risk of accidental water pollution through leaks of heat transfer fluid (Tsoutsos, Frantzeskaki, and Gekas, 2005). Construction of hydropower dams and reservoirs especially the large ones can effect the quality of water positively in the impounded area. Reservoirs generally act as traps for nutrients and sediments, since these matters tend to settle down when water is discharged into the reservoir area. As a result, reservoirs are reliable and provide higher quality water supply sources for irrigation and domestic and industrial use. On the other hand, sedimentation depletes capacity of a reservoir and increases flood risks at the upstream (Chapter 5). Additionally, reservoirs provide for fisheries because of the storage of high amount of nutrients in the water (Kaygusuz, 2009).

Operations of dams and reservoirs can negatively impact the quality of water downstream river channel below the dam. The water discharged through the turbine is almost free of sediments and nutrients but it can scour and erode the streambed and banks. This scouring effect can have significant negative impacts on the flora, fauna, and structure of biological community in the downstream river channel. In addition to this, dams and reservoirs also change aquatic habitats. Riverine habitat is replaced with reservoirs, and downstream habitat may be altered as a result of modifications in flood regime and trapping of sediments in the reservoir (UNEP, 2000; Ligon, Dietrich, and Trush, 1995).

Headwater streams provide unique habitats for aquatic biota and are extremely important sources of sediment, nutrients, and organic matter for downstream areas. Hydropower dams act as physical barriers and their presence hinder the longitudinal movement of organisms and downstream export of matter and nutrients. In addition, as a result of flow reductions in the de-watered reach of river between dams and turbines, discontinuities between upstream and downstream areas river fragmentations occur (Anderson, Pringle, and Freeman, 2008). De-watered reaches downstream from dams typically have slower water velocities, warmer water temperatures, and shallower habitats compared with adjacent upstream and downstream areas. This change in water quantity leads to habitat alterations, and can eventually impact distribution of aquatic organisms and affect their long-term survival in the river (Anderson, Pringle, and Freeman, 2008).

Any release of polluted water from the ***geothermal plants*** into rivers or lakes can damage aquatic life and make the water unsafe for human and agricultural uses due to presence of poisonous chemicals, minerals and gases in the geothermal fluid used for energy. The most serious environmental effect of the geothermal industry is pollution of fresh water from arsenic. For example, due to discharge of geothermal waste water contaminated with arsenic from the Wairākei geothermal power station in New Zealand, the levels of arsenic in the Waikato River almost always exceed the World Health Organization standard for drinking water (Stewart, 2007). It also contaminates the Waikato River with hydrogen sulphide, carbon dioxide, mercury at concentrations that have adverse, if not calamitous effects (Abbasi and Abbasi, 2000). However, thorough risk and environmental impacts assessment would allow avoiding such problems.

Among the ***ocean*** power technologies, the barrage tidal stations can increase some water pollution upstream. Brackish water waste and polluted polyethylene membranes from the salinity gradient energy (SGE) sites can adversely impact the local marine and river environment. For OTEC technology, catastrophic failure such as thermal fluid escape has only some minor local effects. Up-welling effect of bringing nutrient-rich deep water to the surface can occur. This mixing may be beneficial for aquatic lives but further study is required. If water is discharged at proper depth, effect is essentially eliminated (Vega, 1999). For the wave energy systems, uncertainties exist on the specifics of toxic compounds to be used in the power installations and possibility of their release into the sea water.

For ***wind*** energy production, water is not used, except for making the wind farm equipment and cleaning the rotor blades. Wind energy is one of the technologies least influencing the water sources (US DOE, 2009), regarded to both on-shore and off-shore devices.

There are options and measures available and are in practice to reduce social and environmental impacts of hydropower projects. Several promising concepts for sediment control at intake and removal of sediment from reservoirs and settling basin have been developed and practiced (Chapter 5). The use of regulating pond downstream of the powerhouse enables steady release of water and therefore reduces the risk of erosion.

9.3.5 Ecosystems

Cultivation of bioenergy and biofuel crops can directly affect biodiversity, both positively and negatively. These effects include small scale changes to species abundance at field level, as well as larger scale issues such as changes in landscape diversity, and potential impacts on primary and secondary habitats (Firbank, 2007). Bioenergy cropping has the potential to benefit biodiversity by mitigating climate change, which can have significant impacts on ecosystems and biodiversity.

Cultivation of bioenergy crops may eliminate niches for some species living on that land through conversion processes, but can create niches for a new suite of species (Firbank, 2007). There are three major adverse impacts of introduction of bioenergy crops. ***First*** is the loss of a high quality habitat; either by replacing it with bioenergy crops, or by introducing major changes in land use and management (e.g. increased extraction of wood fuel from woodland). The ***second*** negative impact occurs through introduction of invasive crop species, e.g., giant reed and miscanthus (Barney and Ditomaso, 2008). The ***third*** major negative impact arises when linear habitat features such as lines of trees, hedgerows, water edge and ponds are either added or removed. This can consequently cause losses of habitat and species dispersion (Firbank, 2007). On the positive side, bioenergy crops provide a stabilized vegetation cover that can offer habitat for some elements of native biodiversity (Fan, Freedman, and Gao, 2007).

Construction and operation of water reservoirs/dams for ***hydropower*** generation can cause harm to ecosystems and loss of biodiversity (Rosenberg et al., 1997; IUCN, 2001; Fearnside, 2001; Criag, 2001). Loss of biodiversity compromises the structure and function of ecosystems, which can in turn compromise the economic well-being of human populations. Hydropower development may cause losses of biodiversity well in excess of natural, background losses (Coleman, 1996). For example, the reduction or extirpation of native species through alteration of physical habitat or introduction of exotic species is a form of biodiversity loss connected with large-scale hydroelectric development (Power, Dietrich, and Finlay, 1996). These losses could occur over extensive spatial and temporal scales. Rancourt and Parent (Rancourt and Parent, 1994) documented loss of biodiversity for the La Grande development project in Canada which operates a chain of reservoirs. Fearnside (Fearnside, 2001) listed loss of forests which led to loss of natural ecosystems in the Tucuruı´ Dam in Brazil.

As to the ***geothermal*** power plants, some "open loop" heat pump systems may affect aquatic ecosystems if they draw water from a water body and discharge warmer or cooler water back into the water body, and/or pollute it.

The ***ocean*** power stations do not largely influence land ecosystems. Some adverse effects can occur for the coastal landscapes, mostly due to occupation of the territory during construction. Wave stations can partially block the coast from wave impacted erosion, but they also can re-distribute natural sedimentation in the coastal zone. The tidal barrages can flood the coastal areas depending on the elevations, at least for certain time periods. For the offshore stations, the high voltage transmission cables have the potential to influence the aquatic animals that are sensitive to electromagnetic fields, thus disrupting their ability to navigate (Gill, 2005). The power generation and transmission structures may affect local water movements, which are fundamental to some aquatic species (Montgomery et al., 2000) and also determine the transportation and deposition of sediments (Gill, 2005).

Technology wise, differential impacts of ***ocean*** power infrastructure on ecosystems and biodiversity can occur. The tidal barrages are potentially the most harmful to the marine and coastal ecosystems unless the effects are addressed seriously. The change in water level and possible flooding would affect the vegetation around the coast. The quality of the water in the basin or estuary would also be affected; the sediment levels would change the turbidity of the water and can affect fish and birds. Fish would undoubtedly be affected unless safe fish passes are installed. Decline in fish population would affect population of birds and they will migrate to other areas with more favourable conditions. However, emergence of new environment may allow different species of plant and creature to flourish and their overall impacts need to be independently assessed (ESRU, 2009). However, Colwell (Colwell, 1997) argued that problems could arise during quantification of environmental capital of the recreated environment compared to the original one.

Sea streams (including tidal ones) generally are not as strong as those for a tidal barrage. The latter might have an effect on the aquatic life in that particular area. These site-specific by-products can be avoided or minimized through proper environmental impact assessments (ESRU, 2009). For example, at La Rance station in France, 10 years after the construction, the biodiversity situation was back to normal in the estuary, compared to neighbouring estuaries (Mao and Gerla, 1998).

The SGE ocean technology can influence the local salt and fresh water mixing regime. Each species of aquatic plant and animal is adapted to survive in either marine, brackish, or freshwater environments. The main waste product of this technology is brackish water and its large quantity discharge into the surrounding waters may significantly alter aquatic environment. Fluctuations in salinity will result in changes in the plant and animal community. Variation in salinity occurs where fresh water empties into an ocean or sea, these variations become more extreme on for both bodies of water with the addition of brackish waste waters. Extreme salinity changes in an aquatic environment may be detrimental to both animals and plants due to sudden severe salinity drops or spikes (Montague and Ley, 1993).

Organisms impinged by an OTEC ocean power plant are caught on the screens protecting the intakes, fatal to them. Entrained organisms may be exposed to biocides, and temperature and pressure shock. Entrained organisms may also be exposed to working fluid and trace constituents (trace metals and oil or grease). Intakes should be designed to limit the inlet flow velocity to minimize entrainment and impingement (Vega, 1999). OTEC plant construction and operation may affect fishing. Fish will be attracted to the plant in part due to redistribution of nutrients, potentially increasing fishing in the area. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced (Vega, 1999).

For ***wind*** energy production, fatalities of birds and bats by flying into the turbine rotors have been reported in many regions of the world. In Denmark, overall, less than 1% of the ducks and geese fly close enough to the turbines to be at any risk of collision (Desholm and Kahlert, 2005). In the early 1980s, a large number of raptor fatalities were reported at Altamont Pass, California (Orloff and Flannery, 1992). However, most turbines in North America, have low impacts on birds and bats. Studies by the U.S.-based National Wind Coordinating Committee indicate an average bird kill of two to three birds per turbine each year. Direct mortality and injury of birds have also been reported from the U.K. However, the majority of studies of collisions caused by wind turbines have recorded relatively low levels of mortality (Painter, Little, and Lawrence, 1999).

There are many ways to minimize risks to local and migratory birds and bats. Current wind turbine technology offers solid tubular towers to prevent birds from perching on them. Turbine blades also rotate more slowly than earlier designs, reducing potential collisions. Specialists consider the location of common migratory bird/bat routes and, wherever possible, avoid those areas for wind farms. Other effects such as noise, interference into natural habitats, etc., do not pose serious challenge in most cases if necessary assessment is done before installation. With appropriate precautions, there is almost no effect on biodiversity (see also Chapter 7.6.2). For off-shore wind power farms, no significant negative effect was found, and in some areas, biodiversity has increased due to artificial reefs appearance (Danish Energy Authority, 2006).

9.3.6 Human Health

As was previously mentioned, using biomass fuels instead of fossil fuel produces lower emissions of human health-harming substances and thus helps to improve quality of life (Sims, 2004). However, use of biomass in traditional cooking stoves is a source of indoor air pollution through high particulate emissions and thus constitutes a health hazard. Sugarcane fire has significant health impacts as reported in southeast of Brazil. Elements such as black carbon and tracer elements generated from sugar cane burning were those most associated with both child and elderly respiratory admissions in hospitals (Cançado et al., 2006).

Solar energy is considered a clean energy source with essentially zero emissions in terms of air pollution and greenhouse gas production. As a result, it is not harmful and can contribute to cleaner air and improved public health (Palanivelraja and Manirathinem, 2009). In some cases, PV modules contain materials that are hazardous to human health to waste streams and recycling of materials. A life cycle analysis of batteries for stand-alone PV systems indicates that the batteries are responsible for most of the environmental impacts, due to their relatively short life span and their heavy metal content (Tsoutsos, Frantzeskaki, and Gekas, 2005).

Health impacts of ***hydropower*** reservoirs are well researched. Major health impacts are spread of vector borne diseases associated with the reservoirs itself and irrigation projects. Lerer and Scudder (Lerer and Scudder, 1999) documented health concerns beyond vector-borne diseases which include impacts through changes in water and food security, increases in communicable diseases and the social disruption caused by construction and involuntary resettlement (Table 3).Water supply from hydropower projects for domestic consumption is beneficial for communities (Chapter 5).

Table 9.3. Potential health impacts of large dam projects

Impact Area	Health impact
Upstream catchment and river	Changes in flood security, water related diseases, difficulties with transportation and access to health facilities
Reservoir area	Involuntary resettlement, social disruption, vector borne diseases, water related diseases, reservoir induced seismicity
Downstream river	Food security affected on flood plains and estuaries (farming and fishing), water related diseases, dam failure and flooding
Irrigation areas	Changes in food security, vector borne and water related diseases
Construction activities	Water related diseases, sexually transmitted diseases, HIV/AIDS due to migrated labors, accidents and occupational injuries
Resettlement areas	Communicable diseases, violence and injury, water related diseases, loss of food security
Country/regional/global	Macro-economic impacts on health, inequitable allocation of revenue, health impacts of climate change

Source: (Oud and Muir, 1997).

Geothermal power plants, except for few cases, are clean in terms of human health. However, hydrogen sulphide emissions (0.1 ppmv as against permissible 0.03 ppmv) from the Geysers, California power plant have resulted in complaints of odor annoyance and health impairment (Anspaugh and Hahn, 1979). Concerns raised by the local residents of respiratory diseases, asthma, eye problems, cold and flu from a geothermal energy project in Kenya (Marita, 2002). With established monitoring systems in potential areas of water and air pollution, the geothermal plants become practically safe for people. The hot mineral water can be used for resorts.

Mostly, the ocean power generation is remote from the settled regions, even from the coastal areas. Except for rare situations like possible water pollution behind the tidal barrages, these technologies do not influence the human health directly. Accidents at OTEC plants can lead to limited emission of gases like ammonia and chlorine.

Wind turbines, particularly older designs, emit noise that can be heard near wind farms. According to the U.S. Renewable Energy Policy Project, the noise from a typical wind farm at 350 meters distance can vary between 35 and 45 decibels, a non-harmful level (see chapter 7.6.3.3). Sound levels can grow with increases in wind speeds, and are objectionable to some people. To minimize noise levels, operators are using improved rotor technology, constructing plants away from densely populated areas and including sound-absorbing materials in the generator. The frequency and volume of this noise can be controlled, but not eliminated by wind turbine design. At the same time, wind turbines do not produce infrasound at a level detectable by humans or that has been shown to have any impacts on health (Leventhall, 2006; Rogers, Manwell, and Wright, 2006).

9.3.7 Built Environment

Growing ***bioenergy*** crops can affect the built environment, specifically the visual aspect and settlement routine. Depending on the original land use (prior to growing the energy crops), these tall crops such as Miscanthus and short rotation coppice willow (3 to 5 m high) may impact the character and visual appearance and perception of the landscape (Lovett et al., 2009).

As was mentioned before, ***solar*** energy technologies such as small PV systems and space and water heating systems are typically installed on existing buildings and do not occupy large land areas. Thus, they are not likely to disturb the visual aspects of environments to a great extent. However, large areas are required for central PV systems (Tsoutsos, Frantzeskaki, and Gekas, 2005).

Hydropower projects create both adverse and beneficial impacts on the built environment. Inundation of infrastructure that includes houses, rural roads, business centers, archeological and historical sites usually occur. During construction of Kaptai hydropower project in Bangladesh in the 1960s, damage to human settlements and infrastructure occurred. The lake inundated the homes of 18,000 families and displaced 100,000 tribal people, of which 70% were ***Chakma*** tribal people. The dam also flooded the original Rangamati town and the palace of the Chakma Raja (king) (Parveen and Faisal, 2002). A 50-km stretch of highway was inundated during construction of the Samuel Dam in Brazil (Fearnside, 2005). Hydropower projects also facilitate construction of new infrastructures like roads, highways and urban centres. The reservoirs are usually used for recreational purposes.

Geothermal power plants occupy relatively small area and do not require storage, transportation, or combustion of fuels. These qualities reduce the overall visual impact of power plants in scenic regions. Transmission lines and other power-related infrastructure usually are the same as for other types of power plants or less visible.

For ***ocean*** power plants, visual impacts are particularly important in areas of designated coastline and those used for recreational purposes. Ocean energy infrastructure could cause visual impacts if they are constructed around such areas. Wave energy devices may be potential navigational hazards to shipping as they could be difficult to detect visually or by radar. Several of the areas proposed for wave energy devices around European coasts are in major shipping channels and hence there is always an element of risk that a collision may occur (Thorpe, 1999).

Because ***wind*** farms are composed of large numbers of turbines and tend to be located on or just below ridgelines or within sight of shores, they can often be seen for a long distance. As a result, some people object to the visual impacts of wind turbines. To reduce these impacts, operators sometimes paint wind turbines to blend in with their natural surroundings. During planning for new projects, they also consider the spacing, design and uniformity of the turbines and locate wind farms away from populated centres. Actually, acceptance of wind farms by people increases once the wind power plant has been built, and for some people they seem attractive (Sathyajith, 2006). Wind power development could result in appearance of wind farms in recreational areas, which should be assessed thoroughly. Experience in Europe and U.S. has shown that wind turbines can easily and safely coexist with all types of radar and radio installations (Brenner, 2008).

9.4 Implications of (sustainable) development pathways for renewable energy [TSU: this has been changed from the original title 'Socio-economic impacts: global and regional assessment' and needs to be approved by IPCC Plenary]

Environmental consequences of energy consumption have been neglected for too long, because the idea of continuing economic growth is still central to policy makers across the globe. Clearly, it would be preferable to concentrate on providing energy services that will satisfy the needs of the people rather than working towards increasing the capacity of supply, based mainly on non-renewable resources.

It is widely accepted that energy is linked with more or less all aspects of sustainable development. It is an engine for growth and poverty reduction, and therefore it has to be accorded high priority and this has to be reflected in policies, programs and partnerships at national and international levels (WEHAB, 2002). The provision of energy in a sustainable way is therefore pivotal to the aim of achieving sustainable development.

To make global energy systems compatible with sustainable development requires a sustained effort that includes awareness raising, capacity building, policy changes, technology innovation and investment. The shift towards a sustainable energy economy also requires sound analysis of the options by policymakers, good decisions and the sharing of experience and knowledge of individuals and organizations involved in the many practical challenges that such a transition presents. These activities, and the resulting changes, are needed in industrial as well as developing countries (WEHAB, 2002).

These interactions involve science, technology, learning, production, policy and demand, so that entrepreneurs innovate largely in response to incentives coming from the wider innovation system (Foxon, 2008). The technology has to be appropriate for a specific context, so that the target community has the capacity to afford it and to maintain it.

Renewable resources can also become non-renewable if the rate of utilization exceeds the capacity of the planet to recycle them. In other words, excessive consumption can lead to limits in the availability of renewable resources, and consumption itself can become unsustainable (Gutierrez, 2009). Thus, pathways to sustainable use of renewable energy generation and use have to take these limits into consideration.

The feasibility of stabilizing GHG concentrations is dependent on general socio-economic development paths. Climate policy responses should therefore be fully placed in the larger context of technological and socio-economic policy development rather than be viewed as an add-on to those broader policies (Swart, Robinson, and Cohen, 2003). Progress measurement allows understanding how quickly can be built a renewable energy platform, meeting basic human needs, discouraging wasteful consumption and investing in - rather than depleting - natural and cultural capital (Worldwatch Institute, 2008). This requires a transition or a bridge from the current industrial economy’s dependence on fossil fuels to alternative or renewable energy technologies. The shift from our dependence on non renewable, polluting energy resources to renewables will take time and needs to be carefully planned. Policy frameworks will need to be put in place that will enable that transition. In the context of development pathways for renewables and possible implications long-term sustainability aspects of intergenerational, as well as intragenerational equity issues will need to be discussed, to satisfy the basic principle of sustainable development. Criteria for a sustainable energy future include the availability of resources, security of supply, environmental compatibility, as well as social and economic compatibility and energy production that is associated with minimum risks.

9.4.1 Future scenarios of renewables

The previous sub chapters were discussing the impacts of renewables on the environment (9.2), as well as impacts of renewables on socio-economic aspects (9.3). The aim of this subchapter is to consider future scenarios for renewable energy development and define different pathways.

In 2005 renewables produced 16% of world primary energy. Globally, electricity made up 19%, mostly from large hydropower and the rest from other renewables such as wind, biomass, solar, geothermal and small hydropower. Biomass and solar energy contribute to hot water and heating, biofuels provide transportation fuels and energy for industry and power generation. Most renewable technologies, except large hydropower, have been growing at rates of 15-60% annually since the late 1990s. It is this group of technologies that are projected to grow the fastest in the coming decades (Martinot et al., 2002).

Future scenarios of renewables for different regions, different end-user sections and different energy sources need to consider a broad spectrum of possible RETs, as well as the associated risks, the affordability and limitations of the proposed technologies. Furthermore, to achieve low stabilisation targets, not only all technology options have to be evaluated, but also all sources of CO2 and non-CO2 emissions have to be considered (PIK, 2009).

When considering different future scenarios for renewable energy in the context of sustainable development, questions like how are we going to deal with a conventional baseline in terms of equity, trade, security, environment, as well as the impact of subsidies, need to be addressed. What will be possible outcomes in the medium to long-term? And how will this impact on how development pathways are determined.

To determine different pathways it is essential to first have a desired future vision or target and then work out a way on how to achieve that vision or target. In this case the target is an increase in renewable energy deployment which in turn will lead to a more sustainable development pathway. A method used to incorporate sustainable development into the strategic planning process is "backcasting" (Robinson, 1982). The idea behind backcasting is to define the goal or destination and then work backwards from the destination to the current situation. In this case the overarching vision is to keep the level of CO_2 at or below 450 ppm in terms of CO_2 equivalent concentration and keep the global temperature increase at or below 2°C. A part of this vision is the increased use of renewable energy.

As part of an international project on low carbon society scenarios, several global modelling studies like Akimoto (Akimoto et al., 2008) and Remme and Blesl (Remme and Blesl, 2008) have reported renewable electricity as an essential option to achieve deep emissions cut by 2050. Some studies emphasise drastic supply-side decarbonisation pathway, with almost half of primary energy supply comprising solar, wind, biomass, nuclear and CCS by 2050 (Edmonds et al., 2008).

However, as stated earlier, the renewable energy, technology and infrastructure roadmap depends on the desired future vision. This has been amply demonstrated by Fujino et al (Fujino et al., 2008) in a low carbon study of Japan with a target of 70% reduction by 2050 through two different future scenarios – technology-oriented society and nature-oriented society.

Once the pathway has been determined, the potential barriers to development pathways for renewable energy technology innovation/implementation have to be identified. Many barriers are well known, however, overcoming these barriers remains difficult. Other barriers may be less obvious and consequently more difficult to remove. (See subsection 9.1.3 Barriers and Opportunities for more details). For this reason many modelling studies on drastic emissions reduction by 2050 foresee a significant role of renewable energy only after 2020, with other options playing a dominant role in the short run. For instance, Praetorius and Schumacher (Praetorius and Schumacher, 2009) see CCS as a bridging technology toward a renewable energy future.

9.4.2 Global and Regional Development pathways for renewable energy

The development of renewable energy technologies has to take place within the wider context of sustainable development, including economic and social development, protection of the environment and enhancement of equity. This realization is in sync with the growing consensus, as emphatically stated in Akashi et al (Akashi et al., 2007), that the challenges of climate change too are best addressed within the overall context of promoting sustainable development. A sustainable energy system is a system consisting of (renewable energy) technologies, laws, institutions, education, industries and prices governing energy demand and supply for the sustainable development process (Diesendorf, 2007).

Given their large cumulative emissions and higher income levels, the immediate burden of development and financing renewable technologies (RETs) should fall on the shoulders of industrialized countries. This does not mean, however, that many developing countries do not have technology bases that enable them to make significant R&D contributions to RETs. For developed nations, the reduction of the cost/power ratio must drive their research agenda (Wagner, 2004).

To facilitate a global transition to renewable energy will require large investment in national, regional and local energy infrastructures in developing as well as developed countries and economies in transition. For instance, Fujino et al (Fujino et al., 2008) estimate a direct annual cost of 6.7-9.8 trillion yen (or 73-103 billion US$ at 2008-09 exchange rate) for technology investments in renewable energy, CCS and energy efficiency, in order to achieve drastic CO2 reduction on the energy supply side in Japan by 2050. Such a transition will require national governments to channel appropriate financial resources for intensive economy-wide change in technologies, industrial structures, land use and energy infrastructures. These investments will need to come from the public and the private sectors and will have to take many forms, including financial incentives from government; loans and capital investment from banks, private investors, venture capital funds and communities; as well as new innovative markets that contribute to the benefits of renewable energy and energy efficiency (CanREA, 2006).

There are a number of national and international funds that provide grants or interest-free loans to developers of energy efficiency and renewable energy projects. These include among other the Global Environmental Facility (GEF), the Global Village Energy Partnership (GEVP) and the Renewable Energy and Energy Efficiency Partnership (REEEP) (CanREA, 2006). There are a number of innovative funding models available, including the Clean Development Mechanism (CDM); Dealer-Credit Model (Grameen Shakti); Consumer Credit Model; Supplier Credit Model; Energy Service Company Model; Revolving Fund and the Global Environment Facility (GEF). In a global modelling study, Barker et al (Barker, Scieciu, and Stretton, 2008) recommend efficient and targeted use of carbon tax revenues to promote innovation and deployment of low carbon options like those based on renewable energy. They report that such investment effects can lead to a rise in global GDP. Similar mechanism of ‘carbon fee’ to subsidize new renewable energy options is recommended by Johnson (Johnson, 2010).

Developing countries face two main energy challenges; firstly, to meet the energy needs that are essential for economic growth and poverty reduction; secondly, to reduce the threat of regional and global environmental disruptions, particularly addressing the vulnerability of societies to the negative impacts of climate change (Usher, 2007). Barker (Barker, Scieciu, and Stretton, 2008) and Remme (Remme and Blesl, 2008), in global modelling analysis for low carbon society scenarios, indicate a greater share of global emission reduction by the developing countries up to 2050. Hence the energy challenge faced by developing countries is enormous.

To meet the rapidly growing energy needs of present and future populations in developing countries, and to reduce poverty, will require large capital investments (WEHAB, 2002). Many renewable energy companies in developing countries are frustrated by the lack of interest in their businesses from finance institutions, either to finance their operations or to lend to their customers (Usher, 2007).

The large CO2 reduction potential in developing countries can be realized if there is greater alignment between national and global environmental regimes, CO2 mitigation actions are integrated within domestic economic and sustainable development goals, and instruments like CDM are modified appropriately (Shukla, 2008; La Rovere, 2006; Mwakasonda, 2006). Development pathways for renewable energy in developing countries have to ensure that the chosen energy options will be able to improve productivity of resource use, increase economic prosperity and provide positive benefits across all three dimensions of sustainable development (WEHAB, 2002). The development pathway for renewable energy in developing countries has to be compatible with climbing the energy ladder and economic development. Therefore, programs like the UNEP's Rural Enterprise Development programs are a first step towards a pathway for renewable energy in the developing world (Usher, 2007).

A recent initiative dealing with these issues is the African Rural Energy Enterprise Development (AREED) programme which was launched in 2001 under the joint auspices of the United Nations Environment Programme (UNEP), the United Nations Foundation (UNF), E+Co, and UNEP Risoe Centre and with funding from the UNF, SIDA, BMZ and the Dutch government (Akuffo and Obeng, 2008). This initiative has succeeded in developing an ingenious plan of loan provision, building capacity in bankable business plan development, analysing market conditions and identifying efficient energy systems for Small and Medium Enterprises (SMEs). However, according to Akuffo and Obeng (Akuffo and Obeng, 2008), energy SMEs in Africa are facing several constraints and challenges including: lack of relevant policies and institutional framework to provide sufficient leverage for SMEs to tap into new energy business; lack of capacity building in energy system development and commercialization; limited rural energy market; inherently high initial cost of renewables and energy efficient products; and poor access to clean energy financing. This suggests that without an enabling policy framework, SME energy providers in Africa will not be in a position to participate in the emerging energy market. What is needed is a multidimensional approach that has the effect to transform energy systems, social systems, economic systems, and institutions at an unprecedented rate and scale (O'Brien, 2008).

The provision of renewable energy has not been defined as a Millennium Development goal in its own right; nevertheless, access to clean energy services is an important pre-condition not only for environmental sustainability but also for the achievement of most of the other millennium development goals. The development pathways for renewable energy in developing countries have to therefore closely align themselves with the MDGs. Developing countries have to build knowledge and manufacturing capacity in the renewable energy sector within their own countries. It is imperative that researchers and innovators from developing countries remain there and contribute to increasing capacity within their countries instead of leaving the countries to follow a more lucrative career path in a developed country.

Renewable energy can contribute to sustainable development in developing countries, particularly in communities within rural areas which are often not grid connected, in the form of solar home systems (SHSs) for illumination, extending the working day, improving education, reducing the risk of fire from kerosene lamps and improving health problems associated with kerosene lamps. Similarly, wind pumps and solar pumps provide water for irrigation and drinking, improved stoves reduce indoor air pollution, as well as reducing the amount of biomass needed to cook. Biodiesel has the potential to provide energy services for the poor and to create jobs in rural areas (UN-Energy, 2007).

Some developing countries have the opportunity to leapfrog the more polluting fossil fuel based technologies and industries and move directly to more advanced renewable energy technologies and avoid some of the dirty stages of development experienced by industrialised countries The adaptation of technologies to the local context is an essential part of leapfrogging, and the process has to occur in parallel with ongoing social, economic and institutional changes (Sauter and Watson, 2008). Through the leapfrogging concept, developing countries have the strategy to adopt early in their development process the best and most efficient technologies available, so as not to repeat the path followed in the past by industrialized countries, when they industrialized. It is an answer to arguments frequently used to justify a “provisional right to degradation”, since the basic needs of the population would have to be met by development at any environmental cost. Adopting the best technologies available, success is founded on the previous understanding of the impacts deriving from the possible choices for a certain society (Goldemberg and Lucon, 2010).

Microenergy, a capillary type of distributed energy generation, is an important option to leapfrog, aiming to provide energy services to the poorer. Adequate technology transfer and microfinance schemes allow small-scale installations to be affordable for application in developing countries, not only reducing occupational, local and global environmental impacts but also helping to break the vicious cycle of poverty. Developing countries cannot afford to be dependent on technology transfer and foreign supply to sustain their technological progress. Instead, technology transfer needs to be coupled with capacity building. This requires finance mechanisms that are appropriate for the specific conditions within which they are applied. In the case of providing finances to the rural poor, Grameen Shakti in Bangladesh has come up with a micro-credit scheme to finance renewable energy technologies to reduce down payment and offer free after sales service solutions that empower women, the disadvantaged, create jobs, facilitate rural development and protect the environment (Barua, 2008).

In the case of developed countries, there are also more sustainable developmental options to consider. Electricity grids across Europe are 40 years old and fast approaching the end of their operating lives. This presents an opportunity for fresh thinking and innovation, exploring possibilities of alternative energy options, based to a large extent on renewable energy resources. The Global Energy Network Institute (GENI) proposed a strategy for developing remote renewable energy sources and linking them to population centers via long distance electrical transmission lines (GENI, 2007).

Most large scale renewable energy sites are located far from population centers. Today, interconnection of renewable energy sources is a viable and feasible energy alternative, from a technological viewpoint (GENI, 2007). With the development of high-voltage valves, it is now possible to transmit DC power at higher voltages and over longer distances.

In 2008 the Trans Mediterranean Renewable Energy Co-operation (TREC) proposed an interconnected grid between Europe, North Africa and the Near East. This is an ambitious plan to turn Europe, North Africa, and the Near East into a super-grid based on renewable resources, ranging from solar (solar CSP and Solar PV), wind, hydro, biomass and geothermal.

To enable the development of renewable energy requires national programs and policies to support renewable energy markets in order to establish renewable friendly laws and regulations, promote renewable friendly building codes and standards, stimulate long term financing and provide sustained financial support for projects

According to PEER (PEER, 2009) the following should happen to stimulate increased energy market by renewable energy: (i) Climate-based subsidies and budget allocations could be increased or new ones introduced; (ii) Subsidies and taxes with harmful climate impacts could be removed or redesigned; (iii) Budget allocations and taxes with favourable side effects from a climate point of view could be increased and; (iv) Rules and texts stipulating the way in which present budget allocations may be used could be more climate-based by stipulating climate-based limits or goals for the administrative bodies that govern these means (PEER, 2009).

Similarly, the White Book from the DESERTEC Foundation posits that a scenario that meets all criteria of sustainability will require determined political support and action. It lists five focal points for national and international policy for all countries in Europe, the Middle East and North Africa (EUMENA): (1) Increase support for research, for development and for the market introduction of measures for efficient supply, distribution and use of energy (efficiency focus); (2) Provide a reliable framework for the market introduction of existing renewable energy technologies, based on best practice experience and increase support for research and development for promising enhancements (renewable energy focus); (3) Initiate a EUMENA-wide partnership for sustainable energy. Provide European support to accelerate renewable energy use in MENA (interregional cooperation focus); (4) Initiate planning and evaluation of a EUMENA High Voltage Direct Current super-grid to combine the best renewable energy sources in this region and to increase diversity and redundancy of supply (interconnection focus) and (5) Support research and development for shifting the use of fossil fuels from bulk electricity to balancing power production (balancing power focus) (TREC).

Ashina (Ashina et al., 2010), in a study of low carbon society scenario for Japan by 2050, recommend early and large investments in renewable energy technology options, as that would have multiple strategic advantages like early learning leading to early reduction of technology cost, smoother turnover in energy infrastructures, and higher possibility of alternative options in case a dominant technology fails unexpectedly. Similar conclusions have been arrived at by Strachen (Strachan, Foxon, and Fujino, 2008a) and Akimoto et al, (Akimoto et al., 2008).

In a modelling analysis of a scenario with 80% CO2 reduction in UK by 2050, Strachen (Strachan, Pye, and Hughes, 2008b) highlight the role of international drivers like technology costs, fossil fuel prices, supply of imported resources, international aviation emissions, trading mechanisms and global LCS consensus, in influencing sectoral and technology portfolio distribution of decarbonization efforts including renewable energy options.

It is clear that the governments at several levels – country, province/prefecture, city, village – will have to act early and proactively to influence major changes in the infrastructures, technology and fuel choices and behaviours of businesses and consumers to adopt renewable energy. For instance, the government of Japan initiated in 2009 a long-term project to combat global warming, called "environment model cities," in which 13 municipalities have been given bold targets to reduce GHG emissions by 50-60 percent by 2030-2050 as compared to 1990 or 2005 levels (Okuoka and et al, 2009). For instance, Kyoto city government has set a target of 50% GHG reduction by 2050 compared to 1990 level. The mitigation initiatives are selected by municipalities to fit local conditions, economy and resources. For example, Sakai city, with help of its own and central government's subsidies, is set to begin operating in 2011 one of largest solar PV stations in Japan that will provide power to many households, and to install PV facilities in schools. Yasuhara town, being in a mountain area, has launched a project to recycle wood waste from lumber mills for use a fuel for heating greenhouses by farmers. Shimokawa town in Hokkaido has planned to cultivate willows for use as charcoal and processing into bioethanol.

The methodology for analysis required to assess local or city level low-carbon scenarios would have to be different from a country level analysis, as local economies are much more open with uncertain socio-economic activity and easier and fluctuating cross-border flows of people, energy, material and capital. An analysis for Kyoto city using Extended Snapshot tool, as a part of backcasting methos, showed feasibility of the target of 50% GHG reduction by 2030 by means of energy demand reduction in various end-use sectors and a drastic increase of share of renewable energy to 12.6% of primary energy supply by replacing oil and coal (Gomi, Shimada, and Matsuoka, 2009). Similar analysis was done for Shiga prefecture of Japan (Shimada et al., 2007; Gomi et al., 2007). Both the studies found that majority of the 50% GHG reduction by 2030 can be achieved by local (city or prefecture) level actions alone. Such actions include decentralized renewable energy generation and use in end-use sectors, besides centralize renewable electricity, energy efficiency, and behaviour and land use structure changes.

9.4.3 Development pathways for renewable energy in different end-use sectors

Unlike centralized energy generation based on fossil fuel or uranium, distributed energy generation based on local renewable energy sources provides diversity which in turn means greater strength in guarding against unforeseen events. It offers a risk management strategy that reduces the potential of adverse impacts resulting from interruptions in supply, or excessive price rises in any single supply sector.

9.4.3.1 Built-environment

Buildings consume a lot of energy. Direct emissions from buildings grew by 26% between 1970 and 1990 (IPCC, 2007). Furthermore, the buildings sector has a high level of electricity use and therefore the total of direct and indirect emissions in this sector is much higher (75%) than direct emissions (IPCC, 2007) In recent years, there has been a lot of emphasis placed on energy efficiency. To meet this energy demand, renewable energy can be used. The built environment offers many opportunities for this. Roofs can be used to produce renewable heat with solar collectors, or renewable electricity with solar panels. In addition, renewable heat can be extracted from the ground, using heat pumps. In some cases small wind turbines can be mounted on the roofs to produce electricity. Through the combination of efficient use of energy and the use of local, energy sources, a situation can be achieved where renewable energy meets the biggest part of the energy demand in buildings (ECN) [TSU: reference incomplete].

Low energy houses, also known as green buildings, eco houses or low carbon houses will need to be used in combination with renewable energy technologies. For example, in Guangzhou, China, a 71 story office building combines an energy efficient design with both solar and wind power to operate at zero net-energy consumption (Ayres and Ayres, 2010).

According to the EU Commission, in low energy buildings, as much as 80% of the operational costs can be saved through integrated design solutions. By 2009, around 20.000 low energy houses had been built, mainly in Germany and Austria (European Commission, 2009). The EU Commission aims to have all new home constructions meet the standards set for low energy houses (Ayres and Ayres, 2010).

Outside Europe, similar developments are happening; for example, Japan is currently discussing plans to adopt a goal for zero energy buildings by 2030 and some US states such as California are moving in that direction (European Commission, 2009). In the US, the first passive house was completed in 2009, in Berkley, California (Ayres and Ayres, 2010).

9.4.3.2 Transport

Today's transport sector is predominantly based on combustion of fossil fuels, making it one of the largest sources of urban and regional air pollution and greenhouse gases. The growth in direct emissions from transport between 1970 and 1990 was 120% (IPCC, 2007). However, the movement of goods and people is crucial for social and economic development. Consequently, there is a need to move towards sustainable mobility. Solutions need to be found that address mid-term, as well as long term concerns about transportation, energy and emissions.

According to UNEP (no date) this requires: (i) Urban planning, changing lifestyles and production patterns to reduce the need for transport at the source; (ii) Rethinking transport systems, promoting inter-modality and encouraging the use of the most energy efficient mode of transport, i.e., wherever possible switch from air to rail, from the personal vehicle to public transport or non-motorized transportation and; (iii) Improving fuel efficiency of each mode of transport, and promoting the use of alternative fuels. UNEP has identified three key areas of work to assist countries: (1) The improvement of urban planning to promote inter-modality; (2) The diffusion of cleaner technologies and the deployment of relevant policies that drive them to reduce environmental impacts and (3) The introduction of price signals that capture the full costs of different modes of transport.

Options to develop pathways for renewable energy in the transport sector include increasing the energy from biomass from local resources; i.e. ethanol and bio-diesel, preferably from non-edible crops, so that it does not conflict with food security (as the initiative of Shimokawa town in Japan mentioned in 9.4.2). Explore the potential of the electric car using electric motors, based on electricity generated from renewable energy sources. Hybrid cars and to lesser extent battery cars[1] are a proven technology. Additionally, hydrogen and fuel cells based on renewable energy generation have the potential to play a part in transportation. Several countries are involved in hydrogen bus projects, including Brazil, the US, the UK and a number of other European countries. An LCA of emissions of these proposed options needs to be considered.

9.4.3.3 Land-use

Renewable energy and land use is not without its controversy. Some environmentalists argue that the increased use of renewable energy would have severe environmental consequences. Key renewable energy sources, including solar, wind, and biomass, would all require vast amounts of land if developed up to large scale production (Pearce, 2006). Between 1970 and 1990 direct emissions from agriculture grew by 27%, and the total land use, land use change, and forestry grew by 40% (IPCC, 2007).

The EU Parliament (European Parliament, 2009) places importance on monitoring the impact of biomass cultivation, such as through land use changes, including displacement, the introduction of invasive alien species and other effects on biodiversity. It further posits that biofuels should be promoted in a manner that encourages greater agricultural productivity and the use of degraded land.

Educating policy makers as well as the general public of the true impacts of renewable energy through land use changes has to be part of the strategy towards the development of renewable energy on a larger scale.

9.4.3.4 Other end-use sectors

Industry is vulnerable to climate change, and the industrial sector is responsible for a significant share of energy use and CO2 emissions. Achieving sustainable development requires the implementation of cleaner production processes. Industry has a large potential to address climate change issues by enhancing energy efficiency and increasing the use of renewable energy. Biomass is widely used to generate energy for some industries, in particular in the pulp and paper industry. In Europe it is the largest producer and user of renewable energy sources with 50% of its primary energy consumption coming from bio-energy (CEPI (Confederation of European Paper Industries), no date). Biomass is also widely used in countries like Brazil to produce energy as a by-product from sugarcane. Industry can also use solar or wind as a source for its energy. Concentrated solar power is being considered for electricity generation as well as process heat. The International Energy Agency (IEA) is presenting a roadmap for CSP at a summit in June 2010 in Valencia, Spain. It expects CSP to become competitive for peak and mid-peak loads by 2020 in the sunniest places if appropriate policies are adopted. The overall contribution of CSP is anticipated to provide 11% or more of the global electricity demand by 2050 (Environmental Expert, 2010).

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[1] Zebra high-energy battery made from common salt, ceramics and nickel is able to store four times more energy than a lead acid battery holding the same weight and allows a range of up to 400 km (http://www.solartaxi.com/technology/zebra-battery/)

Agriculture has a large role to play in the production and consumption of solar, wind, geothermal, and biomass energy. In the US as well as the EU, farmers are selling energy; for example, electricity generated from wind turbines, biofuels, and products from biomass.

Bioenergy to replace fossil fuels can be sourced from agricultural feedstocks such as dedicated energy crops and by-products or waste from agricultural production. The IPCC report (IPCC, 2007) estimated that the energy production potential from agricultural residues varies between 15 and 70 EJ/yr. "Organic wastes and residues together could supply 20-125 EJ/yr by 2050, with organic waste making a significant contribution (IPCC, 2007)(p. 519).

Dedicated energy crops have still more potential, and according to an estimate by the European Molecular Biology Organization, energy crops could deliver 800 EJ per year without jeopardizing global food supply (1 EJ = 1 × 1018 J) which is considerably more energy than is now consumed globally — 2006 consumption was 500 EJ (Hunter, 2008).

9.4.4 Development pathways for renewable energy in different energy sources

The challenges associated with renewable energy technologies, like intermittency of wind generated grid power and storage of electricity from solar power are well documented. To facilitate development pathways for renewable energy technologies it is therefore essential to finance research to find solutions to these challenges.

Besides the more conventional storage technologies including hydro-pumped and compressed air storage for electricity generation there are examples of alternative, existing storage technologies, like the Vanadium Redox Flow Battery (VRB), which was developed and commercialized by the University of New South Wales (UNSW) Australia. According to the UNSW website, it has shown to have high energy efficiencies between 80 and 90% in large installations and is low cost for large storage capacities. (Skyllas-Kazacos, no date).

Biomass has the potential to supply large amounts of CO2 neutral energy, when not entailing deforestation. It is already competitive in some markets. Currently about 13% of the world's primary energy supply is covered by biomass. Industrialized countries source around 3% of their energy needs from biomass, while Africa's share ranges from 70-90% (WBCSD, 2006). Current use of agricultural biomass for non-food purposes, including energy, amounts to around 9% of agricultural biomass being harvested and grazed for food (Wirsenius, no date). Thus, agricultural products and residues, as well as dedicated energy crops, are a key part of the overall supply of biomass. In 2005 roughly 46 EJ out of the total supply of 490 EJ were derived from biomass making it the most important renewable primary energy source (Sims et al., 2007).

Possible negative impacts associated with large scale biomass farming need to be considered. A framework is required to address issues of land ownership, de-forestation and land-clearing, displacement of people, competition with food production and in some cases emissions from fuel-wood negatively impacting on indoor air quality (See 9.3.1 for more detail on bio-energy).

In addition to residues and purpose grown energy crops, waste products like animal wastes, human wastes (e.g. anaerobic digestion of sewerage sludge to produce bio-gas or inter-esterification of tallow to give bio-diesel) have large potential for carbon neutral energy production. Similarly, municipal solid waste, either combusted in waste-to-energy plants or placed in landfills with the methane gas collected for electricity and heat production play some part (Sims, 2004). Human and animal waste has been in use in countries like China and India for some time to produce biogas (methane) in anaerobic digesters, and the technology is being introduced in some African countries. Its potential as a source of energy for lighting and cooking and waste treatment, particularly in densely populated areas, has to be looked at more seriously.

Box 9.2. Biogas from human Waste – the case of Rwanda (KIST, 2005)

Large prisons, with typically 5,000 prisoners, are a legacy of the troubled past of Rwanda. Sewage disposal from such concentrated groups of people is a major health hazard for both the prison and the surrounding area. The prisons also use fuelwood for cooking, putting great pressure on local wood supplies. A large-scale biogas scheme was developed for prisons in Rwanda to treat toilet wastes and generate biogas for cooking. The after-treatment, bio-effluent is used as fertiliser. Biogas digesters are not a new idea, but in Rwanda has been applied on an enormous scale with great success. A linked system of underground digesters avoids the sight and smell of sewage. System construction provide on-the-job training to both civilian technicians and prisoners. The biogas piped to prison kitchens halves the use of fuelwood. Fertiliser benefits both crop production and fuelwood plantations. Starting operation in 2001, plants are now running in six prisons with a total population of 30,000 people. Annual fuelwood saving is about 27,000 m3 - about 10,000 tonnes of CO_2 equivalent per year. It is expected to install three more each year. The systems installed in Rwanda have an impressive international heritage: the original design came from China, was modified by Germans and finally scaled up and refined by a Tanzanian engineer working in Rwanda. Each individual digester has 50 or 100m3 in volume, built up on a circular, concrete base using bricks made from clay or sand-cement. A 100m3 plant can store 20m3 of gas, but may generate up to 50m3 per day, so it is important that the gas is consumed regularly. Great care is taken to ensure that the effluent is safe to use as fertilizer, with regular laboratory checks for viruses, bacteria and worms. It is used only for crops that stand above ground, such as papaya, maize, bananas, tree tomato and similar tree crops. A prison with a population of 5,000 people produces between 25 and 50 cubic metres of toilet wastewater each day. Using a 500m3 system (five linked digesters), this produces a daily supply of about 250m3 of biogas for cooking. Plants are purchased by the Ministry of Internal Security (£50,000 for a 500m3 plant) through phased payments, with the final 5% paid only after 6 months of satisfactory operation. Trained prisoners operate the systems. To date, over 30 civilians and 250 prisoners have received training, and three private biogas businesses have been started. A certification body keeps quality standards high, avoiding failures that would damage the biogas sector as a whole. There is clear potential for widespread replication of these biogas plants, in Rwanda and many other countries. The International Committee of the Red Cross (ICRC) is a key partner which, together with the government of the Netherlands, has assisted in financing the programme.

Direct solar produces minor emissions during operation, and the overall life cycle environmental performances are improving. For example, all PV technologies generate far less life-cycle air emissions per GWh than conventional fossil-fuel based electricity generation technologies (Fthenakis and Hyung, 2009). Furthermore, because it generates mainly decentralized energy, direct solar potentially increases job opportunities and income in rural areas, particularly in developing countries. Possible negative impacts to consider are issues around land occupation for large solar thermal installations, resulting in change of albedo. The up front costs are relatively high but there are no fuel costs (see 9.3.1 for more detail on direct solar).

Electrical production from geothermal results in an order of magnitude less CO2 per kilowatt-hour of electricity produced compared to burning fossil fuels (Bloomfield, Moore, and Jr., 2003). However, there are some site specific emissions associated with energy production form geothermal. Similar to other renewable technologies it has potential to improve employment opportunities in developing countries. The capital costs are still high; however, variable costs are low. (See 9.3.1 for more detail on geothermal energy).

Hydro power has the capacity to store energy, as well as water for irrigation. However, large hydro dams release methane emissions, have high lifecycle emissions, mainly during construction, and potential to displace people and damage existing settlements. Energy price is very cost competitive. (See 9.3.1 for more detail on hydropower).

Ocean power, particularly wave and tidal power has potential to provide base load energy with no emissions during operations. However, some emissions may arise during manufacturing and installation of the devices. Tidal power may require large structures that have environmental impacts (See 9.3.1 for more detail on ocean energy).

Wind power is the most-cost-effective renewable energy technology producing electricity (except for large hydropower) with some lifecycle emissions but no emissions during operation. It has a positive impact on rural economies. There are some issues about visual and noise pollution, as well as risk of collision for birds and bats (see 9.3.1 for more detail on wind energy).

Development pathways for different energy sources vary; some like wind, hydropower and bio-energy are already competitive and well established; others like direct solar, geothermal and ocean power in particular require assistance to advance their development and scale up production.

9.5 Policy framework for renewable energy in the context of sustainable development [TSU: this has been changed from the original title 'Implications of (sustainable) development pathways for renewable energy' and needs to be approved by IPCC Plenary]

On the global level there is a recognized need for the international community to strengthen its commitment to the scaling up of renewable energy development and use, especially in developing countries (BIREC, 2005).

International organizations like the UN Framework Convention on Climate Change (UNFCCC) (i.e. Clean Development Mechanism), the International Energy Agency, the UN Development Program (UNDP), Energy and Environment, the UN Division of Sustainable Development, the World Bank Energy Program, the UNDP/World Bank ESMAP (Energy Sector Management Assistance Program) and others play an important role in building capacity and improving financing and transfer of technology know-how for renewable energies. For example, UNEP has made support for renewable energy a top priority in its call for a "Global Green New Deal" at the recently held COP14 in Poland (Sawyer, 2009).

Similarly, organizations like the Renewable Energy and Energy Efficiency Partnership (REEEP), , the Global Network on Energy for Sustainable Development (GNESD), the Global Village Energy Partnership (GVEP), the International Network for Sustainable Energy (INFORSE), the UNEP Sustainable Energy Finance Initiative, the World Council on Renewable Energy (WCRE), the World Alliance for Decentralized Energy (WADE), the World Business Council for Sustainable Development (WBCSD) and the World Renewable Energy Congress/Network (WREC/WREN) all aim to accelerate the global market for sustainable energy by acting as international and regional enablers, multipliers and catalysts to change and develop sustainable energy systems.

The International Renewable Energy Agency (IRENA) is a relative newcomer to assist in the promotion of future oriented development pathways for renewable energy. IRENA is the first international organization exclusively focused on the issues of renewable energies. It is a first, but important step on the global level to have a body that aims to close the gap between the large potential of renewables and their relatively low market in energy consumption.

The World Summit for Sustainable Development (WSSD), the Bonn International Conference for Renewable Energies, the G-8 Gleneagles Summit, and other international and regional initiatives all play an important role to promote renewable energy.

On the regional level there is a need to build stronger partnerships between governments, regional authorities and municipalities, energy producers and consumers, market intermediaries, non governmental organizations (NGOs) and financial institutions in order to facilitate a common understanding of the issues, challenges and constraints related to renewable energy development, and to pave the way for greater cooperation among all groups in society (Slavov, 2000).

There is a growing body of regional organisations involved in the advancement of renewable energy technologies. For example, the European Union energy policy aims to create a single, liberalised energy market (electricity and gas) at the EU level that is both transparent and efficient; to diversify sources for greater security of supply; to reduce energy consumption and promote development of new forms of renewable energy (European Parliament, 2007).

On a national level, organizations like NREL in the US have a role to play in the area of R&D, as well as the dissemination about renewable energy to consumers, homeowners and businesses. Similarly, organizations the American Wind Energy Association (AWEA), the Basel Agency for Sustainable Energy (BASE), the Brazilian National Reference Center on Biomass etc assist the development of renewable fuels and electricity that advance national energy goals in their respective countries.

The role of national governments is to provide an enabling policy framework, through government institutions to stimulate technical progress and speed up the technological learning processes so that RETs will be able to compete with conventional technologies, once the environmental costs have been internalised (see Chapter 11 for more detail). Firstly, renewable energy solutions on the local level should be resource and need driven. Local participation in selecting appropriate solutions is important. Studies like the ones conducted by Gregory (Gregory et al., 1997), Nieuwenhout (Nieuwenhout et al., 2000), Taylor (Taylor, 1998) and Lloyd, Lowe and Wilson (Lloyd, Lowe, and Wilson, 2000) stress the importance of technical reliability. To ensure the reliability of a system it is important that local installers and maintenance personnel are adequately trained. The need for improved education programs and improved accreditation of installers for remote areas was recognised in a recent market survey by the Australian Cooperate Research Centre (CRC) for Renewable Energy (ACRE) (Lloyd, Lowe, and Wilson, 2000). Secondly, the renewable energy solution has to be appropriate and fit in with the specific local context. Innovations based on Western style consumerist ideology should not always be presumed to offer the best or only solution to a problem. That does not mean that traditional technology is necessarily preferable. What it does suggest however, is to allocate equal importance to both Western technology and traditional technology, when considering available options and solutions.

The developers of sustainable energy technology based on renewable energy on the local level face the difficulty of designing a system or product that remains flexible enough to be able to adapt to a number of different social, cultural, political, economic and environmental situations and peculiarities and take local knowledge into account, and at the same time can be mass-produced, in order to remain competitive.

9.5.1 Required instruments for sustainable development pathways for renewable energy

Appropriate policy instruments for sustainable development pathways for renewable energy are required on the global, regional, national as well as local level. The available instruments are similar to those used in environmental policies, with similar discussion involved in their choice.

At the international level, multilateral as well as bilateral agreements like the current Kyoto Protocol are imperative to provide a global framework for the promotion of sustainable development pathways for renewable energy. The three instruments or mechanisms that help industrialized countries achieve their Kyoto emission reduction targets agreed to by allowing them to reduce the cost of reduction are emission trading (ET), joint implementation(JI) and clean development mechanism (CDM). These three instruments provide the conditions for the development of pathways for renewable energy development in developing as well as industrialized nations.

The use of subsidies to promote the development of renewable energies worldwide includes the gradual phase out of subsidies to the fossil fuel and nuclear energy production and consumption and instead increasing the provision of subsidies to renewable energy production and use.

At the regional level, the EU proposes a mandatory target of 20% of renewable energy sources in gross inland consumption by 2020, as well as a minimum target for biofuels of 10% of overall consumption of petrol and diesel in transport for 2020.

In the Asia-Pacific region there is a recognized need to strengthen the policy framework to accelerate the implementation of policies towards achieving sustainable development pathways for renewable energy.

At the national level a mix of command and control or regulatory instruments, as well as market based incentives is required. Two of the main instruments are feed in tariffs and certificate markets. These two policy instruments form an essential tool to achieve the desired transformation towards sustainable development in the context of the global climate challenge. Some evidence suggests that countries with successful renewable energy programs are those that have legislated a feed-in tariff, which ensures fixed prices for every kWh that is being produced by renewable energy sources and is fed into the grid. For example, Germany brought in the Renewable Energy Sources Act, (EEG) in 2000, introducing feed-in tariffs, with fixed payment per kWh for a period of 20 years with steady reductions of the payment amounts at a rate of 1.5% per annum (BMU, 2008). Similarly, in 2009, South Africa adopted the Renewable Energy Feed-In Tariff (REFIT) to facilitate the large scale deployment of concentrated solar power (CSP) in an attempt to shift its electricity generation away from coal to mitigate GHG emissions (Edkins, Winkler, and Marquard, 2009). Other mechanisms like the renewable portfolio standard (RPS) have been used in a number of European countries as well as the United States. The RPS has proven to be quite successful in a number of states in the US (US DOE, 2009).

In addition, defining national targets and setting bidding systems, establishing markets for tradable permits for CO2 emissions, green certificate markets and renewable energy certificates are important instruments to promote the development of RETs. Other financial incentives for renewables and energy efficiency are in the form of corporate and personal tax credits, subsidies, as well as loan and grant programs.

9.5.2 Impacts of Renewable Energy on Use of Resources

The deployment of renewable energy is very often pointed out as one of the most important steps on the way to a more sustainable future. Wind power, solar and geothermal power and heat, biofuels and other forms of renewable energy are often called “green”, for they are believed to have no adverse impacts to the environment. Even though this is only partially true, generation of power and heat from renewable sources per se has indeed very little impact on the environment in terms of emissions of polluting substances, unlike the conventional fossil fuel-based technologies.

It is important to understand, however, that in order to produce the conversion technologies, install them, operate, maintain and dismantle them, a broad spectrum of activities and industries needs to be involved, which certainly impact the use of natural resources like water and land. This does not mean to say that renewable energy utilisation is not an ‘environmentally friendly’ option in comparison to conventional fossil fuel technologies. On the contrary, emissions and other negative impacts to the environment are certainly lower for renewable energy technologies. (Pfaffenberger, Jahn, and Djourdjin, 2006)

However, it should be noted that future development of renewable sources could be constrained by air, land, water and other requirements. This issue is specific to each project, because compatibility with requirements differs widely. The constraints depend on many factors, among others population density and compatibility of a project with other requirements.

Two approaches are often used to evaluate resource utilization caused by different generation technologies. Elementary approaches quantify the use of air, land and water (among others) directly utilized in the energy conversion process. More sophisticated approaches identify direct and indirect use of the resources involved. This kind of analysis is used to quantify all the resources involved in the complete life-cycle of the electricity generation process.

A life-cycle assessment (LCA) is an environmental assessment of all of the steps involved in creating a product. Its goal is to give an all inclusive picture of the environmental impacts of products, by taking into account all significant ‘‘upstream’’ and ‘‘downstream’’ impacts. In the power sector, the assessment includes extraction, processing and transportation of fuels, building of power plants, production of electricity and waste disposal. (Gagnon, Bélanger, and Uchiyama, 2002).

Comparative analysis of resources used by power generation systems should take into account the intermittency of the generation technology, thus, resource per energy or average power are preferred instead of resource per installed capacity. For example, it would not be fair to compare bioenergy to windpower in terms of m^2/MW (Gagnon, Bélanger, and Uchiyama, 2002).

It is possible to evaluate the water requirements along the life-cycle for a generation technology, a concept defined as Water Footprint (WF). The WF of a product (commodity, good or service) is defined as the volume of fresh water used for the production of that product at the place where it was actually produced. Most of the water used is not contained in the product itself. In general, the actual water content of products is negligible compared to their WF (Gerbens-Leenes, Hoekstra, and van der Meer, 2009).

9.5.3 Public awareness on RE potential and opportunities

Most renewable energy applications have traditionally been perceived very favorable by the general public maybe with exceptions around some large hydro dams and parts of the bioenergy agenda. Many solar, wind and bioenergy initiatives have originally been rooted in local community initiatives contributing directly to the positive perception. With up-scaling and having the development of new installations being driven by other stakeholders, typically utilities or private power companies it is not evident that the positive public perception is immediately maintained. Increased public resistance to new large installations have been experienced in many countries also beyond the more narrow “not in my backyard” type concerns. Public awareness and acceptance is therefore a very important part of the climate mitigation driven need to rapidly and significantly scaling up the adoption and deployment of RE technologies. Such large scale implementation can only successfully be undertaken with the understanding and support from the public and this will require dedicated awareness raising on the achievements of existing RE options and the opportunities, prospects, and potentials associated with wider scale applications (Barry, Ellis, and Robinson, 2008).

However, poor perception of the benefits of renewable energy technologies will continue to override success registered in the market. In some developing countries (Egypt, Zimbabwe, Tanzania, Ghana), local entrepreneurs who have managed to corner the market with renewable technologies such as solar home systems, solar panels etc. can act as agents of change. For this to happen, they need to have a platform to demonstrate success and respond to informational needs that may arise from potential users. Specific groups such as the finance and industrial sectors, bank and government officials in key finance and economic ministries, private sector, entrepreneurs need to be targeted in order to increase their confidence and uptake in renewables. In addition, the link to sustainable development benefits needs to be clearly articulated to further expand the market for renewable and increase its uptake. For instance, biogas plants have been identified as quite an attractive renewable option given the fact that it can be used as sanitation or agricultural project with energy spin off. Countries in East, North and West Africa have populations that are highly reliant on agriculture; thus pumping technologies such as wind pumps can help boost opportunities for irrigation, guarantee a stable water supply, enhance agricultural productivity and boost livelihood opportunities. Also, the benefits of renewable energy technologies such as PV that can serve rural energy needs such as communication, education, and health need to be shared – often this technology can be used in combination with other energy options for optimal value and for sustainability. Other ancillary benefits relating to avoided emissions for certain renewable as well as the knock-on effect on improved air quality need to be demonstrated to attract women entrepreneurs.

Awareness raising is evidently only one necessary component in gaining public acceptance for increased RE deployment; it will require more direct engagement at the local level for specific policies and installations and often need to be seen as part of a broader sustainable development process. Increased awareness of opportunities for direct use of RE installations e.g. solar water heaters or PV systems in households is a distinct part of the overall expansion of RE utilization.

Providing relevant and carefully targeted information to the different stakeholders including the general public in order to respond to concerns over climate change related issues, and to the private sector to leverage commercial interest and investments in RE, is found to be key and is already happening in many countries (Wolsink, 2007). Various types of information on RE technologies are relevant and the dissemination channels may vary. Examples of these include TV, Internet, social networks, publications, meetings, child education and demonstration. TV is already in use quite widely for information campaigns, corporate promotion, direct marketing, and could also include documentaries providing information about RE applications, climate change aspects etc. The Internet is similarly widely used for providing access to information and awareness material and an increasing number of innovative applications are available for esp. the youth engagement (games, YouTube videos, forums, etc.). Social networks either web based (like Facebook or MySpace) or more traditionally organized can be effective in facilitating communication and impacting opinions. Also to mention are different types of publications (from newspaper articles to leaflets to simple slogan statements and many more), public meetings, talks and quiz games, the inclusion in education curriculum from kindergarten level and upwards and direct demonstration plants with public access. These options may not all apply equally well in all developing countries although some definitely would be highly relevant. Additional specific options for developing countries may include: (i) the involvement of community organisations; (ii) engagement of local leaders/elders in information, decision making and maintenance; (iii) engagement of local communication providers e.g. mobile phone outlets and (iv) use of local radiostations.

It should also be noted that there are many strong economic and political interests vested in the energy sector and opponents to increase RE utilization have significant financial resources to provide information and lobby policy makers. As an element of RE technology support programmes many national or cross–national governmental institutions have initiated RE promotion campaigns aiming to increase public awareness and thus influencing choices of end consumers (see e.g. (European Commission, 2006). Interest groups, NGO's, trade associations, and industry organizations, among others, may also play a central role in this regard.

Experience shows that such efforts as well as related demand side management initiatives may have a large impact on the choices made by consumers and RE deployment over time (Christiansen, 2002). Private sector actors generally show interest in accessing more specific technical and economic data; including availability of RE input resources, technology reliability and commercial maturity, sourcing opportunities, technology cost effectiveness, etc. All part of the information basis that companies require to judge the relevance of entering into new business opportunities either directly or as part of corporate image building. Lately the issue of "carbon footprint" and carbon neutrality have become important corporate concerns for many larger national and multinational companies leading to increased focus on options in clean energy supply, enhanced efficiency and carbon trading.

Besides national initiatives, international platforms for RE information, clearing houses, networks and knowledge sharing forums on RE technology options like Renewable Energy Policy Network for the 21st Century (REN 21) may play important roles, on a broader international scale, for augmenting deployment of RE technologies. REN21 is a global policy network that provides a forum for international leadership on renewable energy. Its goal is to bolster policy development for the rapid expansion of renewable energies in developing and industrialised economies. Other examples include the Energy and Environmental Technologies Information Centres (EETIC) and the Global Renewable Energy Policies and Measures Database and others. The recently established International Renewable Energy Agency (IRENA) is expected to play an important international role in the future in this area. IRENA's mission is to promote the widespread and increased adoption and sustainable use of all forms of renewable energy. IRENA's Member States pledge to advance renewables in their own national policies and programs, and to promote, both domestically and through international cooperation, the transition to a sustainable and secure energy supply.

It is of key importance that information needs to be targeted at and be accessible for very different types of stakeholders and consequently the total spectrum is very broad ranging from small scale rural household RE technology options to large scale off–shore windfarms. This can in most cases not be covered by the same institutions and targeting information at the many different stakeholders is a key challenge both in terms of format and timing.

9.5.3.1 Institutional capacity – policy, encouragement and enforcement

At the national level there are a variety of policy instruments, measures, and activities relevant for policy makers and governmental institutions to increase the deployment of RE technologies (Beck and Martinot, 2004). The adoption of such policies may be directed towards supporting various stages in the RE promotion process from basic R&D at universities, private companies, or non–profit institutions, to demonstration, commercialization, and full deployment stage.

Experiences from countries that have effectively promoted private investments in renewable energy show that national strategies, policies and targets are key elements (REN 21, 2006). Most existing successful national renewable energy strategies have wider goals, such as security of energy supplies, environmental protection, climate change mitigation, renewable energy industry development, and ultimately sustainable development (enhancing energy access, alleviating poverty, addressing gender and equity issues, etc).

Information, data and capacity constraints is often a barrier both for the setting of broad policy priorities and for drafting actual sector-specific legislation. The same constraints may also prevent the private industries, including finance companies, from estimating more accurately the risks of cleaner energy technology investments, and stifles more widespread adoption of cleaner energy technologies by industry especially in many developing countries. Limited institutional and human capacities are a particularly important concern amongst governmental agencies, which face growing demands in the area of climate change, but lack of capacity also hampers the private sector's ability to organize itself in a more effective manner.

Strategies for promoting certain RE technologies may therefore aim at accelerating the innovation process in specific stages of the technology push – and market pull continuum (IEA, 2000). Ranging from identifying an interesting technology and developing it into a product, and only then searching for a marketplace. To the other extreme where the marketplace needs are first analysed and then focus is on developing a new product to meet that need. As stated the reality is often a continuum with a combination of approaches even for a specific technology. However, the institutional capacity to make strategic choices and support schemes for RE implementation often is limited and need to be built in the relevant agencies and organizations.

This need for capacity development for making appropriate planning efforts on RE is most urgent in developing countries, however, the capacity of many industrialized countries to develop and implement RE policies and technologies is still limited (Assmann, Laumanns, and Uh, 2006). This often constitutes a significant and real barrier to increased utilization and deployment of RE technologies (Painuly, 2001).

Furthermore, the process of implementing RE policies spans from goals and targets setting to implementing concrete activities and finally to monitor and verify the results and this requires different types of institutional capacity to secure effective outcomes. Many developing countries have typically received support to develop national policies and plans but lack support for ensuring the successful implementation and follow-up.

Decision making and policy implementation has also in many countries changed from solely being the responsibility of certain government levels to increasingly involving various private sector stakeholders, NGO's, and civil society. This shift is incorporated in the inclusive concept of governance, which reflects the need to involve and give influential mandate to relevant parties in order to reach desired and successful outcomes (REN 21, 2006).

Participatory approaches to encourage stakeholder involvement as well as local democracy considerations are therefore key issues to achieve wider support of deployment of RE initiatives in a broader sustainable development context. Planning efforts and governmental intervention in the area of various RE technologies may also be understood as one element, i.e. the institutional infrastructure, of the technology system of innovation in question (Jacobsen and Johnson, 2000). Therefore, increasing RE technology deployment depends on a comprehensive understanding of other involved actors and the interactions between them in this innovation system.

In very broad terms, policies can be grouped into seven main categories i) research, development and demonstration incentives; ii) investment incentives; iii) tax measures; iv) incentive tariffs; v) voluntary programs; vi) mandatory programs or obligations; and vii) tradable certificates. (REN 21, 2006). The evolution of these policies since the 1970s reflects among other things, an increased market orientation or policies moving from regulation towards economic policy tools. Presently, feed-in tariffs, obligations and tradable green certificates are emerging as the main policy instruments in many developed and increasingly some developing countries. Investment incentives and various tax measures do, however, remain important mechanisms to stimulate renewable energy investment, and it remains to be seen if the current financial crisis will affect policy tools in a potential move back towards more direct government regulation.

The gradual shift from regulatory approaches towards more economic and market oriented policy tools also has implications for the expertise required to develop and implement policies reflecting back on the need for new approaches on the capacity building side. This links in many developing countries with broader shift of the whole perception of RE implementation from niche applications and demonstration projects to having targets and policies at national level. The elements in the new paradigm are illustrated in Table 4 from Martinot (Martinot et al., 2002).

Table 4: New Approaches to Renewable Energy Market Development in Developing Countries

Old Paradigm		New paradigm
Technology assessment	⇨	Market assessment
Equipment supply focus	⇨	Application, value-added, and user focus
Economic viability	⇨	Policy, financing, institutional, and social needs and solutions
Technical demonstrations	⇨	Demonstrations of business, financing, institutional and social models
Donor gifts of equipment	⇨	Donors sharing the risks and costs of building sustainable markets
Programs and intentions	⇨	Experience, results, and lessons

Source: (**Martinot** et al., 2002)

9.5.4 Technical capacity – development and deployment

In most cases, the proprietary ownership of RE technologies is in the hands of private sector companies and not in the public domain and the diffusion of technologies also typically occurs through markets in which companies are key actors (Wilkins, 2002).

This necessitates a need to focus on the capacity of these actors to develop, implement and deploy RE technologies in various countries. Therefore, besides considering capacity development at the institutional level, the importance of increasing technological capability at the micro or firm–level needs to be addressed (Figueiredo, 2003; Lall, 2002). The concept of firm–level technological capabilities has in this regard been put forward to characterise the ability of companies, as a whole, to utilise technological knowledge efficiently to assimilate, use, replicate, adapt, and generate changes in existent technologies and the ability to develop new technologies, products, and processes (Lall, 1992; Bell and Pavitt, 1993; Dutrénit, 2004). Companies, as organisations, may incrementally accumulate such capabilities over time enabling the company to undertake progressively more demanding, dynamic and innovative activities. This is by no means an automatic process and the literature identifies both failures and successful outcomes of companies' aspirations to increase their technologies capabilities (Metcalfe, 1995; Figueiredo, 2003).

An important strand of literature especially addresses the factors important for capability accumulation in firms in late–industrialising or emerging economies (Sharif, 1994; Hobday, 1995; Perkins and Neumayer, 2005; Mathews, 2007). In many developing countries, the initial focus will be on attainment of basic level capabilities to conduct operational functions and maintenance of RE technologies and/or to manufacture minor sub–components(Chandra and Zulkieflimansyah, 2003; Bell, 2007). In others, companies may be aspiring to achieve higher levels of innovative capability to adapt and develop RE technologies to changing circumstances. The types of capabilities needed are many-sided and country specific, and concerns various company related functions, including prefeasibility phase activities, project engineering, investment decisions, product and process organisation, and more (Jacot, 1997; Lorentzen, 1998).

A variety of factors may have an effect on fostering the accumulation of technological capabilities for RE technology deployment at the firm-level. Organisational intra-firm aspects are important but macro level structures such as industry specific regulations, political and economic factors, legal issues, cultural and social factors, etc., plays an equally important role. The supporting structure of technology-specific, national, or regional system of innovation for increased RE deployment may therefore be influential (Jacobsen and Johnson, 2000). National and cross-national company partnerships as well as technical assistance and joint cooperation programs for RE technologies may also influence capability accumulation positively.

Capacity building and technical support by or for the public sector can usefully address issues that facilitate more rapid development and implementation of RE by private companies and can for example cover issues like resource and technology data, testing and licensing, research and development. Resource and technology is an area for capacity development especially for developing countries, but also in many industrialised countries is the lack of appropriate data on resources and technology performance an important barrier to increased RETs implementation. Regarding testing and licensing, an important contribution to the successful development of the wind industry was the enforcement of strict testing and licensing procedures – still applicable – which helped ensure that quality of the developed turbines was high and in this way increased the credibility of a new technology. This approach is increasingly replicated in other technology areas and will facilitate credibility both with the end user and with the financing institutions involved in providing capital for the up-front investment. Linked with the more official certification approach could be campaigns aimed at companies creating better awareness of the importance of strict quality assurance to guarantee reliable services and products. Many early experiences with RE technologies in the seventies were based on poor quality products and provided a longer term setback on the market. Concerning research and development, governments individually or in the context of regional or bilateral collaboration will need to step up the investments in general technological advances and demonstrations both on individual technologies, integrated energy systems or implementation measures. Compared to other areas like nuclear fusion and fission the funds devoted to RE research and development have been on a much lower scale. For example the OECD country governments in 2005 are estimated to have spent 9.6 billion USD on energy related research with approx. 1.1 billion for renewable broadly and 3.9 billion on nuclear (OECD, 2008, 2008). This is not arguing for lowering funding for nuclear research but significantly increasing the R&D for RE as is being demonstrated by several countries that have substantially increased funding during 2008-09.

In the context of the UNFCCC technology transfer has been a permanent issue as part of the negotiations and there is a strong focus in current talks to have new dedicated efforts as part of a possible new agreement. This is expected to among other issues to focus on: (i) Development of effective policy frameworks to accelerate the transfer, deployment and dissemination of existing and new technological solutions; (ii) Strengthen investment, research, innovation, information and skills sharing, dissemination and uptake of clean technologies, through bilateral and multilateral partnerships; (iii) Promote sustained and joint efforts between government and the private sector, including the financial sector, to promote the market for new technologies; (iv) Provide technical support to developing countries in conducting and improving their technology needs and in transforming such assessments into bankable technology transfer projects that meet the standards of potential financiers and; (v) Develop international energy management standards to increase the efficient use of existing and future technologies in industry and other sectors.

9.6 Synthesis (consequences of including environmental and socio-economic considerations on the potential for renewable energy, sustainability criteria)

9.6.1 Sustainable renewable energy

From the policy perspective, the main attractions of renewable energy are their security of supply, and the fact that they are environmentally relatively benign compared to fossil fuels. Most forms of renewable energy are available within the borders of one country and or not subject to disruption by international political events. Central and State Governments in many countries have enacted laws and regulations to promote renewable energy and to encourage sustainable technologies. In doing so, they had to define what they meant by “renewable” and “sustainable”, deciding what would be eligible for subsidies and tax concessions. Lobbying frequently interfere in this process, resulting definitions of “renewable” and “sustainable” are often different than their original meaning (Frey and Linke, 2002). At political meetings, the term “sustainable energy” is usually more prescriptive than “energy for sustainable development” (Spalding-Fecher, Winkler, and Mwakasonda, 2005). The questions of renewable and sustainable energy now figure prominently on the political agendas and have their roots in two distinct issues: while renewability is a response to concerns about the depletion of primary energy sources, sustainability is a response to environmental degradation of the planet and leaving a legacy to future generations of a reduced quality of life (Frey and Linke, 2002). Able to provide cost-effective and environmentally beneficial alternatives, the attributes of renewable energy technologies (e.g. straightforward implementation, modularity, flexibility, low operating costs, local availability, security of long-term supply) differ considerably from those for traditional, fossil fuel-based energy technologies (e.g., large capital investments, long implementation lead times, operating cost uncertainties regarding future fuel costs). In this sense, renewable energy technologies are often fully assessed and leading to conclusions of being less cost-effective than the traditional options. Renewable energy resources have also some problematic but often solvable technical and economic challenges (like being generally diffuse, not fully accessible, sometimes intermittent and regionally variable) and may cause local impacts which give rise to concerns and opposition to the development, further fuelled by uncertainties and misinformation (Upreti and van der Horst, 2004). Weighting positive against negative effects can be a complex task. An example are “small hydro” plants pre-defined as renewable and sustainable, whereas “large hydro” is not labelled as this by some legislators, with wide definition variations from jurisdiction to jurisdiction. , from as little as 1MW to as much as 100MW capacity (Frey and Linke, 2002). Another case is bioenergy, as demands grow due to cost-effective strategies for the reduction of greenhouse gas emissions. Trade of biomass-related products changed the traditional view that such fuels should be used in the region where it was produced due to high transport costs and limited availability. There are different reasons for international biomass trade, but the most important drivers are the lower prices (even when sea transport is included), enhanced supply security, favourable energy and subsequent greenhouse gas balances, market access and enhanced socio-economic development. However, concerns arise on the potential negative impacts of bioenergy related activities, e.g. competition with food production; deforestation or high input of agrochemicals; increased water use and many other indirect effects. Criteria and tools are searched for that help to avoid that biomass, unsustainably produced, is sold as a sustainable resource. Previous experiences in the forestry (since 1993) and agricultural (since 1991) sectors are useful tools containing sustainability criteria and indicators (Lewandowski and Faaij, 2006).

9.6.2 Assessment tools and policy implications

The environmental impacts associated with RE clearly vary by technology, location, availability of resources (e.g., water), the potential for human exposure, and local ecological susceptibilities. Tools for environmental impact and sustainability include: (i) life cycle assessment (LCA), to assess the environmental burden of products (goods and services) at the various stages in a product’s life cycle (“from cradle-to-grave”); (ii) environmental impact assessment (EIA), assessing the potential environmental impact of a proposed activity, assisting a decision making process; (iii) ecological footprints analysis, an estimation of resource consumption and waste assimilation requirements of a defined human population or economy in terms of corresponding productive land use; (iv) sustainable process index (SPI), measuring a process producing goods in terms of total land area required to provide raw materials, process energy (solar derived), infrastructure and production facility and disposal of wastes; (v) material flux analysis (MFA), an accounting tool to track the movement of elements of concern through a specified system boundary; (vi) risk assessment, to estimate potential impacts and the degree of uncertainty in both the impact and the likelihood it will occur; (vii) exergy, analysis of the quality of a flow of energy or matter, estimating its useful part. Energy potential surveys and studies have a useful role in promoting renewables. Existing energy utilities are important to determining the adoption and contribution of renewable energy technologies and their integration to the system. The importance of effective information exchange, education and training programs lie in the fact that the use of renewable energy often involves awareness of perceived needs and sometimes a change of lifestyle and design. Energy research, technology transfer and development, together with demonstration projects, improve information and raise public awareness, stimulating a renewable energy market. Financial incentives reduce up-front investment commitments and encourage design innovation (Dincer and Rosen, 2005).

Proper assessments and comparisons of such issues typically require a life-cycle assessment (LCA) approach. Ideally, an LCA will characterize the flows of energy, resources, and pollutants across the life-cycle of an RE technology, which includes activities related raw materials acquisition, manufacturing, transportation, installation and maintenance, operation, and decommissioning. The ecological and human impacts associated with such flows are further characterized across a range of impact metrics (e.g., global warming potential, human health damages, ecotoxicity, and land use). As such, LCA provides a framework for assessing and comparing RE technologies in an analytically-thorough and environmentally-holistic manner. Formal LCA methodologies have evolved over the past 20 years (SAIC, 2006), and have been steadily refined and improved over time through various international working groups (e.g., (UNEP, 2009), professional associations (e.g., (ACLCA, 2009)), and methodological standards initiatives (e.g., (ISO, 2006). As discussed in previous chapters, LCA is now being applied with increasing frequency to environmental analyses of RE technologies, most notably biofuel systems, wind energy, and solar energy. This report also shows that LCA considerations are increasingly being adopted by governments to guide far-reaching policies that accelerate RE technology adoption, such as California's Low Carbon Fuel Standard (California Energy Commission (CEC), 2009) and the U.S. EPA's Renewable Fuel Standard (United States Environmental Protection Agency (EPA), 2009). Despite the increasingly widespread application of LCA to RE technologies, key analytical limitations and challenges exist. Notably, most LCAs of RE technologies focus predominantly on life-cycle energy and GHG emissions characterization, with less attention to other key resource inputs (e.g., water) and environmental impact categories (e.g., ecological and human health impacts). The narrow focus on energy and GHG emissions can probably be attributed to several key factors: (1) the relative ease of data access for life-cycle fuels and GHG emissions compared to more obscure data required for emissions related to other environmental impacts; (2) the obvious policy relevance of understanding GHG emissions abatement potentials of RE technologies; and (3) a lack of scientific methods and consensus on characterizing localized impacts such as land use, biodiversity loss, and ecological and human health impacts. It will be important to address these challenges moving forward so that RE technologies can be assessed across a fuller spectrum of environmental impacts, such as those discussed previously in Section 9.3. More complete LCAs would allow for better understanding of the potential tradeoffs across this diverse range of impacts—and possible unintended consequences associated with large-scale RE technology deployment—such that they can be managed and mitigated through the appropriate policy measures.

As discussed in Chapter 2, a number of fundamental methodological challenges exist as well. Major issues include lack of credible data to conduct full LCAs for most RE technologies, defining sound functional units such that RE technologies can be properly compared to each other and to existing fossil fuel sources, and consensus on analytical system boundaries. Furthermore, for increased policy relevance LCA needs to move beyond characterization of straightforward RE technology "footprints" (i.e., an attributional LCA approach) towards analyses that assess the impacts of RE technologies in more dynamic and macro-economic contexts (i.e., a consequential LCA approach).

A move toward the latter approach would allow the full effects RE technologies on environmental, social, and economic systems to be assessed simultaneously for more informed policy making.

Still, as this report shows, the application of LCA to RE technologies has provided many important insights to date. Previous LCAs have shed light on the net energy and GHG emissions balances of RE technologies compared to fossil fuels, vastly increased our knowledge of the complex life-cycle systems and environmental interactions associated with RE technologies, increased our understanding of potential environmental tradeoffs, and uncovered key methodological and data challenges. As such, this work has laid a critical foundation for continuously improving LCA as a policy-relevant decision-making tool for RE policies.

9.6.3 Sustainable energy policies in developing and developed countries

Energy policy came to the fore with the oil crisis of the 1970s, bringing about considerable concerns over security of energy supply, environmental issues, competitiveness of economies and regional development. Before then, governments had largely paid attention to electrification via grid extension and created large integrated monopolies that generated, transmitted and distributed electricity. In most countries in Western Europe governments were engaged in nuclear power development. In some countries governments also involved themselves in the supply of oil, coal and/or natural gas. Renewable energy sources, with the exception of hydropower in countries having significant hydropower potential, attracted very little interest (Johansson and Turkenburg, 2004). With the crisis, research, development and deployment of renewable energy had flourishing years, until the relative political stability in the Middle East reduced international oil prices, making it difficult for renewable energies to compete in the market. There were exceptions, such as hydropower, an already mature technology. Other renewables, such as biomass, solar and wind, evolved considerably during the crisis, with reducing costs and significant environmental advantages over non-renewable technologies that provided the basis for a new growth after the late 1990´s (Frey and Linke, 2002). Practical experience has shown that support for renewable energy technology development is a way to build a competitive industry that will have a global market, as alternatives to conventional energy sources are increasingly sought.

Energy for sustainable development has three major pillars: (1) more efficient use of energy, especially at the point of end-use, (2) increased utilization of renewable energy, and (3) accelerated development and deployment of new and more efficient energy technologies (Johansson and Turkenburg, 2004). The 9th Session of the CSD, held 16–27 April 2001 in New York, was the first time energy was addressed in an integrated way within the United Nations system. The conclusions of CSD9 are particularly important because they formed much of the basis for the UN World Summit on Sustainable Development (WSSD, also known as “Rio+10) negotiations in Johannesburg, 2002 (Johansson and Turkenburg, 2004). Energy was probably the most intensely debated subject at the WSSD. Proposals were made at WSSD to adopt a global target for renewable energy, increasing the share to 10% by 2010. Although no agreement was reached, the final text recognized the importance of targets and timetables for renewables (Johannesburg Plan of Implementation, paragraph 19) a text that significantly advanced the attention given to energy in the context of sustainable development. Setting a target for renewable energy was one of the most controversial issues during the WSSD. The fundamental issue was whether to set any global target at all. Energy continues to be a ‘cross-cutting issue’, with no dedicated institutional structure for energy within the UN system[2]. Several voluntary energy initiatives (called “Type 2”, contrasting

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[2] UN-Energy is an interagency mechanism on energy, established to help ensure coherence in the UN system’s multi-disciplinary response to the World Summit on Sustainable Development (WSSD) and to ensure the effective engagement of non-UN stakeholders in implementing WSSD energy-related decisions. It aims to promote system-wide collaboration in the area of energy with a coherent and consistent approach since there is no single entity in the UN

with “Type 1” multilateral agreements) were launched at WSSD, but without the character of an international negotiating forum. Political leadership still does not exist on both energy access and cleaner energy. (Spalding-Fecher, Winkler, and Mwakasonda, 2005).

The Clean Development Mechanism (CDM), established under the Kyoto Protocol, is an important driver for renewable energy technologies. However, it is not totally clear that when renewable energy policies may establish mandatory targets, these can or cannot conflict with the additionality criteria of CDM projects. An answer may be in the CDM Executive Board (CDM EB, 2009) decision which has stated that national and/or sectoral policies or regulations that give positive comparative advantages to less emissions-intensive technologies over more emissions-intensive technologies (e.g. public subsidies to promote the diffusion of renewable energy or to finance energy efficiency programs) that have been implemented since 11 November 2001 may not be taken into account in developing a baseline scenario (i.e. the baseline scenario should refer to a hypothetical situation without the national and/or sectoral policies or regulations being in place). Host countries decide whether a project meets its sustainable development needs, but criteria and indicators can be based on previously agreed principles or obligations, such as the Millennium Development Goals or the nationally-prepared Poverty Reduction Strategy Papers. Limitations of comprehensive approaches are the complexity, site and project specificities difficult to the international policy community establishing cross-country frameworks comparability.

The world´s energy system is a very large market and relatively small changes can have a significant influence on efforts to reach sustainability. According to Goldemberg (Goldemberg, 2006b), approximately 1.5 trillion dollars were spent in 2004 on primary energy - without considering the cost of secondary conversion, such as electricity production or fuel refining. Subsidies are difficult to estimate. In the period 1995-98, subsidies to fossil fuels are estimated to be around USD 151 billion per year (coal USD 53 bln/yr; oil USD 52 bln/yr; gas USD 46 bln/yr) while to nuclear these amounted to USD 16 billion/yr and to renewables USD 9 bln/yrbsidies comprise all measures that keep prices for consumers below market level or keep prices for producers above market level or that reduce costs for consumers and producers by giving direct or indirect support, in a wide variety of public interventions not directly visible but is hidden in public and economic structures. Policies that aim to promote the instigation of renewables, but fail to deliver a reliable and economically beneficial supply in the long-term, fail to contribute to the concept of sustainability. To change this situation, solutions encompass extending the life of fossil fuel reserves and expanding the share of renewable in the world energy system through top down and bottom up policies. The best example of a top down approach is the Kyoto Protocol, which established mandatory targets for countries for the reduction of greenhouse gas emissions. A Renewables Portfolio Standard (RPS) is a policy that states may use to remove market barriers to renewable power and ensure that it continues to play a role in the competitive environment that follows restructuring of the electricity generating industry. In their simplest form, Renewables Portfolio Standards specify that a percentage of all electricity generated must come from specified renewable energy sources such as wind, hydroelectric, solar energy, landfill gas, geothermal, and biomass (Goldemberg, 2006a).

National renewable energy policies in South Africa, Egypt, Nigeria and Mali were analyzed by Bugaje (Bugaje, 2006). Main constraints to access of other forms than fuelwood of energy in the rural areas are the high capital costs for electrical grid connection, installation and maintenance of appliances and limited distribution of petroleum fuels due to the poor or lack of private or public transport, as well as limited support services. Renewable energy resources, abundant in all the African countries, would provide a major breakthrough in finding a solution to this energy crisis.

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system that has primary responsibility for energy. Secretariat services are provided by the United Nations Department of Economic and Social Affairs – DESA (UN-Energy, 2006).

While South Africa and Egypt present very encouraging models of renewable energy harnessing and utilization, Mali provides a case study of urgency in addressing sustainable energy policy especially in view of the environmental degradation associated with the traditional energy use patterns. Nigeria is a case of abundance of resources - both conventional and renewable - but lack of infrastructural support to harness the renewable resources. South Africa seeks to increase significantly the share of renewable energy. Egypt has policies to develop and diffuse the application of solar (thermal and photovoltaic), wind and biomass energy technology in the local economy.

For large emerging economies energy choices and the related strategic policies are required at the earliest opportunity, to fulfill four key objectives: (1) to deliver the power needed for economic growth and sustainable development; (2) to ensure security of energy supply; (3) to ensure that energy supply and use are conducted in ways that safeguard public health and the environment; (4) to achieve an equitable distribution of energy services (Weidou and Johansson, 2004). In developed countries, there are examples of how sustainable development strategies constituted by a combination of savings, efficiency improvements and renewables can be implemented. Two major challenges are how to integrate a high share of intermittent resources into the energy system (especially the electricity supply) and how to include the transportation sector in the strategies. Reaching this stage of making sustainable energy strategies the issue is not only a matter of savings, efficiency improvements and renewables. It also becomes a matter of introducing and adding flexible energy technologies and designing integrated energy system solutions (Lund, 2007). Even if technology developments will reduce the specific consumption, the world energy demand is likely to increase in line with its population. Energy and material efficiency and the integration of the renewable resources will therefore have to play a major role for sustainable development. The challenge concerns not only the technologies at the conversion and useful energy level, but also the energy management and infrastructures (Marechal, Favrat, and Jochem, 2005)3.

The Organization for Economic Cooperation and Development, together with the International Energy Agency (OECD, 2008) have organized a dataset of existing renewable energy policies by country, describing issues related to sustainable development. Policies were classified by type (Regulatory Instruments; Financing; Incentives, subsidies; Education and Outreach; Policy Processes; Voluntary Agreement; RD & D; Tradable Permits; Public Investment), by target source (Bioenergy, Geothermal, Hydropower, Ocean, Solar, Multiple RE Sources) and sector (Electricity, Framework Policy, Heating & Cooling, Transport and Multi-sectoral Policy). Examples of such RE-SD policies in force in developing countries include: (i) biofuels promotion laws with Environmental Impact Assessment procedures (Argentina); (ii) promotion of best practices (through UK in several countries); (iii) mandatory solar stills for schools (Barbados); (iv) mini-grid projects (Brazil); (v) mandatory biofuels blending requirements (Brazil, Phillipines); (vi) solar in buildings (China, Fiji, Ghana, South Africa, Uganda); (v) subsidies to renewables in rural areas (China); (vi) efficiency improvements (Turkey) also with closure of inefficient facilities (China); (vii) feed-in tariffs (India); (ix) RE targets (Israel); (x) women empowerment (Mali); (xi) R&D (Russia, Singapore).

9.7 Gaps in Knowledge and Future Research Needs

As noted in the introductory section, there is a two-way relationship between sustainable development and renewables. Renewable sources can reduce emissions that will help to better manage the process of climatic change but this reduction may not be adequate to lower temperature increases to tolerable levels. Sustainable development pathways can help achieve these reductions

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[3] The Board of the Swiss Institutes of Technology suggests pathways to the 2000W per capita society (Marechal et al, 2005)

by lowering the overall need for energy particularly fossil fuel supply. Pathways that improve energy access and infrastructure in rural areas for example can lead to less-carbon-intensive energy demand thus reducing the need for overall energy supply. Identifying, documenting and quantifying such pathways and their impact on renewables is a critical need.

A related important step is to identify non-climate policies that affect GHG emissions and sinks, and ways these could be modified to increase the role of renewable energy sources. Often such policies have to be context specific requiring research and analysis that is local or regional.

The current set of global models has rarely looked at development paths with non-climate policies. Development of such models requires a broader set of researchers with strong quantitative SD background who can help define and understand various development paths such as those described in Appendix A. This applies to both industrialized and developing countries.

Renewables mitigation and adaptation capacity will be critical in the future as implementation of projects and programs begins to play an increasingly important and time-sensitive role. Limiting temperature increases to 2 degrees C for instance requires that global emissions peak within the next decade. Even if agreements are reached soon to limit global emissions, capacity building to implement renewable energy policies, programs and projects will be essential. Turning capacity into rapid action will require cooperation among all stakeholders.

Future research will need to examine the role of renewable energy and its implications on the pursuit of sustainable development goals. Several chapters in this report provide information on the implications of renewable energy sources on various SD attributes. These are noted in Tables 1 and 2, which includes both quantitative and descriptive information about the impacts. Missing in the table is a complete understanding of the life-cycle analysis (LCA) of the implications of the use of renewable energy. The biofuels chapter contains the most information on this topic, but it correctly notes that methods, tools, and data sources are not of sufficient quality and comparability yet. Future work will need to focus on this important aspect of renewable energy, which has few and in some case virtual no direct GHG emissions but may have significant indirect emissions.

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Appendix A: RE and conventional technologies: Impact on selected SD indicators

Each cell entry assumes that:
1. Renewable resource is available, and energy and/or electricity is produced on site.
2. Local emissions may vary by regional grid and site; a range may be provided where data are available.
3. Information below is both qualitative and quantitative (when available). Quantitative data is all supported by public reference (annexed to interested parties).
4. Units of measure used by references for each indicator are included in the table (example: gCO2/kWh). Equivalence table given at end when different units are used by different references.
5. For costs, most updated information from IEA was preferred.

ENVIRONMENTAL ISSUES

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal***	***Hydro***	***Ocean***	***Wind***	***Oil***	***Gas***	***Coal***	
Emissions and Air Quality. Unit: gCO_2e/kWh	Renewable electricity technologies have inherently low life-cycle CO2 emissions as compared to fossil-fuel-based electricity production, with most emissions occurring during manufacturing and deployment. Renewable electricity generation also involves inherently low or zero direct emissions of other regulated atmospheric pollutants, such as sulfur dioxide, nitrogen oxides, and mercury. (**NAP**, 2010)									

	Sustainable GHG emissions, but there is a risk of unsustainable harvesting. Net GHG emissions in most cases of land use change. Local emissions vary according to fuel and technology, including end of pipe controls. (Ranges available from the US EPA AP-42 database) Fuelwood 120 (**Adamantiades** and Kessides, 2009) (92-156) (**Dones**, Heck, and Hirschberg, 2003) LCA Biomass (35 - 178) (**Varun** and Bhat, 2009)	Minor emissions during operations. Lifecycle emissions are more important. PV 90 (**Evans**, Strezov, and Evans, 2009) (9.4 – 300) (**Varun** and Bhat, 2009) 60 (**Adamantiades** and Kessides, 2009) 79 (**Dones**, Heck, and Hirschberg, 2003) (50-160) (**Voorspools**, Brouwers, and D'haeseleer, 2000) Equivalent Life Cycle (19 – 59) (**Jacobson**, 2009) LCA PV (53.4 – 250) (**Varun** and Bhat, 2009) (60-130) (**Voorspools**, Brouwers, and D'haeseleer, 2000) Solar Thermal (36.2 – 202) (**Varun** and Bhat, 2009)LCE (8.5 – 11.3) (**Jacobson**, 2009) (13.6-202) (**Varun** and Bhat, 2009)	Site specific emissions, including sulfur compounds. Lifecycle emissions. Hydrothermal (0-40.3) (**Tester** et al., 2006) 170 (**Evans**, Strezov, and Evans, 2009) (15.1 – 55) (**Jacobson**, 2009) (0-40.3) g/kWh (**Kagel**, Bates, and Gawell, 2007; **Kagel** and Gawell, 2005)	Site specific methane emissions from some reservoirs, high range, few reservoirs of global total 41 (**Evans**, Strezov, and Evans, 2009) (3-27) (**Dones**, Heck, and Hirschberg, 2003) (17 – 22) (**Jacobson**, 2009) Lifecycle emissions, mainly in construction phase. LCA's of hydro indicates: Run off River 3.7 – 18 (**Varun** and Bhat, 2009) Reservoirs (Japan) 237 (**Varun** and Bhat, 2009) Storage 4.5 (**Varun** and Bhat, 2009) Small Hydro (18 - 74.9) (**Varun** and Bhat, 2009)	No emissions during operations. Lifecycle emissions. Neutral (**O'Rourke**, Boyle, and Reynolds) Tidal 14 (**Jacobson**, 2009) Wave 21.7 (**Jacobson**, 2009)	No direct emissions during operations. Lifecycle CO2 emissions due to manufacturing, transport, & installation reported (2.8 – 7.4) (**Jacobson**, 2009) Onshore 9.7 (**Schleisner**, 2000) (24-27) (**Voorspools**, Brouwers, and D'haeseleer, 2000) Offshore 16. 5 (**Schleisner**, 2000) (7.9-9.2) (**Voorspools**, Brouwers, and D'haeseleer, 2000) (14-21) (**Dones**, Heck, and Hirschberg, 2003) Some limited additional CO2 emissions due to balancing reserves needed to manage wind output variability. (25) (**Evans**, Strezov, and Evans, 2009) (16,5-123.7) (**Varun** and Bhat, 2009) LCA (9.7 – 123.7) (**Varun** and Bhat, 2009) (9-25) (**Voorspools**, Brouwers, and D'haeseleer, 2000) 6.6 (**Vestas**, 2006)	Oil 870 (**Adamantiades** and Kessides, 2009) (519-1190) (**Dones**, Heck, and Hirschberg, 2003) 758 (**Tester** et al., 2006) 758g/kWh (**Kagel** and Gawell, 2005) Diesel 730 (**Adamantiades** and Kessides, 2009) LCA Oil Fired 742.1 (**Varun** and Bhat, 2009) Fossil Fuel Plants release 8.5 billion metric tons of carbon directly into the atmosphere (**Adamantiades** and Kessides, 2009)	543 (**Evans**, Strezov, and Evans, 2009) 550 (**Tester** et al., 2006) (485-991) (**Dones**, Heck, and Hirschberg, 2003) Natural Gas 650 (**Adamantiades** and Kessides, 2009) 550g/kWh (**Kagel** and Gawell, 2005) Natural Gas CC 440 (**Adamantiades** and Kessides, 2009) LCA Gas Fired 607.6 (**Varun** and Bhat, 2009)	1004 (**Evans**, Strezov, and Evans, 2009) (949-1280) (**Dones**, Heck, and Hirschberg, 2003) 994 (**Tester** et al., 2006) 994g/KWh (**Kagel**, Bates, and Gawell, 2007), (**Kagel** and Gawell, 2005) Lignite 1240 (**Adamantiades** and Kessides, 2009) Hard Coal 1060 (**Adamantiades** and Kessides, 2009) LCA Coal Fired 975.3 (**Varun** and Bhat, 2009) CCS 255-442 (**Jacobson**, 2009)	No emissions during operations. Emissions during the life cycle may be significant, in mining, uranium enrichment, decommission etc. Potential of radioactive emissions in case of accidents and leakages. LCA 24.2 (**Varun** and Bhat, 2009) LCA (2-4) (**Voorspools**, Brouwers, and D'haeseleer, 2000) 30 (**Adamantiades** and Kessides, 2009) (in the complete nuclear power chain) (9 – 70) (**Jacobson**, 2009) (8-11) (**Dones**, Heck, and Hirschberg, 2003)

Selected Environmental SD	RE Technologies						Conventional Fossil Fuel Technologies			Nuclear
	Bio-Energy	Direct Solar	Geothermal	Hydro	Ocean	Wind	Oil	Gas	Coal	

Water Quantity and Quality Unit: m3//MWh. Indicates water consumption, unless indicated	Agrochemicals may affect water quality . Irrigation required in non-rain fed areas. Possibility of competition with other water uses. Water for cooling thermal plants. Thermal pollution. Leakages can affect ground water quality and recharge. Biodiesel-vegetables 3500000 m3/MWh (**La Rovere**) Biodiesel-perennials 1200000 m3/MWh (**La Rovere**) Biomass (1134 - 1814) Lt/MWh (**Rio Carrillo** and Frei, 2009) Waste (residue) (756 - 1814) Lt/MWh (**Rio Carrillo** and Frei, 2009) Fossil/Biomass steam turbine Open Loop (0.757-1.136) m3/MWhe (**Hightower**, 2009) Closed Loop (1.136-1.817) m3/MWhe (**Hightower**, 2009) Biomass 1.329m3/MWha (**Pasqualetti** and Kelley, 2008) Water Footprint (24 – 143) m3/GJ (**Gerbens-Leenes**, Hoekstra, and Meer, 2009)	Limited water usage and pollution during manufacturing and utilization Can be utilized to disinfect biologically contaminated water Concentrating Solar 2.801m3/MWhe (**Hightower**, 2009) PV 10 kg/kWh (**Evans**, Strezov, and Evans, 2009) 0.0 m3/MWhe (**Hightower**, 2009) Solar Thermal 1.177m3/MWha (**Pasqualetti** and Kelley, 2008) Large Solar Thermal (3.028-3.785) m3/MWha (**Pasqualetti** and Kelley, 2008) PV < 0.004 m3/MWha (**Pasqualetti** and Kelley, 2008) Water Footprint Solar Thermal 0.3 m3/GJ (**Gerbens-Leenes**, Hoekstra, and Meer, 2009)	Minor water usage in the binary-cycle plants (most of them use air cooled circuit) Sulfur emission could be transformed into acid and acid rain. Zero for Geothermal flag cycle generation (0.012 – 0.300) m3/kWh (**Evans**, Strezov, and Evans, 2009) Geothermal 5.110m3/MWhe (**Hightower**, 2009) < 0.0189m3/MWha (**Pasqualetti** and Kelley, 2008)	Possibility for water storage; limited water pollution in the reservoirs from biomass rotting. Release of sediment from water sometime may cause downstream erosion 0.036 m3/kWh (**Evans**, Strezov, and Evans, 2009) 0.715 – 3.145 m3/MWh (**Rio Carrillo** and Frei, 2009) WC for electricity generation in supply lakes (10.000 – 70.000) (**Rio Carrillo** and Frei, 2009) Water footprint 22 m3/GJ (**Gerbens-Leenes**, Hoekstra, and Meer, 2009)	N/A	Limited water usage and pollution during manufacturing and utilization Water Footprint 0-1 m3 /MWh (**Evans**, Strezov, and Evans, 2009)	Risk of spills (0 – 1.814) m3/MWh (**Rio Carrillo** and Frei, 2009) Water Footprint 1.1 m3/GJ (**Gerbens-Leenes**, Hoekstra, and Meer, 2009)	m3/MWh (**Evans**, Strezov, and Evans, 2009) (0.94 - 39.6) m3/MWh (**Rovere** et al.) (0 – 1.814) m3/MWh (**Rio Carrillo** and Frei, 2009) Cycle Combined Open Loop 0.379 m3/MWhe (**Hightower**, 2009) Close Loop 0.681 m3/MWhe (**Hightower**, 2009) Open Loop 1.862 m3/MWha (**Pasqualetti** and Kelley, 2008) CC 1.325 m3/MWha (**Pasqualetti** and Kelley, 2008) Water Footprint 0.1 m3/GJ (**Gerbens-Leenes**, Hoekstra, and Meer, 2009)	Water usage for washing; pollution due to this 0.078 m3/kWh (**Evans**, Strezov, and Evans, 2009) (0.756 -1.815) m3/MWh (**Rio Carrillo** and Frei, 2009) (1.931-2.074) m3/MWha (**Pasqualetti** and Kelley, 2008) Integrated Gasification Combined-Cycle 0.681 m3/MWhe (**Fillmore**, 2009) Water Footprint 0.2 m3/GJ (**Gerbens-Leenes**, Hoekstra, and Meer, 2009)	Water usage for cooling; risk of high pollution 4.1 m3/MWh (**Rovere** et al.) (1.512 – 2.722) m3/MWh (**Rio Carrillo** and Frei, 2009) Nuclear Steam Turbine Open Loop 1.514 m3 /MWhe (**Hightower**, 2009) Closed Loop (1.514-2.725) m3/MWhe (**Hightower**, 2009) 2.972 m3/MWha (**Pasqualetti** and Kelley, 2008) Water Footprint 0.1 m3/GJ (**Gerbens-Leenes**, Hoekstra, and Meer, 2009)

Selected Environmental SD	RE Technologies						Conventional Fossil Fuel Technologies			Nuclear
	Bio-Energy	Direct Solar	Geothermal	Hydro	Ocean	Wind	Oil	Gas	Coal	

Land and soil Unit: m^2/GWh	Agricultural land occupation for growing, possible soil pollution. Biofuels can provide long-term GHG emission mitigation even if displacing vegetation with considerable carbon stocks. Nevertheless, sugar cane plantation implemented only over tropical forests does not contribute to C mitigation and should be avoided due its negative carbon balance and other impacts caused to the environment. (**Pacca** and Moreira, 2009) Biodiesel-wastes 0.04 Biodiesel-vegetables 25,069 m^2/kW (**Rovere** et al.) Biodiesel-perennials 4,200 m^2/kW (**Rovere** et al.) (101 - 193) m^2/GJ (**Fthenakis** and Hyung)	Land occupation for large solar thermal power but usually unused for other purposes Solar Thermal 3561 m2/GWh (**Kagel**, Bates, and Gawell, 2007) 3200 m2/GWh (**Tester** et al., 2006) 2500 m2/GWh annual PV (28 -64) (**Evans**, Strezov, and Evans, 2009) 3237 m2/GWh (**Kagel**, Bates, and Gawell, 2007) 7500 m2/GWh (**Tester** et al., 2006) (164 - 549) m2/GWh (**Fthenakis** and Hyung) 20000 m2/GWh annual(**Tampier**, 2002) Solar Thermal Tower 552 m2/GWh (**Fthenakis** and Hyung) Solar Thermal Parabolic Trough 366 m2/GWh (**Fthenakis** and Hyung)	Limited land occupation; some risk of soil pollution. No soil pollution in currently operating plants. (18 - 74) (**Evans**, Strezov, and Evans, 2009) 404 m2/GWh (**Kagel**, Bates, and Gawell, 2007) 3750 ha/TWh annual(**Tampier**, 2002) 160-900 m2/GWh (**Tester** et al., 2006)	Land submergence for reservoirs, may include some productive soils (73 – 750) (**Evans**, Strezov, and Evans, 2009) Large hydro 75,000 ha/TWh annual(**Tampier**, 2002) Reservoirs (2,350 - 25,000) m2/GWh (**Fthenakis** and Hyung) Run of River 3 m2/GWh (**Fthenakis** and Hyung) 28 ha/TWh annual (**Tampier**, 2002) (1300 - 10500) m2/GW (**Rudnick** et al., 2008)	Minor land occupation on coasts	Limited land occupation (1030 – 3230) m2/GWh (**Fthenakis** and Hyung, 2009) 72 (**Evans**, Strezov, and Evans, 2009) 1335 m2/GWh (**Kagel**, Bates, and Gawell, 2007) 50 m2/kW (**Rovere** et al.) 116,666 m2/GWh annual (**Tampier**, 2002)	Land occupation for mining and processing; possibility of soil contamination (250-2000) m2/GWh annual(**Tampier**, 2002)	Land occupation for developing gas fields and processing and supply installations Natural Gas 0.222 m2/kW (**Rovere** et al.) (250-2000) m2/GWh annual(**Tampier**, 2002)	Significant land occupation for mining, processing and wastes 3642 m2/GWh (**Kagel**, Bates, and Gawell, 2007) 5700 m2/GWh (**Tester** et al., 2006) 3630 m2/GWh annual (**Tampier**, 2002)	Land occupation for mining, processing and wastes 1.74 m2/kW (**Rovere** et al.) 480 m2/GWh annual(**Tampier**, 2002) 1200 m2/GWh (**Tester** et al., 2006)

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal***	***Hydro***	***Ocean***	***Wind***	***Oil***	***Gas***	***Coal***	
Hazardous Waste Risk Unit: tons	Possibility for waste from by-products	N/A	Risk of pollution by toxic water and air. Residual water is usually re-injected into reservoir.	sediments and nutrients during failure of a dam or during flood water	N/A	Minor volumes of hazardous waste produced during manufacturing process.	Risk of spills	Gas leak from the pipeline and fire hazard from the gas field could be dangerous	Risk of fires in waste fields	High risk 12,000 metric tons a year from the world's nuclear power plants, ie, 4.6875 kg/GWh (**Adamantiades** and Kessides, 2009)

Ecosystems and biodiversity	Monoculture growing; Adverse impacts on biodiversity for land clearance; Positive impacts on local biodiversity from stabilized vegetation cover	Some limitation of solar irradiation on the soil surface	Hot water spills, introduction of thermally tolerable species. No major impacts on ecosystems and biodiversity	Biodiversity loss from inundation of forests. New lake habitats created, may replace terrestric with aquatic biodiversity. Alteration of downstream habitat for modification of flood regime and lack of nutrients in the released water	Limitation of biodiversity near dams and some turbines. Introduction of mollusks and water plants on constructions	Direct bird and bat fatalities; some impacts on ecosystem structure. Impacts are modest compared to other human activities, and can be reduced through careful siting.	Change of vegetation and wildlife in the mining and processing areas	Some change of vegetation and wildlife in the gas field areas Fire hazard could be dangerous to ecosystem and biodiversity	Significant change of vegetation and wildlife in the mining areas and waste fields	Risk of radiation-influencing changes in biodiversity

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal***	***Hydro***	***Ocean***	***Wind***	***Oil***	***Gas***	***Coal***	
Natural and built environment/ Visual Aspect	Sometimes positive (blossoming cultures, young forest, etc.). Displacement of poor from the marginal and degraded land	Large areas occupied by installations. Change of albedo; large solar stacks can affect visual aspect of built environment.	Some concerns for impacts on natural areas that might share their use with recreation, and SPA. Potential impacts on natural geothermal features such as geysers	Can cause damage to existing built environment like settlements; New structures can add positive impacts Dams and reservoirs can be used for recreation, navigation, water supply, flood control etc.	Sometimes large structures (dams, barriers, etc.)	Visual impacts can be significant, but depend on project location, attitude of local population, and other factors. Visual impacts, land and marine usage and nuisance effects can be major obstacles for acceptance. Risk of collision for birds and bats; infrasound effects. Complaints from some people; good for other people	Very large mining and processing structures; stacks with fire	Large mining and processing structures	Large waste fields, sometimes large structures	Large constructions and stacks

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal***	***Hydro***	***Ocean***	***Wind***	***Oil***	***Gas***	***Coal***	
Local Emissions Unit : mg/KWh$_{el}$	Emissions contribution to air quality. Indoor PM, CO from fuel wood. PM, CO, NOx from harvest burning and land clearing (including deforestation). CH_4 (17 – 124) N_2O (14 – 130) NO_x (258 – 1360) CO (18 5 – 898) SO_2 (26 – 315) (**Pehnt**, 2006)	PV / Parabolic CH_4 220 / 35.2 N_2O 1.9 / 0.2 NO_x 340 / 72.9 CO 141 / 85.4 SO_2 288 / 46.7 (**Pehnt**, 2006)	Hot Dry Rock CH_4 103.4 N_2O 2.6 NO_x 188.9 CO 208 SO_2 61.6 (**Pehnt**, 2006)	Small Hydro CH_4 (21 – 29) N_2O (0.4 – 0.7) NOx (36 – 49) CO (59 – 74) SO_2 (17 – 28) (**Pehnt**, 2006)		onshore /offshore CH_4 24.1 / 9.8 N_2O 0.2 /-- NO_x 31.1 / 20.9 CO 96.8 /-- SO_2 39.5 /35.4 (**Pehnt**, 2006)	Significant emissions of pollutants (PM, SOx, NOx, VOCs, heavy metals) and GHGs,	Significant emissions of pollutants (less than oil and coal, except NOx in some cases) and GHGs, some of which can be mitigated	Significant emissions of pollutants (PM, SOx, NOx, VOCs, heavy metals) requiring controls for reduction.	No emissions during operations.

SOCIAL ECONOMIC ISSUES

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies()***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal***	***Hydro***	***Ocean***	***Wind***	***Oil***	***Gas***	***Coal***	
Employment Opportunities Unit: Employment Ratio/MW Include: construction, installation, operation and maintenance.	Studies present employment estimates in terms of jobs and job years, and it is important to understand the difference. For example, a study may predict the creation of 15 job years. This is not the same thing as saying 15 jobs. Fifteen job years can mean one job that lasts for 15 years or it can mean 15 jobs that last for one year. It is important to explain carefully or question what the study is showing for potential job impacts. (**EPA**, 2010) $1 million invested in wind or P produces 5.7 job-years vs 3.9 job-years for coal power. $1 million in energy savings in Oregon produces about $400,000 in additional wages per year. (**EPA**, 2010)									

	Increased job opportunities, particularly in rural areas Biomass electric Employment ratio/MW 4 Construction & Installation 0.14 O&M (**Moreno** and López, 2008) Biodiesel 0.32 Employment/kToe of primary energy generated (**del Río** and Burguillo) Biodiesel-wastes 30 jobs/MWh (**Rovere** et al.) Biodiesel-vegetables 98.6 Jobs/MWh (**Rovere** et al.) Biodiesel-perennials 9.76 Jobs/MWh (**Rovere** et al.) Sugarcane bio-energy (3711-5392) Jobs-year/TWh (**Goldemberg**, 2006a) Wood energy (733-1067) Jobs-year/TWh (**Goldemberg**, 2006a) 0.21 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010)	Jobs in rural and urban areas Solar PV Employment ratio/MW 34.6 Construction & Installation 2.7 O&M (**Moreno** and López, 2008) 7.69 Employment/kToe (**del Río** and Burguillo) (29,580- 107,000) Jobs-year/TWh (**Goldemberg**, 2006a) 0.87 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010) Solar Thermal Employment ratio/thousand m2 2.5 Construction & Installation 5 O&M (**Moreno** and López, 2008) 0.23 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010)	High on local scale compared to natural gas. Because drilling and plant construction must be done at the site of a geothermal resource, local workforce can get better employment opportunities 0.25 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010)	Medium Employment ratio/MW 18.6 Installation & Construction 1.4 O&M (**Moreno** and López, 2008) (**Moreno** and López, 2008) Hydro 250 Jobs-year/TWh (**Goldemberg**, 2006a) Small hydro 120 Jobs-year/TWh (**Goldemberg**, 2006a) 0.27 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010)	High on local scale (Marine energy roadmap)	Employment in manufacturing, installation, and operations. 918-2400 Jobs-year/TWh (**Goldemberg**, 2006a) Direct employment at present estimated at 500,000. (**Global Wind Energy Council (GWEC)**, 2010a) Employment ratio/MW 13 Construction & Installation 0.2 O&M (**Moreno** and López, 2008) 0.36 Employment/kToe (**del Río** and Burguillo) (20 - 45) Jobs/MWh (**Rovere** et al.) 0.17 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010) $1 billion investment in wind generator components creates 3,000 full-time equivalent (FTE) jobs. (**EPA**, 2010) $1 million invested in wind in Iowa produces 2.5 job-years (**EPA**, 2010)	High 260 Jobs-year/TWh (**Goldemberg**, 2006a) Connecticut Employment 2005-2020 (Average annual increase) 430 (**EPA**, 2010)	High 250 Jobs-year/TWh (**Goldemberg**, 2006a) (0.0375–0.075) Jobs/MWh (**Rovere** et al.) 0.11 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010) Connecticut Employment 2005-2020 (Average annual increase) 1668 (**EPA**, 2010)	High 370 Jobs-year/TWh (**Goldemberg**, 2006a) 0.11 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010)	Small 75 Jobs-year/TWh (**Goldemberg**, 2006a) 0.0002 Jobs/MWh (**Rovere** et al.) 0.14 Jobs-year/GWh (over lifetime of project) (**Wei**, Patadia, and Kammen, 2010)
Income and Livelihood	Increase in income in agricultural and forestry sector	Increase income in rural areas of developing countries	Improve livelihood and income in developing countries	Medium – possible loss of productive land. However increase in energy, irrigation	Not developed	Tax payments, land rents, and use of local services can help revitalize the economy of rural communities.	Increases Income – but has negative impact on livelihood in places	Improve livelihood and income	Income generation- High risk occupation	High income generation in a small sector – Living with risk

Economics critical unknowns: □The price of electricity in the future, how prices will be structured, and the explicit or implicit price of CO_2 imposed by any future climate policy (**NAP**, 2010)**.**

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal***	***Hydro***	***Ocean***	***Wind***	***Oil***	***Gas***	***Coal***	
Energy Generation/Supply Costs/ Levelised generation cost. Unit: US/MWh. Source: IEA/OECD/NEA 2010 (**IEA/OECD/NEA**, 2010) & IEA 2008(**IEA**, 2008)	Opportunities for co-generation – reducing cost 2009 (50 – 140) 2050 (49 – 123)	Still relatively high- but becoming more competitive 2009 PV 5% discount rate (215 – 600) 10% discount rate (333 – 600) CSP 2009 (136 - 243) 2030 PV 2030 (140 – 305) CSP 2030 (70 – 220)	Capital-intensive, with low variable costs and no fuel costs Hydrothermal 2009 (65–80) 2030 (30 - 87) 2050 (29 - 84) Hot dry rock (150 – 300) year 2005. (80 – 200) year 2030. (60 – 150) year 2050	High-capacity, low-cost means of energy storage Large Hydro 2009 (45 – 105) 2030 (30 – 115) 2050 (30 – 110) Small Hydro 2009 (48 – 156) 2030 (52 – 130) 2050 (49 – 120)	Not developed Tidal Barrage (60 – 100) year 2005 (50 – 80) year 2030. (45 - 70) year 2050. Tidal Current 2009 (195 -220) 2030 (45 -90) 2050 (40 – 80) Wave (195 -220) 2030(45 -90) 2050(40 -80)	Can be competitive with fossil generation in limited situations. Onshore 5% discount rate (48 – 163) 10% discount rate (70 – 234) Offshore 5% discount rate (101 – 188) 10% discount rate (146 – 261) Onshore cost reduction by 2050: 15-35%, Offshore cost reduction by 2050: 20-45% (**IEA**, 2008)	Fluctuating Price; competitive but subsidized for some uses	Competitive – but subsidized for some uses 5% discount rate (67 – 105) 10% discount rate (76 – 120)	Competitive – but subsidized for some uses 5% discount rate (54 – 120) 10% discount rate (67 – 142)	Competitive – but subsidized 5% discount rate (29 – 82) 10% discount rate (42 – 137)

Additional items to add to price of energy supplied	The cost of new transmission and upgrades to the distribution system will be important factors when integrating increasing amounts of renewable electricity. Transmission improvements can bring new resources into the electricity system, provide geographical diversity in the generation base, and allow improved access to regional wholesale electricity markets. -The structure of renewable portfolio standards, tax policies (production and/or investment tax credits), and other policy initiatives directed at renewable electricity (**NAP**, 2010)				

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal Energy***	***Hydro Power***	***Ocean Energy***	***Wind***	***Oil***	***Gas***	***Coal***	

Investment Unit: US/kW Sources: IEA, 2008 (**IEA**, 2008) & IEA/OECD/NEA 2010 (**IEA/OECD/NEA**, 2010)	Potential for large and small scale investment 2009 (2,960 – 3,670) 2030 (2,550 – 3,150)	Large potential for investors - solar growth 30% every year from 2000 to 2005 PV 2009 (5,730 – 6,800) 2030(2,010 -2,400) CSP 2009 (3,470 – 4,500) 2030 (1,730 -2,160)	Asian countries urging large investment in geothermal Hydrothermal 2009 (3,470 –4,060) 2030 (3,020 – 3540) 2050 (1,400 – 4,900) Hot dry rock 2005 (5,000 – 15,000) 2030 (4,000 – 10,000) 2050 (3,000 – 7,500)	Large and small projects still expanding Large Hydro 2009 (1,970 – 2,600)2030(1,940 – 2,570)Small Hydro 2005 (2,500 – 7,000) (2,200 – 6,500) year 2030. (2,000 -6,100) year 2050.	Developing market Tidal Barrage (2,000 – 4,000) year 2005 (1,700 – 3,500) year 2030. (1,500 - 3,000) year 2050. Tidal Current (7,000 - 10,000) year 2005 (5,000 - 8,000) year 2030. (3,500 – 6,000) year 2050. Wave (6,000 - 15,000) year 2005 (2,500 - 5,000) year 2030. (2,000 – 4,000) year 2050.	Capital investment needs are significant, both for wind projects and associated transmission infrastructure, but world's fastest growing energy source Onshore (**IEA/OECD/NEA**, 2010) 2009 (1,900 – 3,700) 2030 (1440 – 1,600) Offshore (**IEA/OECD/NEA**, 2010) 2009 (2890 – 3200) 2030 (2280 – 2530) Onshore: (1,350 – 2,000) Offshore: (3,200 – 4,600)	Demand increase – Mainly in upstream – risk because of uncertainty over remaining reserves	Demand increase Acts as driver Uncertainty of remaining reserves is risk GNL CC (520- 1800)	Large potential because of expansion in the coal sector – China, India, US 2009 Without CCS (900 – 2,800) With CCS (3,223-6,268)	Heavily promoted to combat climate change – re-emerging investment opportunities III+ 2,600 (current) 2,100 (year 2025) IV 2,500 (year 2030) 2,000 (year post 2050)

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal Energy***	***Hydro Power***	***Ocean Energy***	***Wind***	***Oil***	***Gas***	***Coal***	
Displacement of people people/MW	Case specific. Large scale biomass farming requires adequate land ownership, which may cause displacement of people in some cases and on others may provide jobs in the rural area and therefore additional settlements.	Very unlikely to cause displacements. Providing decentralized energy enhances access and thus better dwellings in isolated areas, relieving population pressure in urban areas.	Case specific, but people displacement may be very rare and in small scale. Improves decentralized energy and settlements close to the energy source.	Case, site, technology specific. Risks of significant displacements, requiring adequate assessments and compensation. (0 – 120) (**Rudnick** et al., 2008)	Very unlikely to cause displacements. Providing decentralized energy enhances access and thus better dwellings in isolated areas, relieving population pressure in urban areas.	Very unlikely to cause significant displacements, but some onshore projects can cause nuisances that effects in local communities, Effects can be minimized by appropriate siting rules and procedures.	Pipelines and other infrastructure projects may displace people. Local pollution from refineries may also have such effects.	Pipelines and other infrastructure projects may displace people.	Mining and quarrying, as well as local pollution (e.g. water contamination) may cause displacements.	Relatively few local displacements close to the power plant. Large accidents can cause very large scale displacements.
Gender equity	Improved biomass systems (e.g. efficient cookstoves) enhance lifestyles and lighten domestic workload. Large scale biomass provides jobs on a gender friendly basis. Biomass power & biomass gasification is relevant for both men and women. (**IRADe**, 2009)	Improved systems enhance lifestyles. Decentralized energy has potential to provide more and gender friendly jobs. Solar PV Plants is relevant for both men and women. (**IRADe**, 2009)	Gender neutral.	Gender neutral. Small Hydro is partially relevant for women. (**IRADe**, 2009)	Gender neutral.	Gender neutral. Power wind is relevant for both men and women. (**IRADe**, 2009)	Conventional energy, usually gender neutral. However, some fuels (e.g. kerosene and LPG) may be the first substitutes to fuelwood for climbing the energy ladder thus promoting gender neutrality,	Gender neutral. Biogas plant is specifically relevant for women (**IRADe**, 2009).	Usually gender neutral, but primitive use of this solid fuel causes domestic health impacts, affecting mainly women, children and the elderly.	Gender neutral.

Water Security	Water usage, wastewaters	Medium	Low	High	Too early to know	Medium	Spills	NA	Coal washing, water contamination	Potential high contamination

Selected Environmental SD	***RE Technologies***						***Conventional Fossil Fuel Technologies***			***Nuclear***
	Bio-Energy	***Direct Solar***	***Geothermal Energy***	***Hydro Power***	***Ocean Energy***	***Wind***	***Oil***	***Gas***	***Coal***	
Poverty Reduction	Cooking, jobs	Reduces poverty	Low	Medium - high	Low	Medium - high	High	High	High	Low
Sanitation	Improved landfills	NA	NA	NA	NA	NA	(-)medium	NA	(-)high	NA
Food Security	Competition for land, cooking, source of fertilizers.	Drying grains					Fertilizers, cooking.	Cooking	NA	NA
Energy Security	Secure source more subject to climate conditions	Secure	Secure source	Secure source more subject to climate conditions	Early technology	Intermittent available	Geopolitical issues, finite	Geopolitical issues, finite.	Largely available	Diversifies sources but poses risks
Energy Access	Wide, easy access particularly for the poor	Easy access particularly for poor.	Limited	Somewhat limited		Somewhat limited				
Energy Affordability	High affordability	Upfront costs	Upfront costs	Long project life, cheap energy after investment is amortized	High initial costs	Competitive technology, providing energy at nearly same cost as conventional				

Infra-structure	Roads for biomass transport	Required, for large scale CSP	Required	Long transmission lines, large dams	Required	Transmission lines		Very intensive in infra-structure.		Security related infrastructure, final waste disposal sites

INTERGOVERNMENTAL PANEL ON climate change

Chapter 10

Mitigation Potential and Costs

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Author(s):	CLAs:	Manfred Fischedick, Roberto Schaeffer
	LAs:	Akintayo Adedoyin, Makoto Akai, Thomas Bruckner, Leon Clarke, Volker Krey, Ilkka Savolainen, Sven Teske, Diana Urge-Vorsatz, Raymond Wright
	CAs:	Sibi Bonfils
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COMMENTS BY TSU TO EXPERT REVIEWERS

Please note that Box 10.2 and 10.3 are to be found at the very end of the document after the bibliography. These two boxes were omitted in the first version of the SRREN SOD.

Please note, that Figures 10.2.8 and 10.2.9 have now axis labels. This labelling has been missed in the first version of the SRREN SOD.

Yellow highlighted – original chapter text to which comments are referenced

Turquoise highlighted – inserted comment text from Authors or TSU i.e. [AUTHORS/TSU: …]

This chapter has been allocated 68 template pages, currently it counts 79 pages (excluding this page and bibliography), so it is 11 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened.

10. Mitigation Potential and Costs

CONTENTS

EXECUTIVE SUMMARY

RE is expected to play an important, and increasing, role in achieving ambitious climate mitigation targets. Although many RE technologies are becoming increasingly market competitive, many innovative technologies in the field of RE still have a long way to go before becoming mature alternatives to non-renewable technologies. Assessing the future role of technologies requires a reflection of different assumptions on key parameter (e.g. cost parameters), an integrative perspective, interactions with other mitigation technologies and the overall energy system has to be considered.

A comprehensive scenario survey (investigation of 165 scenarios representing the most recent integrated modelling literature) shows fundamental differences regarding the role of RE on climate mitigation: for any given GHG mitigation goal, the rate and magnitude of RE deployment is highly variable across the scenarios. The resulting differences, and therefore corresponding uncertainties in terms of the future of the energy system in general and the role of RE in particular, are understandable. Although the scenarios indicate that, all other things being equal, more aggressive mitigation will lead to greater deployment of RE, there are two determining factors that substantially influence this relationship:

(1) the character of the underlying drivers of energy system scale (energy demand) – economic growth and the proclivity to underpin this growth with energy consumption – and

(2) the relative competitiveness of additional options for reducing GHG emissions.

This latter category includes not just the two competing low-carbon energy supply options – fossil energy with CCS and nuclear energy – but also end-use technologies that can reduce energy demand as well as behavioural changes that can lead to reduced demands for energy services.

For any given mitigation goal, RE deployments are at their highest when energy demand is high and when scenario assumptions see RE as more competitive relative to other available supply options. However, different assessments on key parameters and other objectives besides mitigation lead to many scenarios that achieve large RE deployments, even without efforts to mitigate GHG emissions. There are many objectives in energy policies other than climate change mitigation, such as increasing energy security, reducing energy import dependence, making energy more affordable, reducing pollution levels or creating job opportunities, that RE can contribute to and that have served as reasons for establishing incentive schemes to support RE deployment in the recent past in various countries and will continue do so in the future. Additionally, there are many mitigation scenarios with relatively small RE deployments. However, regardless of the various uncertain factors, one fundamental area of consensus among the scenarios stands out: RE expands well beyond its current levels in the vast majority of the mitigation scenarios. By 2050, deployments in many of the scenarios reach 200 EJ/yr or up to 400 EJ/yr, compared to about 62 EJ/yr in 2007.

At a regional level, the scenarios consistently show larger RE deployment levels over time in both Annex 1 and non-Annex 1 countries, particularly in the latter. This result is consistent with the general result that the bulk of mitigation over time must take place in the non-Annex 1 countries given their increasing share of global emissions.

Therefore, the scenarios do generally confirm the intuition about several aspects of RE deployments. Despite the uncertainty in deployment levels, they are highest when mitigation is most aggressive, when the drivers of energy system scale (energy demand) are at their strongest, when demand-side responses to mitigation are smallest, and when RE is most competitive with competing low-carbon options (nuclear energy and fossil energy with CCS) or the application of the latter technologies is limited within the given scenario frame conditions.

The already more mature technologies, such as hydroelectric power, see relatively less expansion and there is less variance in their deployment levels compared to emerging technologies, such as solar power. Deployments of, under the current status, less mature technologies take more time and ultimately exhibit far greater variance across scenarios because of more uncertainty about their technical and economic potentials. Bio-energy deployment is of a dramatically higher scale over the coming 40 years than any of the other RE technologies. By 2050, wind and solar become the second and third most important technologies in terms of deployment levels.

A regional breakdown for the scope of future RE deployment shows growing shares in every world region, but deployment rates still are significantly lower than their technological limits. Therefore, technical potentials are not the limiting factors for the expansion of RE.

A more in depth look on four selected illustrative scenarios (representing the whole range of the investigated 165 scenarios) and, in particular, on the possible contribution of RE in different regions and sectors respective for different applications show a substantial range of results. The total share of RE based electricity production varies significantly from 21% (2020), 22% (2030) and 24% (2050) under Business-as-usual conditions and 38% (2020), 61% (2030) and 95% (2050) pursuing ambitious mitigation targets and limiting access to competing mitigation technologies. The contribution to the heating sector in all scenarios by 2050 lays between 24% following a Business-as-usual pathway and 91% anticipating an advanced market development triggered by specific mitigation targets. However, even if substantial growth rates are combined with these RE deployment paths, they are, in general, lower than what was achieved in the RE industry within the last decade. Furthermore, the resulting RE deployment for most of the RE technologies requires only a smaller part of the given technical potential.

Regarding primary energy demand, the contribution of RE lays between 15% in 2050 under Business-as-usual conditions and, depending on mitigation targets and the settings for competing mitigation technologies, between 34 and 80 % in more mitigation-oriented scenarios. That is combined with a substantial CO_2 reduction potential, which is hard to calculate correctly as it varies substantially by using different CO_2-calculation methods. Under Business-as-usual conditions and using average numbers for CO_2-emission factors, some 6.3 Gt CO_2/a can be avoided by 2050. The most ambitious deployment path for RE is connected with a mitigation potential of 26.5 Gt CO_2/a by 2050, which is equal to approximately 75% reduction of energy-related CO_2-emissions of the analysed baseline scenario.

Cost curves present RE deployments from a different perspective. The concept of abatement, energy and conservation supply curves nowadays is a very often used approach for mitigation strategies setting and prioritizing abatement options. One of the most important strengths of this method is, of course, that the results can be understood easily and that the outcomes of those methods give, on a first glance, a clear orientation as they rank available options in order of cost-effectiveness.

While abatement cost curves are very practical and can provide important strategic overviews, it is pertinent to understand that their use for direct and concrete decision-making has also some limitations. Most of the concerns are, amongst others, related to simplification issues, difficulties with the interpretation of negative costs, the reflection of real actor's choice, uncertainty factors with regard to discount rates as a crucial assumption for the resulting cost data, the missing dynamic system perspective considering relevant interactions with the overall system behaviour (in particular necessary for the determination of the emission factor), and the sometimes not very sufficient documentation status.

The reviews of the existing regional and national literature on RE, as well as mitigation potential literature as a function of costs, show a very broad range of results. In general, it is very difficult to compare data and findings from RE supply curves, as there have been very few studies using a comprehensive and consistent approach and detailing their methodologies, and most studies use different assumptions (technologies reviewed, target years, discount rates, energy prices, deployment dynamics, technology learning, etc.). Concerning the analyzed regional/country studies it is worth to mention that they attribute fairly low abatement potentials to RE under USD100/tCO_2 – typically in the single-digit range. The findings translated in terms of the potential role of RE for mitigation pathways from the analyzed studies are somehow quite different from answers given through other methods (even from a scenario-based RE-supply-curve analysis conducted here).

As most of RE technologies are in early stages of their respective innovation chains, which cover research and development, demonstration, deployment and the final step to commercialization, learning by research (triggered by research and development expenditures) and/or learning by doing (resulting from capacity expansion programs) effects might result in considerable lower costs in the future.

Over time, energy generation costs of the most important innovative RE technologies have shown significant declines. In general, cost decreases are well described by empirical experience curves with global learning rates ranging between 10 and 17% (wind onshore), and 15 to 21% (photovoltaic). Differences in observed learning rates, especially national ones and those referring to biomass, can be explained by differences in geographical conditions, investigated types of technologies, as well as temporary imbalances between supply and demand.

In order to realize the learning effects mentioned above and to approach the break-even point, significant upfront investments are needed (deployment costs). On a global scale, following different scenarios (and depending on whether or not competing technologies, such as nuclear and CCS, are admissible), annual investment needs in the order of 100 to 1,000 billion USD are expected in case that ambitious climate protection goals (e.g., the 2°C mean temperature change limit) are pursued. These numbers allow assessing future market volumes and resulting investment opportunities, as well as resulting policy requirements. Due to avoided fossil fuel costs and decreased investment needs for conventional technologies, the additional costs (learning investments) might be considerably lower than the deployment costs. Unfortunately, currently there seems to be no global scenario available calculating the net-effect of RE deployment over time.

RE, which is abundant in many developing as well as developed countries, in that context can be applied as one option to limit the increase in GHG emissions without compromising the development process. The use of RE can also lead to co-benefits, including, for instance, less air pollution and less imports dependency compared to a Business-as-usual path accompanied with positive economic effects. RE deployment can also have positive impacts on trade balances and employment, e.g. in the case of energy biomass production.

Although social and environmental external costs vary heavily amongst different energy sources, and are still connected with a high uncertainty range, they should be considered if the advantages and disadvantages of future paths are being assessed. Typically, the production and use of fossil fuels cause significant external costs dominated often by the costs due to climate change impacts and health effects. In particular, social costs of carbon emissions vary a lot due to differences in methodologies used to assess the impact of the damages far in the future. In most cases, however, RE sources have clearly lower external costs assessed on a life-cycle basis. Thus, the increase of RE in the energy system in many cases reduces the overall external costs of the system. However, also negative cost relevant effects can emerge. According to the results of some economic model studies, a forced increase of RE can raise the price level of energy and slightly slow economic growth in certain situations.

10.1. Introduction

The evolution of future GHG emissions is highly dependent on various factors, particularly on the future demand for energy and a broad availability of mitigation technologies (IPCC 2007).

A large number of different options exist to mitigate anthropogenic GHG emissions. Mitigation measures within the energy system are of special importance, as more than half of global man-made GHG emissions are attributable to the use of fossil fuel energy sources (cf. chapter 1).

The following mitigation options related to energy supply are relevant:

- Using RE (e.g. hydropower, solar, wind, geothermal and biomass) instead of fossil fuel energy sources
- Using nuclear energy instead of fossil energy sources
- Using carbon capture and storage (CCS) technologies
- Improving the efficiency of energy transformation (e.g. through the use of combined heat and power plants) and distribution
- Switching from fossil fuels with high specific CO_2 emissions (especially coal) to fossil fuels with lower specific CO_2 emissions (especially natural gas)

The main mitigation options related to energy demand are as follows:

- Increasing the energy efficiencies of buildings, industry and transport sectors
- Changing consumer behaviours (e.g. using less products and services, in particular those that are energy-intensive)

Furthermore, non-energy-related mitigation potentials exist in some sectors as well. For example, in the agricultural sector crop and grazing land management can be improved to increase soil carbon storage, and rice cultivation techniques as well as livestock and manure management could be altered to reduce CH_4 emissions.

The implementation of mitigation technologies is triggered, amongst others, by cost effects or specific policy incentives (International Energy Agency (IEA), 2008b)

The uncertain future is reflected in the wide, and growing, range of emissions pathways across emission scenarios in the literature (Calvin *et al.*, 2009), as was already well reflected in the most recent IPCC assessment report (IPCC, 2007c). IPCC AR4 focused on the behaviour of the overall energy system and, as such, discussion of single technologies as a matter of course had to be rather short. One of the main questions in that context is the role RE sources are likely to play in the future and how they can particularly contribute to GHG-mitigation pathways.

RE, following the investigated scenarios, is expected to play an important, and increasing, role in achieving ambitious climate mitigation targets. Although some RE technologies are already competitive technologies (e.g. hydropower) and many others are becoming increasingly market competitive, there are still innovative technologies in the field of RE under the given frame conditions that have a long way to go before becoming mature alternatives to non-renewable technologies. Assessing the future role of technologies requires an integrative perspective, and interactions with other technologies, and the overall energy system have to be considered.

Behind this background, this chapter discusses the mitigation potentials and costs of RE technologies taken as a whole and from a systems perspective based on an assessment of the most recent scenario literature available on the subject, as well as, at least for some sections, on inputs (in particular deployment pathways) coming from previous technology chapters (chapters 2-7) in this report. Figure 10.1.1 shows the general logic behind the whole chapter and outlines the main results of the scenario survey which was conducted in this chapter.

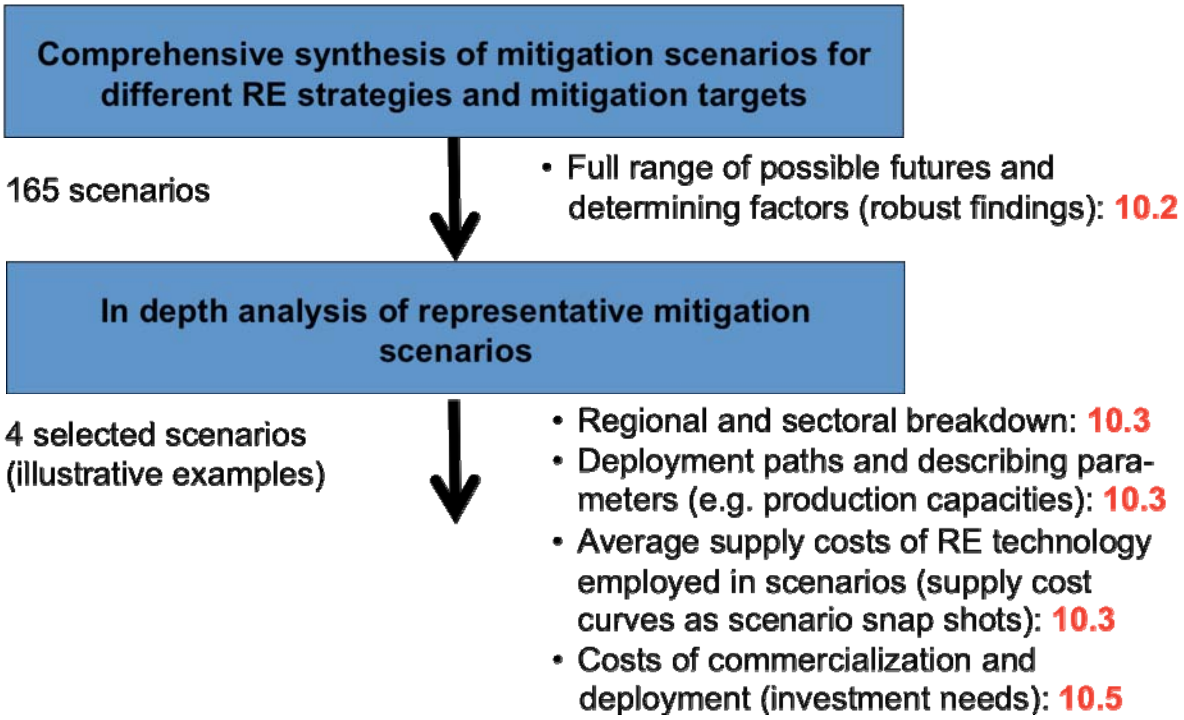

Figure 10.1.1: General logic behind the scenario survey structure conducted in the chapter

In that context, this chapter starts (Section 10.2) by providing context for understanding the role of RE in climate mitigation through the review of a total of 165 medium- to long-term scenarios from large-scale, integrated, energy-economic models as well as from more technology detailed models. The underlying goal of this exercise is, besides others, to gain a better understanding of robust evolutions of RE as a whole and single technologies reflecting different sets of assumptions and systems behaviour.

The section that follows (Section 10.3) complements the review with a more detailed review based on a selected part of the global scenarios, using four scenarios out of the scenario set from the previous section as illustrative representative examples. This section provides a next level of detail for exploring the role of RE in climate change mitigation. As such, while section 10.2, coming from a more statistical perspective, gives a comprehensive overview about the full range of mitigation scenarios and tries to identify the major relevant driving forces and system interactions (e.g. competing technologies) for the resulting RE deployment in the market and the specific role of these technologies in mitigation paths, section 10.3 provides a more detailed view, in particular of the required generation capacity, annual growth rates and the potential costs of RE deployment into the future. Within that context, the section distinguishes between different applications (electricity generation, heating and cooling, transport) and regions. As a link to the technology chapters, the section shows how the potential deployment scenarios and the overall resource potentials from the technology chapters compare with the four chosen scenarios.

In terms of primary energy calculation the direct equivalent methodology is being used here. In that context, Box 10.1 refers to the implications of different primary energy accounting conventions for energy and emission scenarios.

Box 10.1. Implications of different primary energy accounting conventions for energy and emission scenarios

As discussed in Chapter 1, there is no single, unambiguous accounting method for calculating primary energy from non-combustible energy sources: nuclear energy and all renewable energies with the exception of bio-energy. The ***direct equivalent method*** is used throughout this report. The direct equivalent method treats all non-combustible energy sources in an identical way by adopting the secondary energy perspective, which is the focus of chapters 2 to 7. The implications of the direct equivalent method in contrast to the other two most prominent methods – the physical energy content method and the substitution method – are illustrated below based on a selected climate stabilization scenario. The scenario is from Loulou et al. (2009; Teske *et al.*, 2010), and is referred to as 1B3.7MAX in that publication. CO_2-equivalent concentrations of the Kyoto gases reach 550 ppmv by 2100.

Differences from applying the three accounting methods to current energy consumption remain limited (cf. Table 1.x.y). However, substantial differences arise when applying the methods to over long-term scenarios. For the selected scenario, the accounting gap between methods grows substantially over time, reaching 370 EJ by 2100 (see Figure). There are significant differences in the accounting for individual non-combustible sources by 2050, and even the share of total renewable primary energy supply varies between 24% and 37% across the three methods (see Table). The biggest absolute gap for a single source is geothermal energy with about 200 EJ difference between the direct equivalent and the physical energy content method. The gaps for hydro and nuclear energy remain considerable.

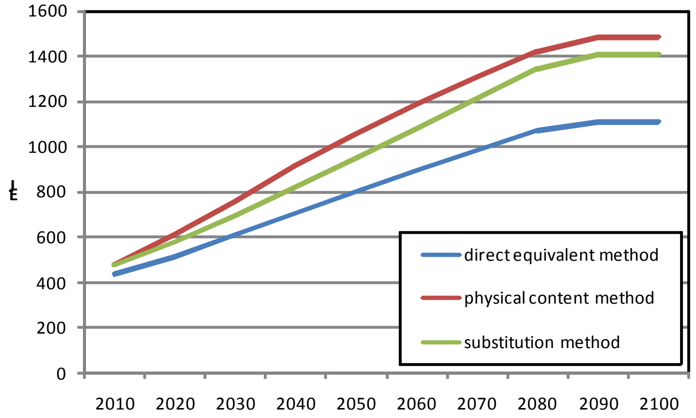

Figure: Primary Energy from non-combulstable energy sources, example scenario [added by TSU]

Table: Primary energy supply [added by TSU]

	Physical content method		Direct equivalent method		Substitution method	
	EJ	**%**	**EJ**	**%**	**EJ**	**%**
Fossil fuels	581.56	55.24	581.56	72.47	581.56	61.71
Nuclear	81.10	7.70	26.76	3.34	70.43	7.47
RE	390.08	37.05	194.15	24.19	290.37	30.81
Bioenergy	119.99	11.40	119.99	14.95	119.99	12.73
Solar	23.54	2.24	22.04	2.75	35.32	3.75
Geothermal	217.31	20.64	22.88	2.85	58.12	6.17
Hydro	23.79	2.26	23.79	2.96	62.61	6.64
Ocean	0.00	0.00	0.00	0.00	0.00	0.00
Wind	5.45	0.52	5.45	0.68	14.33	1.52
Total	1052.75	100.00	802.47	100.00	942.36	100.00

The section that follows (Section 10.4) with the discussion about cost curves focuses more in depth on cost aspects. It starts with a general assessment of the strengths and shortcomings of supply curves for RE and GHG abatement, and then reviews the existing literature on regional RE supply curves, as well as abatement cost curves, as they pertain to mitigation using RE sources. The second part of the section includes a summary of what the different technology chapters have concluded about the individual supply or even resource cost curves for each particular RE technology, including uncertainty. Additionally, and as another perspective on scenario results, the section uses the methodology of supply cost curves to give a sense of how RE technologies are deployed in the chosen four scenarios as a function of costs. The cost curves provide a scenario snapshot for a specific year and a selected region.

The next section (Section 10.5) deals with the costs of RE commercialization and deployment. The idea is to review present RE technology costs, as well as expectations on how these costs might evolve into the future. Learning by research (triggered by R&D expenditures) and learning by doing (fostered by capacity expansion programs) might result in a considerable long-term decline of RE technology costs. The section, therefore, presents historic data on R&D funding as well as on observed learning rates. In order to allow an assessment of future market volumes and investment needs, investments in RE are discussed in particular with respect to what is required if ambitious climate protection goals are to be achieved, and compared with investment needs in RE following more or less a Business-as-usual pathway. In that context, for consistency reasons results from the same four illustrative scenarios are used as in section 10.3.

The following section (Section 10.6) synthesizes and discusses social, environmental costs and benefits of increased deployment of RE in relation to climate change mitigation and sustainable development. It, therefore, continues the discussions of chapter 9, but it is more focused on economic aspects.

Gaps in knowledge and uncertainties associated with RE potentials and costs are discussed in each of the sections of the chapter and summarized at the end of the chapter.

10.2. Synthesis of mitigation scenarios for different RE strategies

This section reviews 165 recent medium- to long-term scenarios from global energy-economic and integrated assessment models. These scenarios are among the most sophisticated explorations of how the future might evolve to address climate change; as such, they provide a window into current understanding of the role of RE technologies in climate mitigation.

The integrated nature of the scenarios reviewed in the section is particularly valuable for understanding the role of RE in climate change mitigation. In climate stabilization regimes, RE must compete with other options for reducing GHG emissions, including nuclear energy, fossil energy with CCS, energy efficiency and behavioural changes. It is therefore useful to place RE sources into the larger context of the energy system and the economy as a whole, particularly when the goal is to understand the role of RE from a long-term perspective, to 2030, 2050 or even beyond.

The discussion in this section is motivated by four strategic questions. First, what RE deployment levels are consistent with different CO_2 concentration goals; or, put another way, what is the linkage between CO_2 concentration goals and RE deployments? Second, over what time frames and where will RE deployments occur and how might that differ by RE technology? Third, what is the linkage between the costs of mitigation and RE deployments? Finally, what factors, for example, resource availability and characteristics of competing mitigation options, influence the answers to all of the above?

10.2.1. State of scenario analysis

10.2.1.1. Types of scenario methods

The climate change mitigation scenario literature largely consists of two distinct approaches: quantitative modelling and qualitative narratives (see Morita *et al.*, 2001; Fisher *et al.*, 2007) for a more extensive review). There have also been several attempts to integrate narratives and quantitative modelling approaches (Nakicenovic and Swart, 2000; Morita *et al.*, 2001; Carpenter *et al.*, 2005). The review in this section relies exclusively on scenarios that provide a quantitative description of the future. These scenarios are valuable because of they provide estimates of renewable deployments and other important parameters and because they explicitly and formally represent the interactions between technologies and other factors. It is important to observe, however, that there is enormous variation in the detail and structure of the models used to construct the quantitative scenarios in this review.

Many authors have attempted to categorize these models as either bottom-up and top-down. For several reasons (see Box 10.2), this review will not rely on the top-down/bottom-up taxonomy. The important methodological characteristics of the scenarios reviewed in this section are: (1) they take an integrated view of the energy system so that they can capture the interactions, at least at an aggregate scale, between competing energy technologies; (2) they have a basis in economics in the sense that decision-making is largely based on economic criteria; (3) they are long-term and global in scale, but with some regional detail; (4) they include the policy levers necessary to meet emissions outcomes; (5) and they have sufficient technology detail to explore RE deployment levels at both regional and global scales. Many also have integrated view beyond the energy system, for example, fully coupled models of the agriculture and land use more generally.

10.2.1.2. Strengths and weaknesses of quantitative scenarios

Scenarios are a tool for understanding, but not predicting, the future. They provide *a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships* (IPCC, 2007c). Scenarios are thus a means to explore the potential contribution of RE to future energy supplies and to identify the drivers of renewable deployment.

The benefit of scenarios generated using integrated models, such as those reviewed in this section, is that they capture many of the key interactions with other technologies, other parts of the energy system, other relevant human systems (e.g., agriculture, the economy as a whole), and important physical processes associated with climate change (e.g., the carbon cycle), that serve as the environment in which RE technologies will be deployed. This integration provides an important degree of internal consistency. In addition, they explore these interactions over at least several decades to a full century into the future and at a global scale. This degree of spatial and temporal coverage is crucial for establishing the strategic context for RE.

The design, assumptions, and focus of the scenarios covered in this assessment varies greatly; some are based on more detailed representation of individual renewable and other energy technologies and aspects of systems integration of RES, while others focus on the implications of RE sources deployment for the economy as a whole. This variation in methods, assumptions, and focus provides a window into the deep uncertainties associated with future dynamics of the energy system and the role of RE sources in climate change mitigation.

Several caveats must be kept in mind when interpreting the scenarios in this section. First, maintaining a global, long-term, integrated perspective involves tradeoffs in terms of detail. For example a weakness of the scenarios is that they do not represent all the forces that govern decision making at the national or even the company or individual scale, in particular in the short-term.

Further, these are not power system models or engineering models, and they must therefore gloss over many details that influence the performance and deployment of RE. For example, the representations of limitations on variable electricity generation on the grid are often represented in stylized fashion. The level of sophistication in representing these details varies substantially across models. Integrated global and regional scenarios are therefore most useful for the medium- to long-term outlook, i.e. starting from 2020 onwards. For shorter time horizons, tools such as market outlooks or short-term national analysis that explicitly address all existing policies and regulations are more suitable sources of information.

Second, the scenarios do not represent a random sample of possible scenarios that could be used for formal uncertainty analysis. They were developed for different purposes and are not a set of "best guesses". Further, many of the scenarios represent sensitivities, particularly along the dimensions of future technology availability and the timing of international action, and are therefore related to one another. Some modelling groups provided substantially more scenarios than others. In scenario ensemble analyses based on collecting scenarios from different studies, such as the review here, there is a constant tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into our collective lack of knowledge about the future.

10.2.2. The role of RE sources in scenarios

10.2.2.1. Overview of the scenarios reviewed in this section

The bulk of the scenarios in this assessment (see Table 10.2.1) come from three coordinated, multi-model studies: the Energy Modeling Forum (EMF) 22 international scenarios (Clarke *et al.*, 2009), the ADAM project (Knopf *et al.*, 2009; Edenhofer *et al.*, 2010) and the RECIPE comparison (Luderer *et al.*, 2009; Edenhofer *et al.*, 2010) that harmonize some scenario dimensions, such as baseline assumptions or climate policies across the participating models. The value of using these scenario sets is that there is consistency within these sets that allows for comparison of how the role of RE might change with the alteration of one or several key factors. The remaining scenarios come from individual publications. Although the 165 scenarios are by no means exhaustive of recent literature, the set is large enough and extensive enough to provide robust insights into current understanding of the role of RE in climate change mitigation.

The full set of scenarios covers a large range of CO_2 concentrations (350-1050 ppm_v atmospheric CO_2 concentration by 2100, see Table 10.2.1), representing both mitigation and no-policy, or baseline, scenarios. The full set of scenarios also covers time horizons 2050 to 2100, and all of the scenarios are global in scope.

Table 10.2.1 Energy-economic and Integrated Assessment models considered in this analysis. Note that the total number of scenarios per model various significantly.

Model	# of scenarios	baseline scenarios	policy scenarios				Comparison project	Citation
			1st best	2nd best technology	2nd best policy	2^{nd} best technology & policy		
AIM/CGE	3	1	1	0	1	0	---	
DNE21	7	1	3	3	0	0	---	(Akimoto et al., 2008)
GRAPE	2	1	1	0	0	0	---	(Kurosawa, 2006)
GTEM	7	1	4	0	2	0	EMF 22	(Gurney et al., 2009)
IEA-ETP	3	1	2	0	0	0	---	(IEA, 2008)
IMACLIM	8	1	2	4	1	0	RECIPE	(Luderer et al., 2009)
IMAGE	17	3	5	6	0	3	EMF 22 / ADAM	(van Vuuren *et al.*, 2007; van Vliet *et al.*, 2009; van Vuuren *et al.*, 2010)
MERGE-ETL	19	4	3	12	0	0	ADAM	(Magne et al., 2010)
MESAP/PlaNet	1	0	0	1	0	0	---	(Krewitt et al., 2009)
MESSAGE	15	2	4	7	2	0	EMF 22	(Riahi *et al.*, 2007; Krey and Riahi, 2009)
MiniCAM	15	1	5	4	3	2	EMF 22	(Calvin et al., 2009)
POLES	15	4	3	8	0	0	ADAM	(Kitous et al., 2010)
ReMIND	28	4	6	14	4	0	ADAM / RECIPE	(Luderer *et al.*, 2009; Leimbach *et al.*, 2010)
TIAM	10	1	5	0	4	0	EMF 22	(Loulou et al., 2009)
WIATEC	3	1	2	0	0	0	---	(Truong, 2010)
WITCH	12	1	4	4	3	0	EMF 22 / RECIPE	(Bosetti et al., 2009; Luderer et al., 2009)
TOTAL	165	27	50	63	20	5	---	

Table 10.2.2 Number of long-term scenarios categorized by CO_2 concentration levels in 2100 and by inclusion of delayed participation in mitigation and limitations on nuclear and CCS deployment. The CO2 concentration categories are defined in the IPCC AR4, WGIII, see (Fisher et al., 2007) with the exception of category IV which is extended here from to 600 ppm_v, because the lowest baseline scenarios reach concentration levels of slightly more than 600 ppm_v by 2100.

	CO_2 concentration by 2100 [ppm_v]	# of scenari os	policy scenarios			
			1st best	2nd-best technology	2nd best policy	2nd best technology and policy
Baselines	>600	27	---	---	---	---
Category III+IV	440-600	97	33	42	17	5
Category I+II	350-440	41	17	21	3	0

The scenarios are valuable in that they represent the most recent work of the integrated modelling community; all of the scenarios in this study were published during or after 2006. The scenarios therefore reflect the most recent understanding of key underlying parameters and the most up-to-date representations of the dynamics of the underlying human and Earth systems. The scenarios are also valuable in that they include a relatively large number of "2nd-best" scenarios which represent less optimistic views on international action to deal with climate change (2nd-best policy) or address consequences of limited technology portfolios (2nd-best technology). The assumptions regarding 2nd-best policy vary considerably across the scenarios, but are mostly taken from the EMF 22 study (Clarke *et al.*, 2009) and the RECIPE project (Edenhofer *et al.*, 2009; Luderer *et al.*, 2009) and captured delayed action by developing countries. Technology availability is not defined homogenously across all scenarios in the analyzed set, but the limited technology portfolio studies that are highlighted here are those with limitations on the deployment of fossil energy with CCS and of nuclear energy.

A final distinguishing characteristic of the scenarios is the level of detail on RE deployment levels. RE information for this assessment was collected at a level of detail beyond that found in most published papers or existing scenario databases, for example those compiled for IPCC reports (Morita *et al.*, 2001; Hanaoka *et al.*, 2006; Nakicenovic *et al.*, 2006).

10.2.2.2. Overview of the role of RE in the scenarios

Not surprisingly, there is a strong correlation between fossil and industrial CO_2 emissions and long-term CO_2 concentration goals across the scenarios (Figure 10.2.1). This is consistent with past scenario literature (Fisher *et al.*, 2007). Perceived uncertainty in the nature of key physical processed underlying the global carbon cycle is sufficiently small in relation to other factors to maintain cumulative emissions over the century within relatively tight bounds. Beyond uncertainty in the carbon cycle, the variation in emissions pathways is largely influenced by assumptions regarding factors that influence the allocation of emissions over time. This includes the rate of technological improvements, underlying drivers of emissions in general such as economic growth, and methodological approaches for allocating emissions over time.

The relationship between RE deployment and CO_2 concentration goals is far less robust (Figure 10.2.2). On the one hand, the scenarios demonstrate a generally rising trend in renewable deployments as the stringency of the constraint is increased. In other words, larger RE deployments to be associated with more stringent CO_2 concentration goals. At the same time, there is enormous variance among deployment levels for any CO_2 concentration goal. This indicates a lack of consensus among scenario developers as to what might emerge.

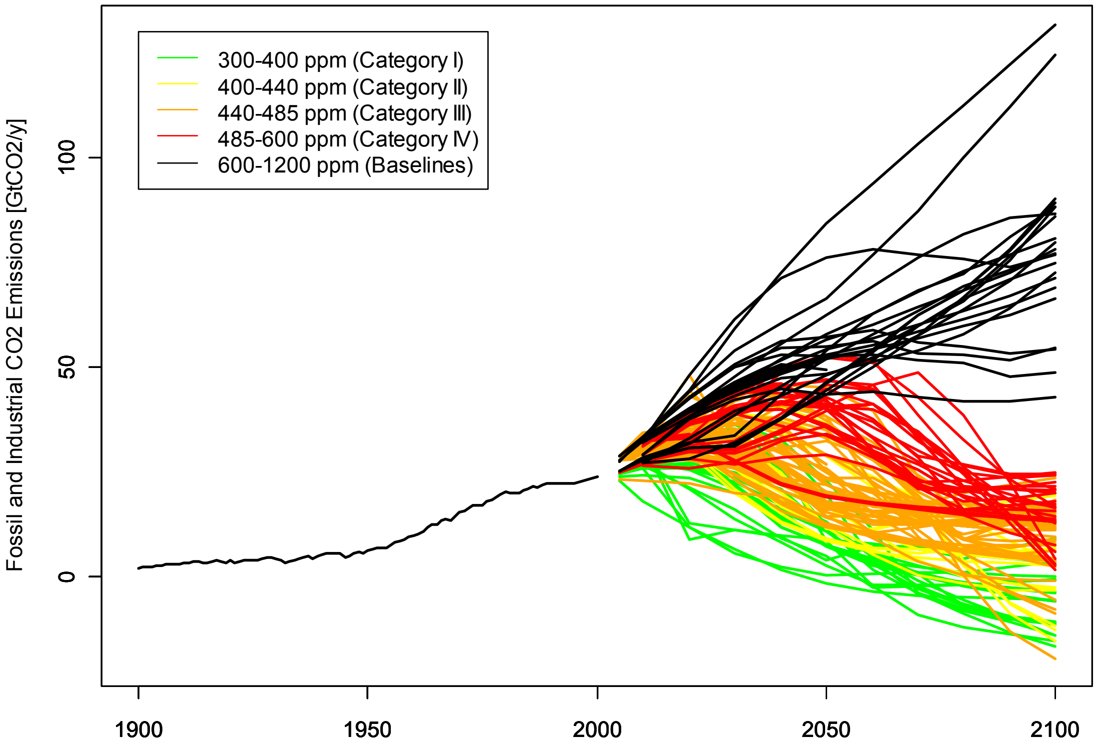

Figure 10.2.1. Historic and projected global fossil and industrial CO2 emissions of the long-term scenarios between 1900 and 2100 (colour coding is based on categories of atmospheric CO2 concentration level in 2100, adapted from (Krey and Clarke, 2010).

Several additional points deserve mention. First, although there is a high range of renewable deployments associated with any CO_2 goal, the highest deployments are associated with the most stringent of the CO_2 concentration goals. Second, the absolute magnitudes of RE sources deployment are dramatically higher than those of today in the vast majority of the scenarios. In 2007, global renewable primary energy supply in direct equivalent stood at 60.8 EJ/yr (IEA, 2009)[1]. In contrast, by 2030 many scenarios indicate a doubling of RE deployment or more compared to today. By 2050, deployments in many of the scenarios reach 200 EJ/yr or up through 400 EJ/yr. This is an extraordinary expansion in energy production from RE. The ranges for 2100 are substantially larger than these, reflecting continued growth throughout the century. Finally, RE deployments are quite large in many of the baseline scenarios. These large deployments result directly from the assumption that energy consumption will continue to grow substantially throughout the century and assumptions regarding the relative competitiveness of, and resource bases for, RE technologies in comparison to those for competing sources such as fossil energy and nuclear power. Both of these factors will be discussed in the coming sections.

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[1] Note that there is a small difference to the value of 62.5 EJ published by the IEA due to the different primary energy accounting methods used. See Box 10.1 and Chapter 1.3.1.2 for additional background on this topic.

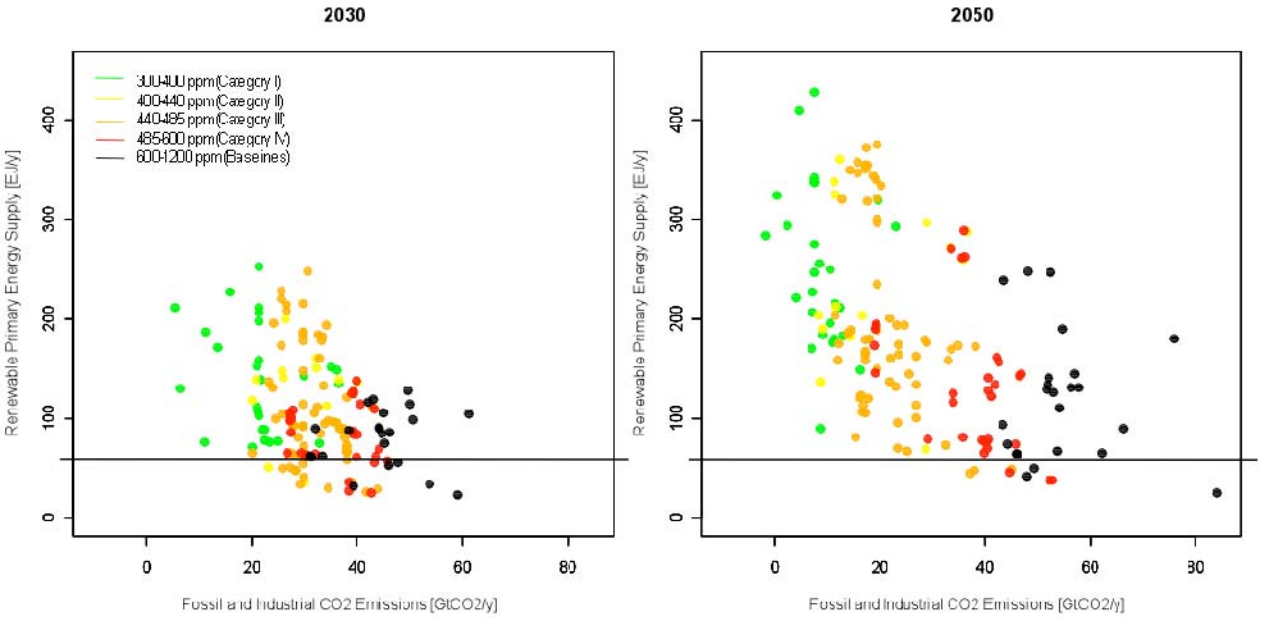

Figure 10.2.2 RE deployments across all scenarios as a function of fossil and industrial CO_2 emissions in 2030, 2050 and 2100 (colour coding is based on categories of atmospheric CO2 concentration level in 2100). The black vertical line shows the renewable primary energy deployment in 2007 which amounts to 60.8 EJ (adapted from Krey and Clarke, 2010).

10.2.2.3. Setting the Scale of RE Deployment: Energy System Growth and Long-Term Climate Goals

The deployment of RE in climate mitigation does not take place in a vacuum; it takes place in the context of a growing demand for energy and competing low-carbon energy sources. This section discusses the influence of energy system growth and Section 10.2.2.4 explores the competition with other low-carbon energy supply sources.

CO_2 mitigation puts downward pressure on total global energy consumption by increasing energy prices, but the effect is generally small enough that there is far less correlation in the scenarios between total primary energy consumption and long-term climate goals (Figure 10.2.3) than there is for CO_2 emissions and long-term climate goals (Figure 10.2.1.). In other words, the effect of mitigation on primary energy consumption is overwhelmed by variation in assumptions about the fundamental drivers of energy consumption. The variation results from the lack of consensus about these drivers; these are forces that simply cannot be understood with any degree of certainty today.

The variation in primary energy consumption increases with the stringency of the concentration goal. Although this assessment has not explored this phenomenon in detail, it is consistent with the following logic. The baseline scenarios are less varied because few scenarios envision primary energy demands decreasing over the coming century without emissions constraints. The emission constrained scenarios are more varied because these scenarios may assume, on the one extreme, abundant low-carbon options (leading to high primary energy demands) or, on the other extreme, approaches to mitigation based on reducing the demand for energy (leading to low primary energy demands).

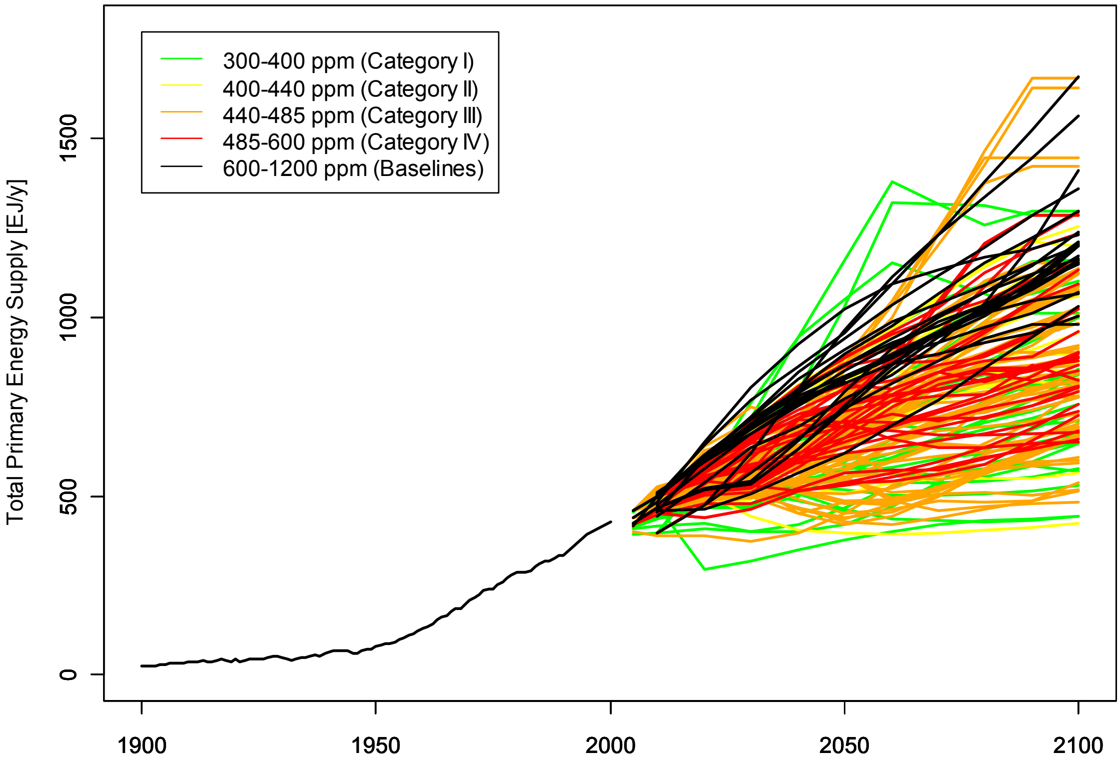

Figure 10.2.3 Historic and projected global primary energy supply (direct equivalent) across both baseline and mitigation scenarios (colour coding is based on categories of atmospheric CO2 concentration level in 2100 (adapted from Krey and Clarke, 2010).

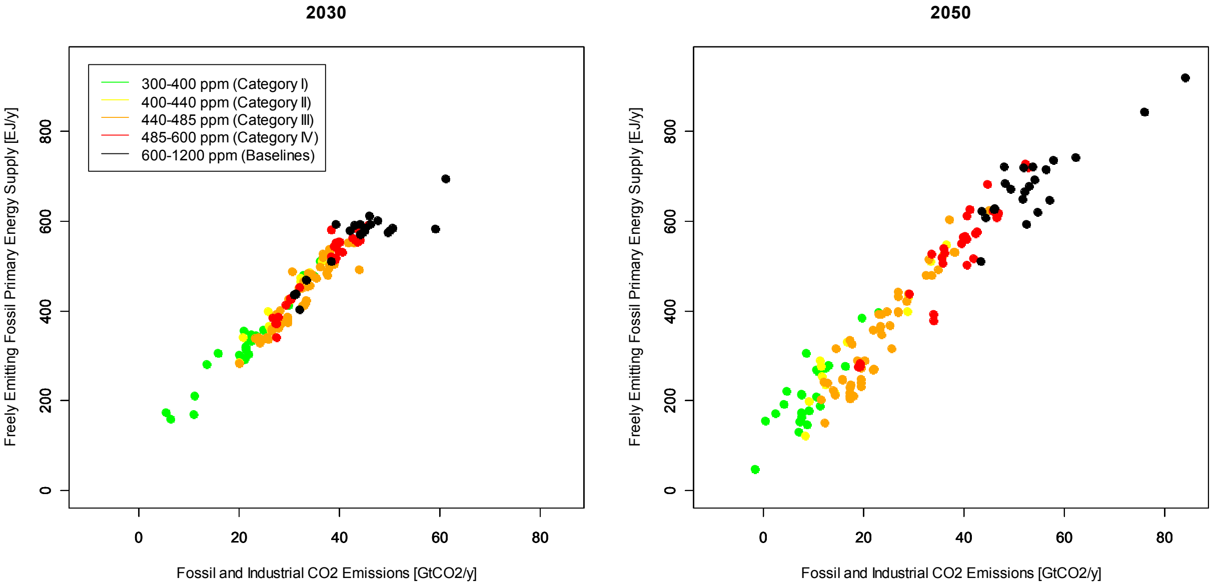

Figure 10.2.4 Freely emitting fossil primary energy consumption in the long-term scenarios by 2030 and 2050 as a function of fossil and industrial CO_2 emissions (colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (adapted from Krey and Clarke, 2010).

In contrast to the variation in total primary energy, the production of freely-emitting fossil energy (fossil sources without CCS) is tightly constrained by the long-term CO_2 concentration goal and the associated CO_2 emissions at any point in time (Figure 10.2.4). Meeting long-term climate goals requires a reduction in the CO_2 emissions from energy and other anthropogenic sources. Important earth systems, most notably the global carbon cycle, put bounds on the levels of CO_2 emissions that are associated with meeting any particular long-term goal; this, in turn, bounds the amount of energy that can be produced from freely-emitting fossil energy sources. Factors leading to flexibility in freely-emitting fossil energy include: the ability to switch between fossil sources with different carbon contents (e.g., per unit of energy natural gas has a lower carbon content than coal); the potential to achieve negative emissions by utilizing bio-energy with CCS or forest sink enhancements; and differences in the time path of emissions reductions over time as a result of differing underlying model structures, assumptions about technology and emissions drivers, and representations of physical systems such as the carbon cycle.

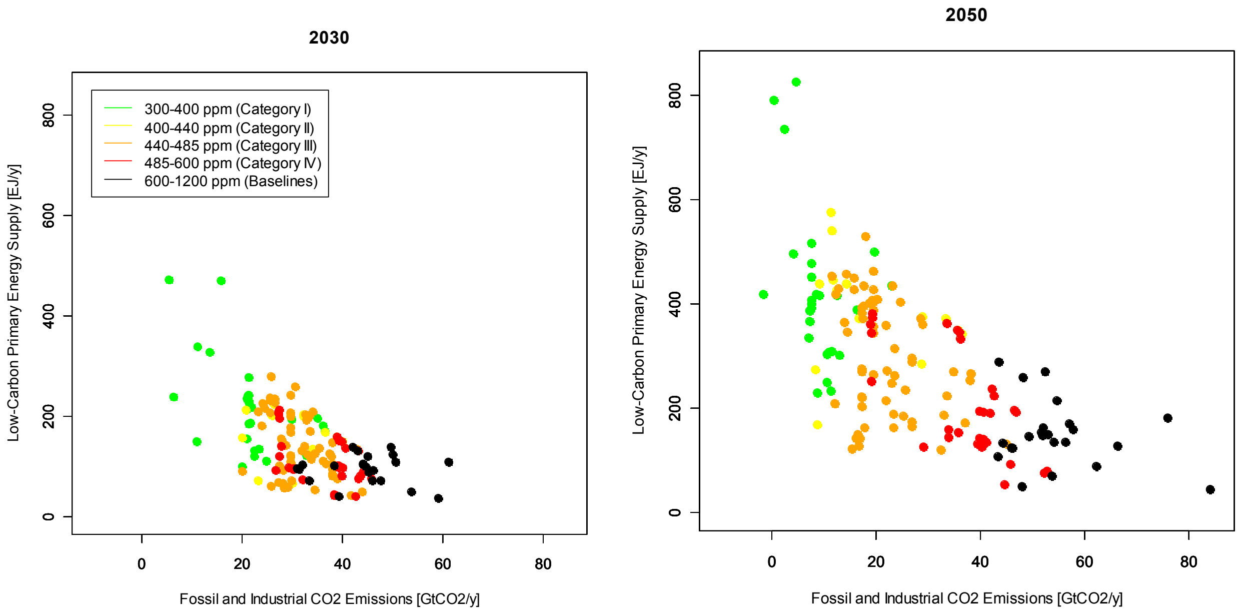

Figure 10.2.5 Global low-carbon primary energy supply in the long-term scenarios by 2030 and 2050 as a function of fossil and industrial CO2 emissions (colour coding is based on categories of atmospheric CO2 concentration level in 2100, (adapted from Krey and Clarke, 2010).

RE is only one of three major low-carbon supply options. The other two options are nuclear energy and fossil energy with CCS. The demand for low-carbon energy (the total of all three) is the difference between total primary energy demand and the production of freely-emitting fossil energy (see Figure 10.2.5). Total low-carbon energy production is correlated to the long-term concentration goal because freely-emitting fossil is partially offset by increasing production from low-carbon sources (Clarke et al., 2009; O'Neill et al., 2010). Total energy consumption also generally decreases in response to mitigation efforts because of higher fuel prices that make the implementation of additional energy efficiency measures economic[2]. However, as discussed above, the demand response from mitigation is swamped by variability in demand more generally across a scenario set such as the one explored here. The result is that although there is a strong correlation

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[2] Note that this is not always true. There have been scenarios in which primary energy increases because of large-scale electrification in response to climate policy (see, for example, Loulou, R., M. Labriet, and A. Kanudia, 2009: Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. *Energy Economics*, **31**(Supplement 2), pp. S131-S143.

between the CO_2 concentration goal and low-carbon energy, there is still substantial variability in low-carbon energy for any given CO_2 concentration goal.

The competition between RE, nuclear energy, and fossil energy with CCS adds another layer of variability in the relationship between RE deployment and CO_2 concentration goal (the left panel in Figure 10.2.5). Given the variability in pathways to a long-term goal, the variability in energy consumption, and the competition between three low-carbon supply options, there is a great deal of variability in the relationship between CO_2 concentration goals and RE deployment levels (see Figure 10.2.2). At the same time, there is a clear correlation between CO_2 concentration goals and RE deployment levels; more stringent goals are associated with higher RE deployments on average, and the highest RE deployments are associated with the tightest goal.

10.2.2.4. Competition between RE sources and other forms of low-carbon energy

It was not possible to systematically understand or articulate the competitiveness between RE and other supply options across the scenarios in this assessment as a means to understand the basis for RE market shares. This would require a level of information (e.g., detailed cost information by technology by region, underlying non-climate policy assumptions) from each of the scenarios far beyond what was collected for this study. It is also methodologically difficult, because of the complexity of the energy system in which different supply options compete. For example, the competitiveness of wind power depends on a range of factors beyond turbine costs, including the distribution of wind sites and their quality (i.e., wind class), transmission distances and costs to bring wind energy to the grid, and the technologies (e.g., electricity storage technologies) and management techniques available for managing large levels of intermittent electricity supply technologies on the grid. This sort of complexity does not lend itself to simple descriptions of technology competitiveness and is, indeed, a primary reason that integrated models are required to understand the deployment of RE technologies. (It should be emphasized again that the models in this study do not capture all of the technical or societal issues that might influence RE deployment levels.)

Although such a systematic exploration was not possible, it was possible to highlight the role of technological competition by exploring scenarios with explicit limitations on competitors to RE: energy sources with CCS and nuclear energy. Constrained CCS scenarios simply exclude the option to install CCS either on new or existing power plants or other energy conversion facilities with fossil or bio-energy as an input (e.g., refining). Constrained nuclear energy scenarios take on three forms. Two approaches maintain nuclear deployments at or below today’s levels, allowing current stocks to retire over time and not allowing any new installations, or maintaining the total deployment of nuclear at current levels, which might reflect either lifetime extensions or just enough new installations to counteract retirements. A third option applied in a number of scenarios is to maintain nuclear deployment over time in mitigation scenarios at baseline levels. The difficulty in interpreting this third category of scenarios is that nuclear energy expands to substantially different degrees across scenarios, limiting comparability and, in many cases, providing an intermediate constraint on nuclear energy (see caption of Figure 10.2.6 for details).

All other things being equal, when competing options are not available, RE deployments will be higher (Figure 10.2.6). Two effects simultaneously contribute to the increase of the renewable primary energy share. First, with fewer competing options, RE will constitute a larger share of low-carbon energy. Second, higher mitigation costs resulting from the lack of options puts downward pressure on total energy consumption because end use options become increasing economically attractive. The relative influence of these two forces varies across models.

It is interesting to note the relatively small influence on RE deployment levels from the absence of only one of the two competing low-carbon options. One possible explanation for this behaviour is that these two options both provide base-load power, and they are often close substitutes in the integrated models. When one is not available, the majority of the generation it would have provided is provided instead by the other rather than by RE sources, several of which (solar and wind) provide intermittent rather than base-load power.

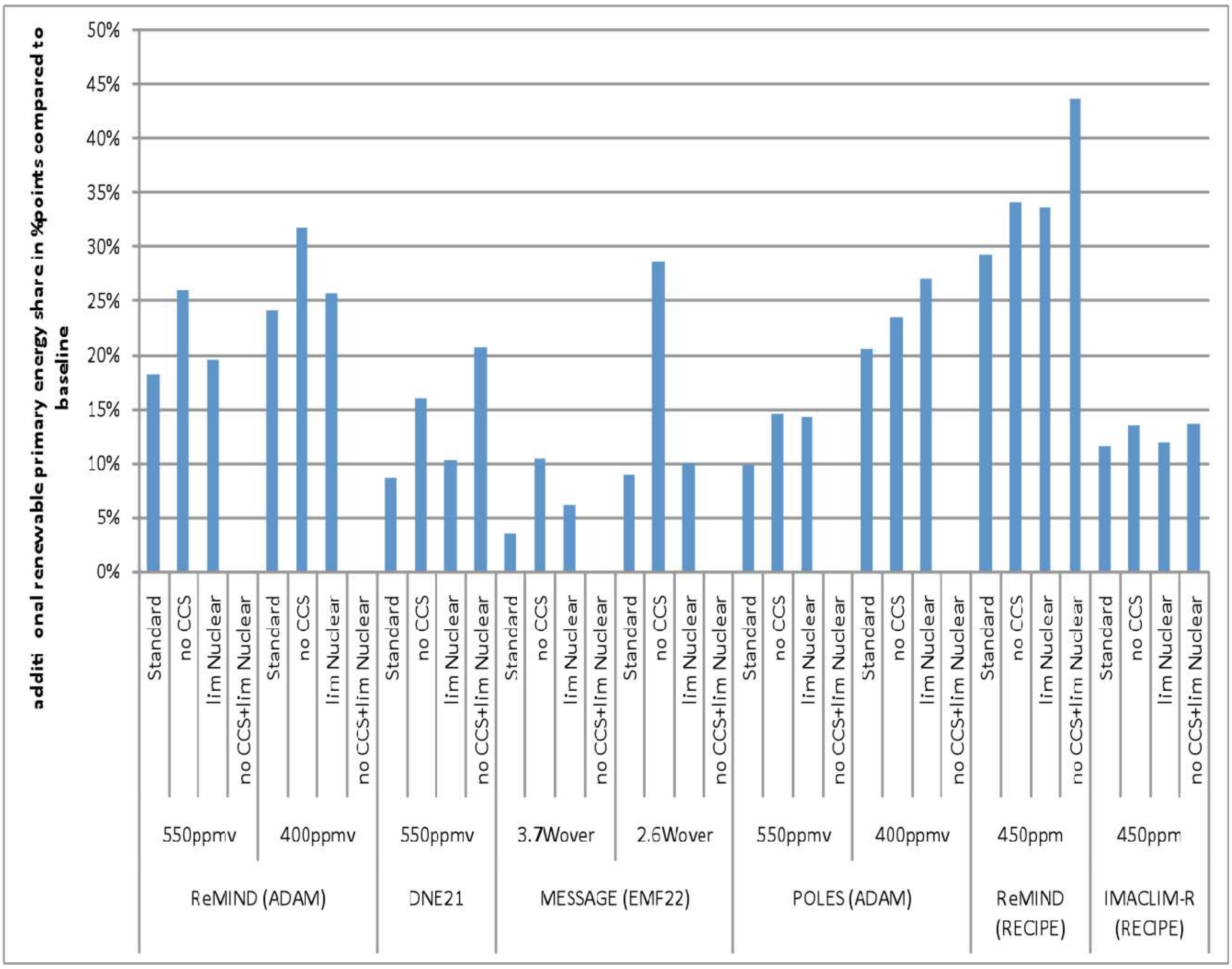

Figure 10.2.6 Increase in renewable primary energy share by 2050 in constrained in the technology scenarios compared to the respective baseline scenarios. The definition of “lim Nuclear” and “no CCS” cases varies across models. DNE21 and POLES model a nuclear phase-out at different speed, MESSAGE limits the deployment to 2010 levels, and ReMIND and IMACLIM-R limit nuclear energy to the contribution in the respective baseline scenarios which still implies a significant expansion compared to current deployment levels. In the “no CCS” cases, all models completely exclude CCS as an option with the exception of ReMIND (ADAM) that constrains cumulative CO_2 storage to 120 $GtCO_2$. POLES (ADAM) allowed higher GHG emissions in the “400 ppm_v no CCS” case compared to the “400 ppm_v standard” case to make the scenario feasible (adapted from Krey and Clarke, 2010).

At the same time, it is important to reemphasize that technology competition is only one factor influencing RE deployment levels; it cannot by itself explain the variation in RE deployments associated with different mitigation levels. The discussion to this point should make clear that for any mitigation level, the fundamental drivers of energy system scale – economic growth, population growth, energy intensity of economic growth, and energy end use improvements – along with the technology characteristics of RE technologies themselves are equally critical drivers of RE deployments. Nonetheless, if environmental, social, or national security barriers largely inhibit *both* fossil energy with CCS and nuclear energy, then it is appropriate to assume that RE will be required to provide the bulk of low-carbon energy (**Error! Not a valid bookmark self-reference.**2.7). If only one of these options is limited, then the RE deployment proportions of low-carbon energy are generally higher than they would otherwise be, but the degree of this effect is dependent on the ability of the other of these options to take up the slack in lieu of RE.

A fundamental question raised by limited technology scenarios is whether one or more energy supply options are "necessary" this century to meet low stabilization goals; that is, could the goal still be met if these technologies were not available. One way to explore this issue is to identify scenarios that were attempted with limited technology, but that could not be produced by the associated models. These attempts give a sense of the difficulty of meeting stabilization goals with limited technology options, although, in most cases, they cannot truly be considered as indications of physical feasibility (Clarke *et al*., 2009). These attempted scenarios tell a mixed story. In some cases, models could not achieve stabilization without nuclear and CCS; however, in others, as shown in **Error! Not a valid bookmark self-reference.**2.7, models were able to produce these scenarios. Several studies found that limits on RE deployments kept models from achieving stabilization goals (see, for example, Figure 10.2.12). Other studies have indicated that it is the combination of RE, in the form of bio-energy with CCS that makes low stabilization goals substantially easier (Clarke *et al*., 2009).

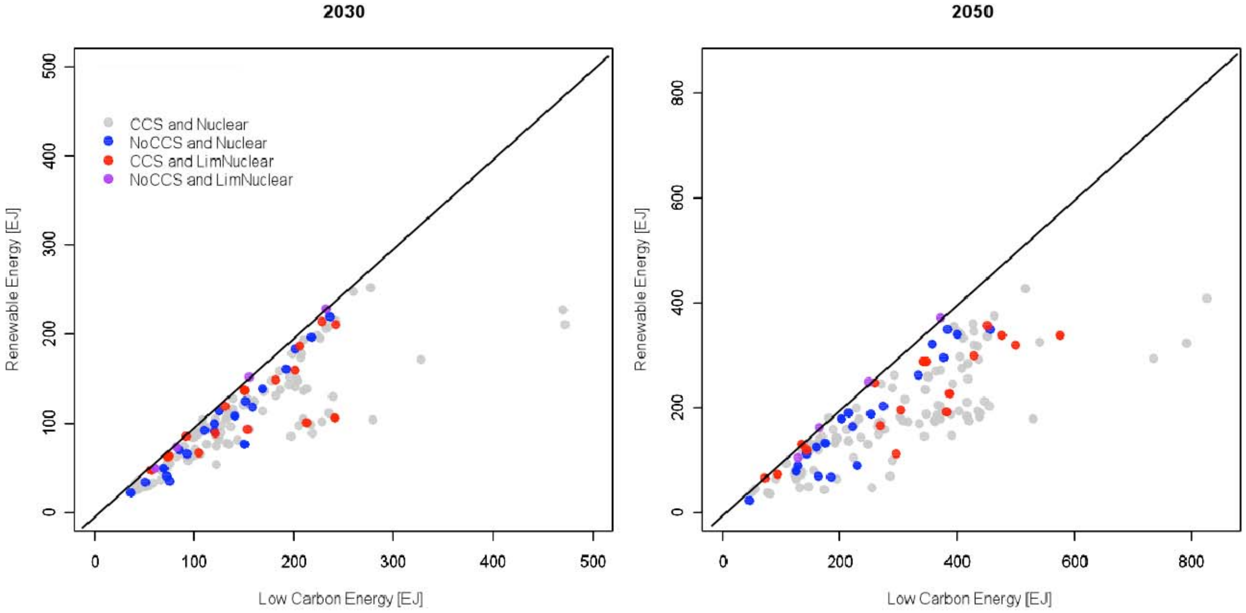

Figure 10.2.7 RE deployment plotted against total low-carbon energy primary energy supply in 2030 and 2050, depending on the availability of the competing low-carbon energy supply options CCS and nuclear energy (adapted from Krey and Clarke, 2010).

10.2.2.5. RES deployment by technology, over time, and by region

There is great variation in the deployment characteristics of individual technologies (Figure 10.2.8 and Figure 10.2.9). Several dimensions of this variation bear mention. First, the absolute scales of deployments vary considerably among technologies. Bio-energy deployment is of a dramatically higher scale over the coming 40 years than any of the other RE technologies, although it should be noted that the figures include traditional biomass which contributes close to 40 EJ in the base year with a modest decline over time in most scenarios. By 2050, wind and solar constitute a second tier of deployment levels. Hydroelectric power and geothermal power deployments fall into a lower tier.

The variation in these deployment levels represents variation in assumptions by the scenario developers regarding the cost, performance, and potential of these different sources. They indicate, for example, that most scenario developers have used assumptions that make solar power, bio-energy, and wind power the most likely large-scale contributors in the 2050 time frame and beyond; there is room for growth in hydroelectric power and geothermal power, but the potential for this growth is limited.

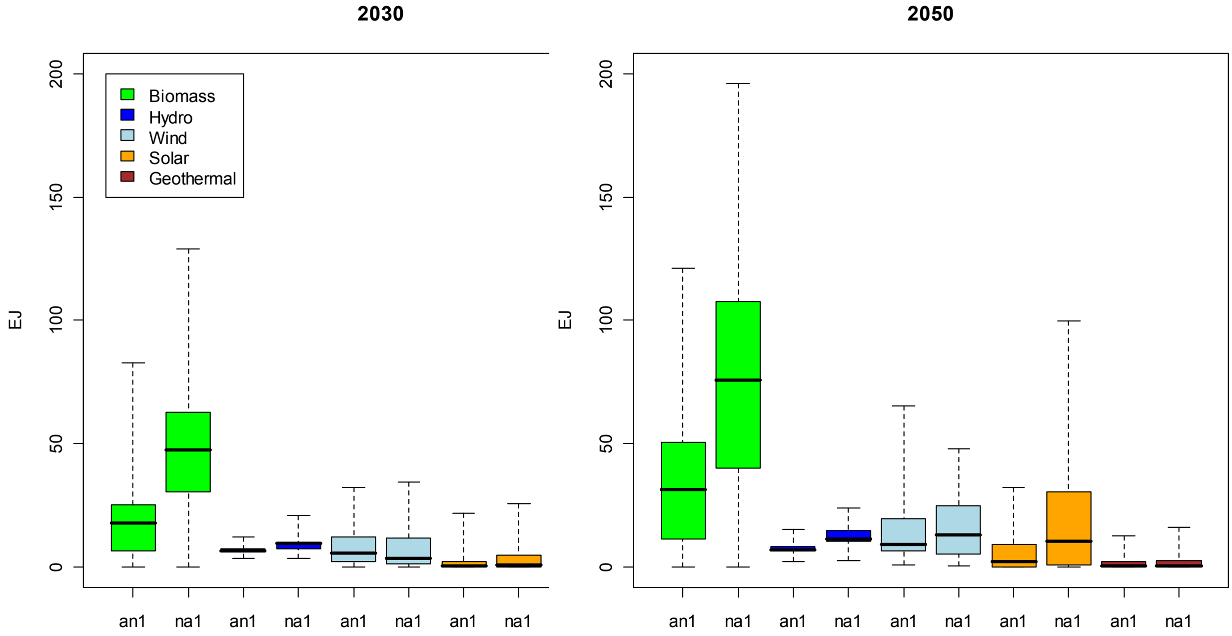

Figure 10.2.8 Renewable primary energy consumption by source in Annex I (an1) and Non-Annex I (na1) countries in the long-term scenarios by 2030 and 2050. [The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios.] (adapted from Krey and Clarke, 2010).

Second, the time-scale of deployment varies across different RE (Figure 10.2.8 and Figure 10.2.9), in large part representing differing assumptions about technological maturity. Hydro, wind and biomass show a significant deployment over the coming one or two decades in absolute terms. These are the most mature of the technologies. (Note that the bio-energy assumed here may include cellulosic approaches, which are an emerging technology.). Solar energy is deployed to a large extent beyond 2030, but at a scale that is surpassing that of the other RE sources apart from biomass, capturing the notion that there is substantial room for technological improvements over the next several decades that will make solar largely competitive and increase the capability to integrate solar power in the electricity system. Indeed, solar energy deployment by 2100 is on the same scale at bio-energy production. Direct biomass use in the end-use sectors is largely stable or even slightly declining across the scenarios. It should be noted that direct use is dominated by traditional, non-commercial fuel use in developing countries (Figure 10.2.8 and Figure 10.2.9) which is typically assumed to decline as economic development progresses. This decrease cannot be compensated by an increase in commercial direct biomass use in the majority of scenarios. In contrast, biomass that is used as a feedstock for liquids production or an input to electricity production – commercial biomass – is increasing over time, reflecting assumptions about growth in the ability to produce bio-energy from advanced feedstocks, such as cellulosic feedstocks.

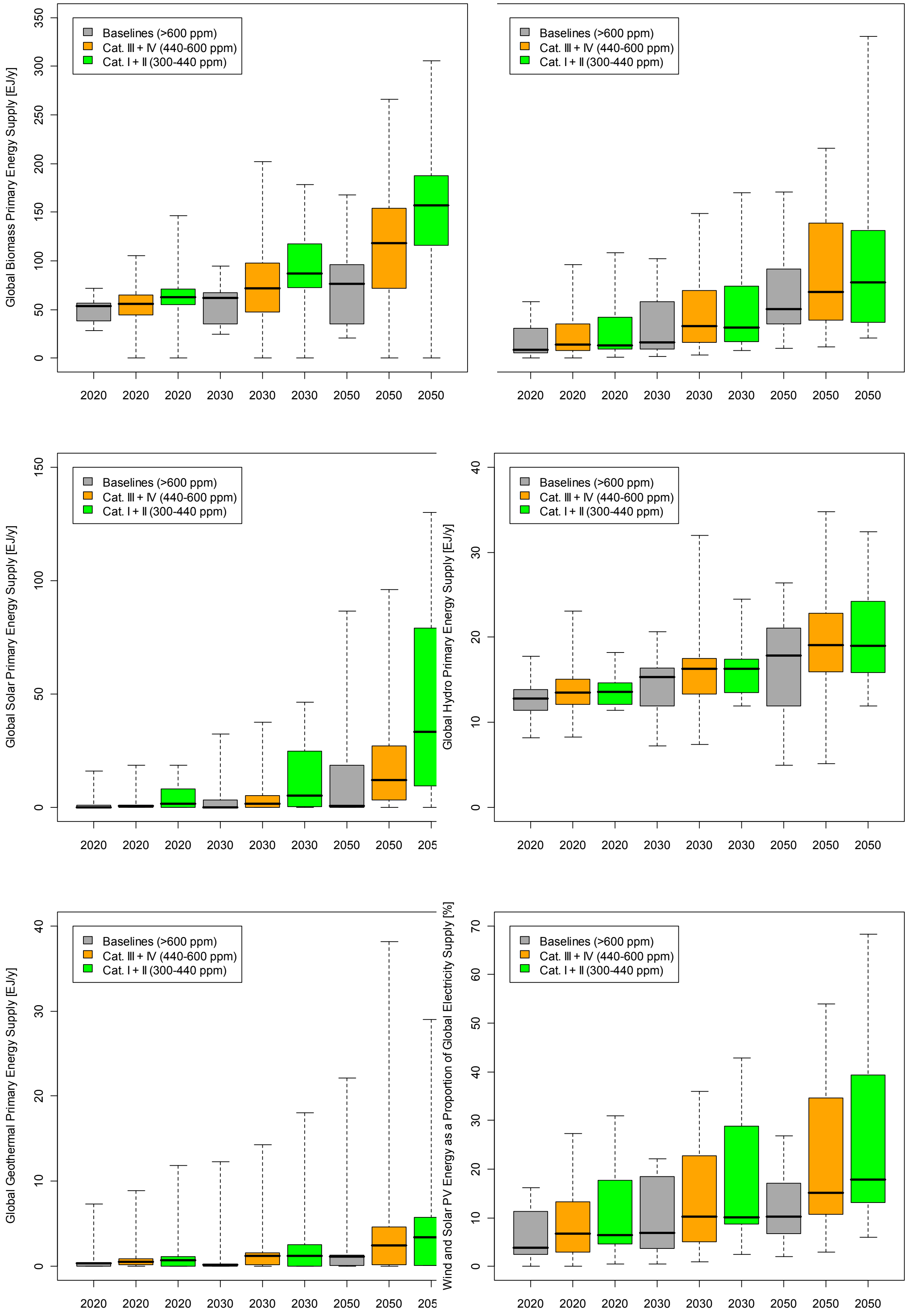
Baselines (>600 ppm)
Cat. III + IV (440-600 ppm)
Cat. I + II (300-440 ppm)
Global Biomass Primary Energy Supply [EJ/y]
0
50
100
150
200
250
300
350
2020
2030
2050
Global Solar Primary Energy Supply [EJ/y]
0
50
100
150
205
Global Hydro Primary Energy Supply [EJ/y]
0
10
20
30
40
Global Geothermal Primary Energy Supply [EJ/y]
0
10
20
30
40
Wind and Solar PV Energy as a Proportion of Global Electricity Supply [%]
0
10
20
30
40
50
60
70

Figure 10.2.9 Global primary energy supply of biomass, wind, solar, hydro, geothermal and share of variable RE (wind and solar PV) in global electricity generation in the long-term scenarios by 2020, 2030 and 2050, grouped by different categories of atmospheric CO_2 concentration level in 2100. [The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios.] (adapted from Krey and Clarke, 2010).

Third, the deployment of some RE in the scenarios is driven mostly by climate policy (e.g. solar, geothermal, commercial biomass) whereas the deployment of others is largely independent of climate action (e.g. wind, hydro) (Figure 10.2.9). This is also to a large degree a reflection of assumptions regarding technology maturity. Wind and hydro are already considered largely mature technologies, so the imposition of climate policy would not provide the same increase in competitiveness as it would for emerging technologies such as solar, geothermal, and advanced bio-energy.

Finally, the distribution of RE deployments across countries is highly dependent on the nature of the policy structure. In scenarios that assume a globally efficient climate regime in which emissions reductions are undertaken where and when they will be most cost-effective, non-Annex 1 countries begin to take on a larger share of RE deployment compared to Annex I countries toward mid-century. This is a result of the assumption that these regions will continue to represent an increasingly large share of total global energy consumption (see, for example, Clarke *et al.*, 2009), along with the assumption that RE supplies are large enough to support this growth.

The notion that deployment in the non-Annex 1 will become increasingly important is robust across scenarios; in the long run, meeting the stricter goals will require fully comprehensive global mitigation. At the same time, a more realistic assumption regarding the near- to mid-term is that mitigation efforts may differ substantially across regions. In this real-world context, the distribution of RE deployments in the near-term would be skewed toward those countries taking the most aggressive action. As an example, Figure 10.2.10 shows the change in RE deployment in China in 2020 and 2040 from the Energy Modelling Forum 22 study (Clarke *et al*., 2009). This study explored the implications of delayed participation by non-Annex 1 regions on meeting long-term climate goals. In the delayed accession scenarios, China takes no action on climate prior to 2030. After 2030, China begins mitigation. Not surprisingly, the relative deployment of RE in 2020, when China is not taking on mitigation actions (the left panel in Figure 10.2.10). The effect of delay on RE deployments is ambiguous in 2050, after China has begun mitigation (the right panel in Figure 10.2.10). This ambiguity is due in large part to the fact that China would need to quickly ramp up mitigation efforts by 2050 if action has been delayed but the same long-term climate target is to be met as in the case with immediate action.

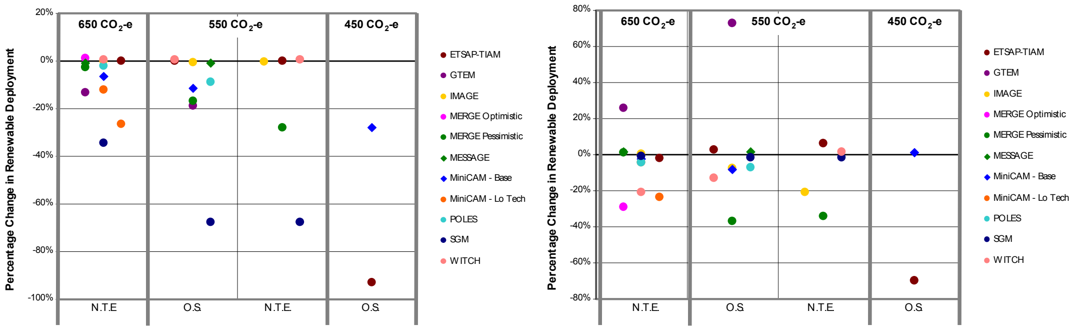

Figure 10.2.10 Change in RE deployment in China across EMF 22 scenarios as a result of delayed accession in 2020 (left panel) and 2040 (right panel) (Clarke *et al*., 2009). In addition to the Kyoto gases CO_2-equivalent concentration level by 2100, the study explored the differences between overshoot (O.S.) and not-to-exceed (N.T.E) in the before 2100.

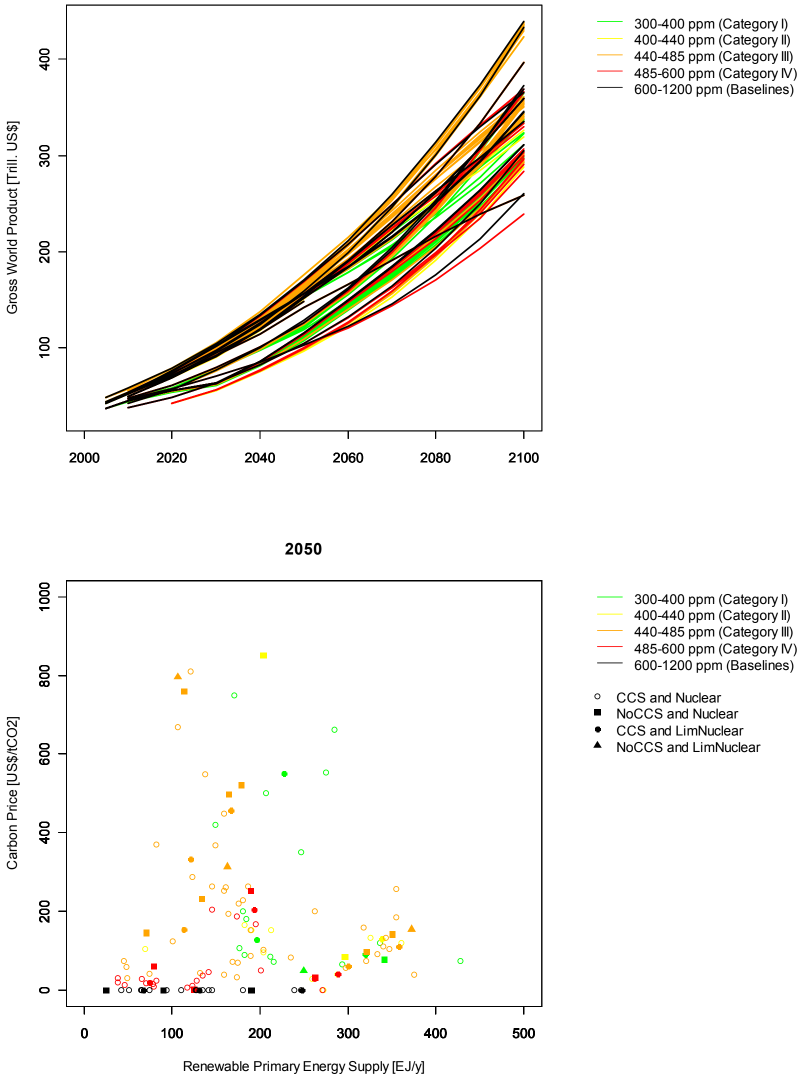

Figure 10.2.11 Carbon prices as a function of RE deployment levels in 2050 and Gross World Product development in the scenarios until 2100. The colour coding is based on categories of atmospheric CO_2 concentration level in 2100. Different symbols in the graph denote the availability of CCS and nuclear energy (adapted from Krey and Clarke, 2010).

10.2.2.6. RE and the Costs of Mitigation

One way that researchers characterize the challenge of mitigation is to quantify its economic consequences. Questions about mitigation costs have often been posted in the context of particular technologies, such as RE technologies. A typical question is how much CO_2 abatement and at what cost can be provided by RE technologies? It was not considered feasible to provide mitigation cost results using the scenarios in this assessment, primarily because assignments of mitigation to particularly technologies is not an output of integrated models; such assignments are the result of post-processing, offline, accounting calculations that rely on analyst judgment about key assumptions. Applying these assumptions to the scenarios would blur the signal from the scenarios themselves. In addition, these analyses are not accounting for the benefits of climate mitigation (e.g. less severe climate change impacts in the long term, reduced need for adaptation), energy security and air pollution (e.g. reduced health expenditures) due to the deployment of RE technologies (see e.g. Nemet and et al., 2010). A more detailed discussion of co-benefits can be found in section 10.6.

There are, however, several related questions that can be explored directly with the outputs from the 165 scenarios. One such question is: what sorts of RE deployment levels will be associated with what sorts of carbon prices? This question was posed and explored in the most recent IPCC assessment report (IPCC, 2007c), which asserted that RE could provide 30-35% of global electricity generation at carbon prices below \$50/tCO_2 . Although higher RE deployments are generally associated with higher CO_2 prices in the scenarios in this assessment (right panel of Figure 10.2.11), there is a great deal of variation in this correlation. Interacting, and to some degree counteracting, forces confuse the relationship. More aggressive mitigation generally calls greater deployment of low-emissions energy sources, including RE, which raises CO_2 prices. On the other hand, to the extent that RE technologies have higher performance, larger supplies, or lower cost, they will both have higher deployments and make mitigation cheaper. These two effects are not disentangled in this section. It is only noted here that the scenarios reviewed here generally do not indicate a clear correlation between RE deployments and carbon prices.

One limitation of CO_2 prices as cost metrics is that they only provide the marginal costs of abatement and not the total cost. Cost measures such as changes in GDP or consumption, or total mitigation costs can provide a broader sense of the cost implications of RE. Although mitigation tends to reduce GDP (Fisher *et al.*, 2007), the other forces that drive GDP exert a larger influence on total GDP than mitigation. This means that RE deployments in response to climate mitigation will not be tightly linked to total global GDP (see left panel of Figure 10.2.11).[3]

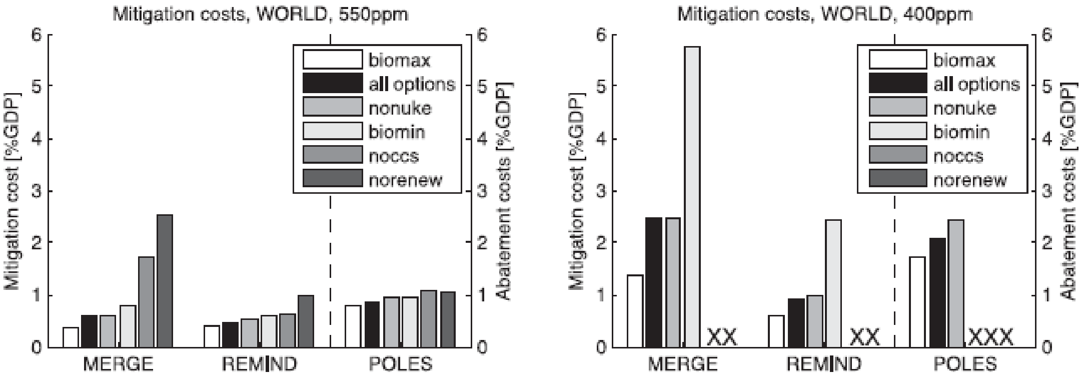

Figure 10.2,12 Mitigation Costs from the ADAM Project under Varying Assumptions Regarding Technology Availability for long-term stabilization targets of 550 and 400 ppm_v CO_2-equiv (Edenhofer et al., 2010). In the legend, “all options” refers to the standard technology portfolio assumptions in the different models, while “biomax” and “biomin” assume double and half the standard biomass potential of 200EJ respectively. “noccs” excludes CCS from the mitigation portfolio and “nonuke” and “norenew” constrain the deployment levels of nuclear and RE to the baseline level which still potentially means a considerable expansion compared to today. The “X” in the right panel indicate non-attainability of the 400 ppm_v CO_2-equiv target in case of limited technology options.

A more appropriate reflection of the relationship between the economic consequences of mitigation and RE deployments is the relationship between deployments and mitigation costs. Several of the analyses that produced scenarios for this study explored the relationship between mitigation costs and the presence or absence of RE and competing low-carbon technologies. Consistent with

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[3] Note that a minority of researchers have argued that climate mitigation could lead to increased economic output (e.g. Barker, T., H. Pun, J. Köhler, R. Warren, and S. Winne, 2006: Decarbonizing the global economy with induced technological change: Scenarios to 2100 using E3MG. *Energy Journal*, **27**(SPEC. ISS. MAR.), pp. 241-258.). The basic argument is that under specific assumptions induced technological change due to a carbon price increase leads to additional investments which trigger higher economic growth.

intuition, these studies demonstrate that the presence of RE technologies reduces the costs of mitigation. This is not surprising; more options should not increase costs. More important is the relative magnitude of the costs in these studies when RE growth is constrained relative to cases in which fossil with CCS and nuclear energy are constrained. For example, in both the ADAM (Edenhofer et al., 2010) and RECIPE projects (Luderer *et al.*, 2009), each involving three models, the cost increase that results from the absence of the option to expand on RE deployment is not of a distinctly different order of magnitude than the cost increase from the absence of the option to implement fossil energy with CCS or expand production of nuclear energy beyond today's levels or beyond baseline levels (see Figure 10.2.12).

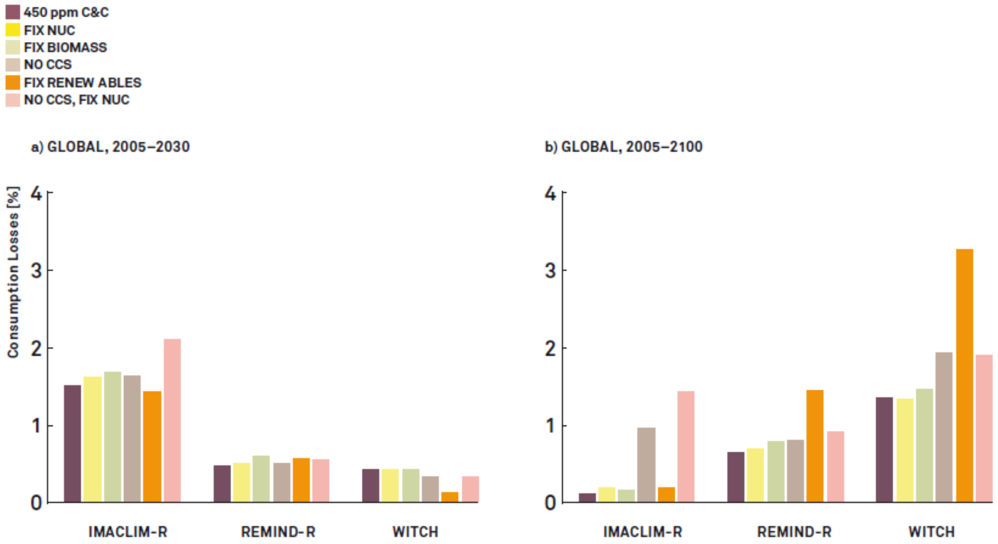

Figure 10.2.13 Mitigation costs from the RECIPE project under varying assumptions regarding technology availability for a long-term stabilization target of 450 ppm$_v$ CO$_2$ (Luderer et al., 2009). Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to baseline levels (all other technologies) for the periods 2005–2030 (a) and 2005–2100 (b). Option values are calculated as differences of consumption losses of a scenario in which the use of certain technologies is limited with respect to the baseline scenario. Note that for WITCH, the generic backstop technology was assumed to be unavailable in the "fix RE" scenario.

10.2.3. The deployment of RE sources in scenarios from the technology perspective

The scenarios in this section were produced using models with global, integrated models. These models have several advantages, but they also have the weakness that they pay only limited attention to many critical factors that ultimately will influence the deployment of RE. As a means to better understand the role of these forces, the scenarios from this section are briefly explored in the "long-term deployment in the context of carbon mitigation" sections of chapters 2 to 7. The aim of these individual-technology explorations is to identify potential barriers that an expansion of RE may face and enabling factors to achieve the higher RE deployments levels as found in the scenario literature. This section briefly summarizes the key elements of those sections.

Resource Potential: In general, even the highest deployment levels were not considered to be constrained by the available resource potential at the global level for all of the RE categories. However, because RE resources are regionally heterogeneous, some of the higher deployment levels may begin to constrain the economically most attractive sites, for example, for wind energy.

For some resources, availability is highly geographically constrained, for example, ocean energy sources (tidal, OTEC, ocean current, salinity gradient).

Regional Deployment: Economic development and technology maturity are primary determinants of regional deployment levels. Regional policy frameworks for RE need to be economically attractive and predictable. For mature technologies such as hydro power the majority of available potential in OECD countries has been exhausted and the largest future expansion is expected in Non-OECD countries of Asia and Latin America. For wind energy, which has seen high expansion rates, mostly in Europe and North America over the past decade, a greater geographical distribution of deployment than currently observed is likely to be needed to achieve the higher deployments indicated by the scenario literature. The other, less-mature technologies will likely initially focus on expansion in affluent regions (Europe, North America, Australia and parts of Asia) where financing conditions and infrastructure integration are favourable.

Supply Chain Issues: In general no insurmountable medium- to long-term constraints of materials, labour and manufacturing capacity were identified that would prevent higher deployment levels in the scenarios. For example, the wind industry has witnessed rapid expansion over the past that led to globalization of the production chain, but further scaling up of the industry will be needed to reach the capacity addition rates seen in the more aggressive scenarios. It is also important to recognize that markets and supply chains for some technologies are global (e.g. wind, solar PV) while others (e.g. passive solar and low temperature solar thermal) to date are purely local.

Technology and Economics: Because the maturity of the renewable technologies is highly variable, so is the need for cost and technological advancements. On the one end of the spectrum, hydro power is competitive with conventional thermal power plants, while on the other end of the spectrum, commercial-scale ocean energy demonstration plants do not yet exist. For both ocean and wind energy more remote offshore locations will need technology advancements and cost reductions. Similarly, concentrating solar power (CSP), but also solar PV and enhanced geothermal systems (EGS) will require improvements of the technology itself, but in particular further reductions of electricity generation costs. In the case of bio-energy, further technical advancements are required especially for next-generation bio-fuels and bio-refineries, where analyses indicate that technological progress could allow for competitive 2nd generation bio-fuel production around 2020 if R&D and near-term market support are offered.

Systems Integration and Infrastructure: Systems integration is challenging for the variable electricity generation technologies wind, solar PV and wave energy (see section 8.2.1). Technical (flexible backup capacity, inter-connection, storage) and institutional (market access, tariff structure) solutions will need to be implemented to address transmission constraints and operational integration concerns. For example, in specific locations, hydro power plants with reservoirs and/or pumped storage can help to operate electricity networks with high penetration of variable RE reliably. Substantial new transmission infrastructure may be required under even modest expansion scenarios to connect remote resources, for example, off- but also onshore wind, CSP, conventional hydrothermal power. A greater reliance on offshore wind is likely for regions such as Europe which require the development of offshore transmission infrastructure. Ocean energy faces similar integration challenges of variability and offshore grid connection and thus synergies may exist in the deployment of these technologies (Section 8.2.1.6). To gain greater penetration into conventional energy supply systems, other RE carriers such as heat, biogas, liquid bio-fuels and solid biomass all need integration into existing system infrastructure as outlined in Chapter 8.

10.2.4. Knowledge Gaps

The coverage of different RE sources in the scenario literature varies significantly. Mature technologies such hydro power are thus covered by all models reviewed in this assessment while less mature and deployed technologies, in particular ocean energy, offshore wind, concentrating solar power and partly also geothermal energy are addressed by a much smaller set of scenarios. One reason is that there is less demand to specifically address less mature technologies or those that are a priori assumed to have lower contributions. A second reason is that there is a lack of high quality global resource (preferably gridded) data for some renewable resources (e.g. geothermal, the various ocean energy forms) which is a precondition for constructing resource supply curves that are inputs to energy-economic and integrated assessment models.

10.3. Assessment of representative mitigation scenarios for different RE strategies

While chapter 10.2 coming from a more statistical perspective gave a comprehensive overview about the full range of mitigation scenarios and tried to identify the major relevant driving forces for the resulting market share of RE and the specific role of these technologies in mitigation paths, this chapter focus on regional and sectoral perspectives. For this more in-depth analysis from the given general overview, four scenarios have been chosen representing different illustrative energy and emission pathways (see table 10.3.2). The primary data for this analysis have been provided by the scenario authors and/or institutions.[4]

10.3.1. Technical Potentials from RE sources

Before looking on the role RE is given by different scenarios, it is worth to know about the upper application limit. The overall technical potential for RE – i.e. the total amount of energy that can be produced taking into account the primary resources, the socio-geographical constraints and the technical losses in the conversion process – seems to be huge and several times higher as the current total energy demand (cf. chapter 1).

A meta study from DLR, Wuppertal Institute and Ecofys which has been commissioned by the German Federal Environment Agency provides a comprehensive overview about the technical RE potential by technologies and region (DLR, 2009). The survey analysed 10 of the major studies which estimate global or regional RE potentials. Different types of studies were used, e.g. studies that focused on all or many RE sources like the World Energy Assessment (UNDP/WEC, 2000) and (Hoogwijk *et al.*, 2004), and studies that only focus on one source, for instance Hofman *et al.* (2002) and Fellows (2000)[5]. The study compared for each RE source, assumptions and regional scope of the relevant studies and special attention has been paid to environmental constraints and their influence on the overall potential. The study came out with an own assessment of potential based on a literature research but also on new calculation from the authors. The assessment provides data for the years 2020, 2030 and 2050 – no ranges given. The technical potential given in Table 10.3.1 can be seen as additive in terms of the needed geographical areas for each RE source and sums up to a total potential of 11,941 EJ/yr in 2050.

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[4] All data from the World Energy Outlook 2008 & 2009, Energy Technology Perspectives 2008 has been provided by the IEA, the energy [r]evolution scenario data from Deutsche Luft- und Raumfahrt (DLR) and data for technology based road maps e.g. `Global Wind Energy Outlook, Sawyer 2008` from industry associations such as Global Wind Energy Council.

[5] Overview of main literature sources analyzed: Aringhoff et al. 2004 World regions Solar CSP 2040/2050, Bartle A. 2002 World regions Hydropower 2010/2020, Bjoernsson et al. 1998 World Geothermal 2020,De Vries et al. 2006, DLR 2005, Doornbosch and Steenblik 2007, Elliot D. 2002, Fellows 2000, Fridleifsson 2001Gawell et al. 1999

		Technical Resource Potential					
		Krewitt et al. (2009)*			**Range of Estimates**		***Source for Range of Estimates****
		2020	*2030*	*2050*	*Low*	*High*	
Electric Power (EJ/y)	Solar PV	1126	1351	1689	1338	14766	Krewitt et al. (2009)
	Solar CSP	5156	6187	8043	248	10603	Krewitt et al. (2009)
	Wind On-shore	369	362	379	70	1000	Chapter 7: low estimate from WEC (1994), high estimate from WBGU (2004) and includes off-shore
	Wind Off-shore	26	36	57	15	130	Chapter 7: low estimate from Fellows (2000), high estimate from Leutz et al. (2001)
	Hydropower	48	49	50	45	52	Krewitt et al. (2009)
	Ocean	66	166	331	330	331	Krewitt et al. (2009)
	Geothermal	4,5	18	45	1,4	144	Krewitt et al. (2009)
Heat (EJ/y)	Geothermal	104	312	1040	3,9	12590	Krewitt et al. (2009)
	Solar	113	117	123	na	na	Krewitt et al. (2009)
Primary Energy (EJ/y)	Biomass Energy Crops	43	61	96	49	1550	Krewitt et al. (2009)
	Biomass Residues	59	68	88	30	170	Krewitt et al. (2009)

World Primary Energy Demand in 2007: 503 EJ/y (IEA WEO 2009)

* Technical potential estimates for 2020, 2030, and 2050 are based on a review of studies prepared by Kewitt et al. (2009). Data presented in

** Range of estimates comes from studies reviewed by Krewitt et al. (2009), as revised based on data presented in Chapters 2-7.

[TSU: Text mussing at end of first footnote.]

[TSU: Electricity Power: Ocean: Range Estimates: low: 330 – figure must be wrong]

Table 10.3.1: Technical Potential by technology for different times and applications

In the literature, generally the assessment about the total (global) technical potential for all RE sources varies significantly from 2,130 EJ/yr up to 41,336 EJ/yr[6]. Based on the global primary energy demand in 2007 (International Energy Agency (IEA), 2009) of 503 EJ/yr following the IEA calculation methodology (physical energy content accounting) respective 482 EJ/yr using the direct equivalent methodology which was chosen as basis for SRREN (cf. chapter 1 and Box 10.1 for the discussion about primary energy calculation) the total technical potential of RE sources at the upper limit would exceed the demand by an order of magnitude. However barriers to the growth of RE technologies may rather be posed by economical, political, and infrastructural constraints. That is why the technical potential will never be realised in total.

The complexity to calculate RE potentials is in particular high as these technologies are comparable young connected with a permanent change of performance parameter. While the calculation of the theoretical and geographical potential has only a few dynamic parameters, the technical potential is dependent on a number of uncertainties. A technology breakthrough or significant technology improvements for example could have a serious impact on the potential. This could change the technical potential assessment already within a short time frame. However, considering the various deployment paths of RE sources discussed in this report, it can be concluded that technical potential is not the limiting factor to expansion of RE generation even although RE having not reached the full technological development limits so far.

10.3.2. Regional and sectoral breakdown of RE sources

To exploit the entire technical potential is neither needed nor unproblematic. Implementation of RE sources has to respect sustainability criteria in order to achieve a sound future energy supply. Public acceptance is crucial to the expansion of RE sources. Due to the decentralized character of many RE technologies, energy production will move closer to consumers. Without a public acceptance, a market expansion will be difficult or sometimes even impossible. Especially the use of biomass has been controversial in the past years as competition with other land use, food production, nature conservation needs etc. accrued. Sustainability criteria have a huge influence on the overall market

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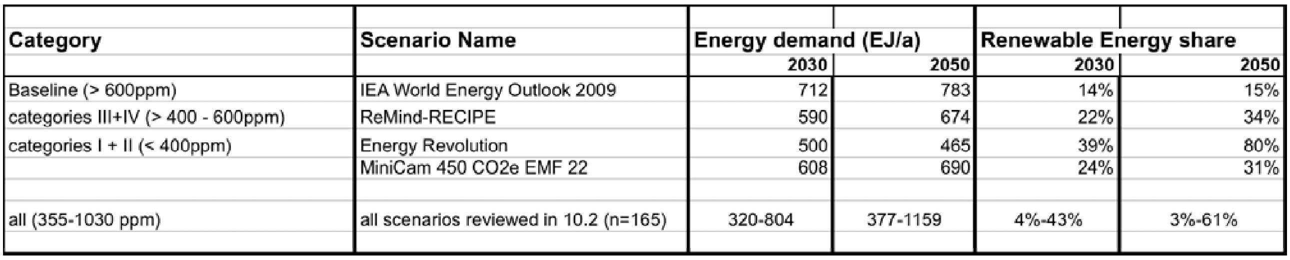
[6] DLR, Wuppertal Institute, Ecofys; Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply; Commissioned by the German Federal Environment Agency FKZ 3707 41 108, March 2009;

potential and whether bio energy can play a crucial role in future energy supply. Much more important especially for policy purposes as the technical potential is the market potential. This term is defined in chapter 1, but often used in different manner. Often the general understanding is that market potential is the total amount of RE that can be implemented in the market taking into account the demand for energy, the competing technologies, and subsidies for any form of energy supply as well as the current and future costs of RE sources, and the barriers. As also opportunities are included, the market potential may in theory be larger than the economic potential, but usually the market potential is lower because of all kind of barriers. Market potential analyses have to take into account the behaviour of private economic agents under their specific frame conditions which are of course partly shaped by public authorities. The energy policy frame work has a profound impact on the expansion of RE sources. An approximation of what can be expected for the future markets can be achieved via using the results of energy scenarios especially those delivering an in depth view on RE technologies from an overall system perspective taking relevant interaction into consideration.

Behind that background the goal of the chapter is, in addition to the more general overview in the previous section, to come out with a range of possible futures based on four representing global energy scenarios (cf. description of storyline in Box 10.3). The selected four scenarios provide substantial information on a number of technical details and represent a wide range of emission categories; from up to 1000 ppm_v – as a baseline - , via category IV + III (>440 – 660 ppm_v) down to category I + II (<440 ppm_v). Additionally, they stand for different RE deployment paths shown in Table 10.3.2 in comparison to the overall range of RE deployment form the full set of scenarios investigated in the previous scenario survey in section 10.2.



Category	Scenario Name	Energy demand (EJ/a)		Renewable Energy share	
		2030	2050	2030	2050
Baseline (> 600ppm)	IEA World Energy Outlook 2009	712	783	14%	15%
categories III+IV (> 400 - 600ppm)	ReMind-RECIPE	590	674	22%	34%
categories I + II (< 400ppm)	Energy Revolution	500	465	39%	80%
	MiniCam 450 CO2e EMF 22	608	690	24%	31%
all (355-1030 ppm)	all scenarios reviewed in 10.2 (n=165)	320-804	377-1159	4%-43%	3%-61%

Table 10.3.2: Overview: Different demand projections of the analysed scenarios. [TSU: all: RE share: 2050: max=61% contradicts with ER share of 80%]

The possible market penetration for each sector, region and time horizon described in the scenarios depends on a number of assumptions. Especially the assumptions of current and future costs for different RE technologies are crucial for the scenario results. Feedback loops have to be considered as the achievement of cost reduction potentials (= learning curves) correlates with possible annual market growth. While there is information available for the cost development within the power sector, there is very little data available for the heating and cooling sector. This is particularly problematic as renewable heat shows not only a huge technical potential, but is in many cases already cost effective (Aitken, 2003).

10.3.2.1. Renewable Power sector

Global energy scenarios provide the greatest detail for the renewable power sector and the available statistical information about the current renewable market is – compared to the renewable heating sector – very good.

Factors for market development in the renewable power sector

Amongst others, cost assumptions are crucial for the resulting deployment path of technologies. The biggest variations in the cost development assumptions can be found for the younger technologies, such as solar photovoltaic, concentrated solar power plants (CSP) and ocean energy. Among these technologies, in particular the cost projections for solar photovoltaic vary significantly, which leads in the scenarios to very different market development pathways. As illustrative example: for 2020, the highest costs projection was US$ 5960/kW [TSU: needs conversion to US$2005] and the lowest projection at US$ 2400/kW[7]. The upper limit was so far even higher than the current market price (Photon International, 2010). That demonstrates a typical problem of scenario analysis covering a young technology market where technology framework conditions and cost degression effects can heavily be underestimated. However, cost projections for photovoltaic in 2050 had a significant lower range from US$ 830/kW for the low case and US$ 1240/kW for the high case.

Among all RE technologies for power generation, for the already very well established onshore wind energy the least variation in cost projection from around +/- 10% over the entire timeframe could be found. Offshore-wind costs projections vary slightly more, due the different regional circumstance of the water depth and distance to the shore. Besides the investment cost estimates another crucial variable is the capacity factor which has – in combination with the assumed installation cost – a tremendous impact on the specific generation costs. The scenario analysis showed that the ranges are rather small and all scenarios assumed roughly the same capacity factors.

Annual market potential for renewable power

Based on the energy parameters of the analysed scenarios, the required annual production capacity has been either calculated (IEA, ReMind, EMF) or has been provided by the scenario authors. Table 10.3.3 provides an overview about the required annual manufacturing capacities (annual market volume) in order to implement the given RE generation within the analysed scenarios. These calculated manufacturing capacities do not include the additional needs for repowering.

Annual market growth rates in the analysed scenarios are very different, and the expectations about how the current dynamic of the market might continue are various. In some cases, a drastic reduction of the current average market growth rates have been outlined. The photovoltaic industry had an average annual growth rate of 35% between 1998 and 2008 (EPIA, 2008). The wind industry experienced 30% annual growth rate over the same time period (Swayer, 2009). While the advanced technology roadmaps from the photovoltaic, concentrated solar power plants and wind industry indicate these annual growth rates can be maintained over the next decade (Swayer, 2009; EPIA, 2010) and decline later, most of the analysed integrated energy scenarios assume much lower annual growth rates for all renewable power technologies.

Besides the expectations for RE technologies, the specific numbers for the overall electricity demand are decisive for specifying the resulting role of RE sources. High power demand and high market development projections are not necessarily from the same scenario. The ReMind and EMF 22 scenarios assume rather high demand developments, while the first one is connected with a relatively high market share of RE sources and the latter one with a comparable low one. The Energy [R]evolution scenario has the lowest demand projection of all analysed scenario and the highest RE share. In that context the renewable market projections (in absolute numbers) for solar and wind are in the medium and high range, but in lower case for hydro and biomass.

The underlying assumptions for the corresponding manufacturing capacities are quite different. In the IEA WEO 2009, for wind power a lower global manufacturing capacity in 2020 is assumed, than there is currently available. This indicates once more the problem to deal with a very dynamic and in this case policy driven sector within scenario analysis.

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[7] While the average market price in 2009 for solar photovoltaic generators (including installation) in Germany was already at around 3,800 Euro/kW (US$ 5,700/kW)[7] for households, larger photovoltaic parks in the MW-range achieved significant lower prices.

On the other hand the high case projections for wind (ReMind) requires an annual production capacity of 175 GW by 2020 – which would represent a 4-fold increase of production capacity on a global level. Both the Energy [R]evolution and EMF 22 scenario project this production capacity later by 2030, leading to a global wind power share of 12% to 15% under the demand projection of the scenarios. The highest global wind share has the ReMind scenario of 24% by 2020, a share which will be reached under the ER 2010 scenario by 2050.

	Energy Parameter								Market Development							
	Generation [TWh/y]				% of global demand - based on the demand projection of the analysed scenario				Annual Market growth [%/y]				Annual Market Volume [GW/y]			
	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 209	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010
2020	27248	32762	28.736	25819												
2030	34307	40638	34.666	30901												
2050	46542	63.384	61.783	43922												
PV 2020	108	220	115	594	0,4%	0,7%	0,4%	2,3%	17%	27%	18%	42%	5	12	6	36
PV 2030	281	2590	277	1953	0,8%	6,4%	0,8%	6,3%	11%	32%	10%	14%	18	163	17	120
PV 2050	640	20790	822	6846	1,4%	32,8%	1,3%	15,6%	10%	26%	13%	15%	40	651	25	211
CSP2020	38	0	186	689	0,1%		0,7%	2,7%	17%		40%	62%	1		3	12
CSP2030	121	0	553	2734	0,4%		1,5%	8,8%	14%		13%	17%	2		9	45
CSP2050	254	0	1545	9012	0,5%		2,5%	20,5%	9%		12%	14%	4		11	66
Wind																
on+offshore2020	1009	4650	2391	2849	3,7%	14,2%	8,4%	11,0%	12%	33%	23%	26%	26	175	83	101
on+offshore2030	1536	9770	4400	5872	4,5%	24,0%	11,9%	19,0%	5%	9%	7%	8%	60	381	171	229
on+offshore2050	2516	14290	7848	10841	5,4%	22,6%	12,5%	24,7%	6%	4%	7%	7%	93	262	146	202
Geothermal																
for power generation																
2020	117	NA	206	367	0,4%	NA	0,7%	1,4%	6%		12%	20%	1		2	4
2030	168	NA	616	1275	0,5%	NA	1,7%	4,1%	4%		13%	15%	2		9	18
2050	265	NA	1197	2968	0,6%	NA	1,9%	6,8%	5%		8%	10%	4		8	21
heat & power	2															
2020	6	NA	NA	66	0,0%	NA	NA	0,3%	13%		NA	47%	0		NA	1
2030	9	NA	NA	251	0,0%	NA	NA	0,8%	5%		NA	16%	0		NA	5
2050	19	NA	NA	1263	0,0%	NA	NA	2,9%	9%		NA	20%	0		NA	11
bioenergy																
for power generation																
2020	337	2208	506	392	1,2%	6,7%	1,8%	1,5%	8%	33%	13%	10%	3	37	6	4
2030	552	3540	953	481	1,6%	8,7%	2,6%	1,6%	6%	5%	7%	2%	10	59	16	8
2050	994	4217	5847	580	2,1%	6,6%	9,3%	1,3%	7%	2%	22%	2%	13	26	40	4
heat & power																
2020	186	NA	NA	742	0,7%	NA	NA	2,9%	2%	NA	NA	19%	1	NA	NA	13
2030	287	NA	NA	1424	0,8%	NA	NA	4,6%	5%	NA	NA	8%	6	NA	NA	27
2050	483	NA	NA	2991	1,0%	NA	NA	6,8%	6%	NA	NA	9%	8	NA	NA	25
ocean																
2020	3	NA	NA	119	0,0%	NA	NA	0,5%	13%	NA	NA	70%	0	NA	NA	4
2030	11	NA	NA	420	0,0%	NA	NA	1,4%	16%	NA	NA	15%	0	NA	NA	12
2050	25	NA	NA	1943	0,1%	NA	NA	4,4%	10%	NA	NA	19%	1	NA	NA	27
hydro																
2020	4027	4186	3369	4059	14,8%	12,8%	11,9%	0,0%	2%	2%	0%	2%	20	25	0	21
2030	4679	5260	3714	4416	13,6%	13,0%	10,1%	0,0%	2%	3%	1%	1%	135	151	109	127
2050	5963	6570	4402	5108	12,8%	10,4%	7,0%	0,0%	3%	3%	2%	2%	157	172	115	67
total renewables																
for power generation (incl. CHP)																
2020	5831	11264	6773	9876	21,4%	20,7%	23,9%	38,3%	4%	12%	6%	10%	57	249	100	197
2030	7644	21160	10513	18827	22,3%	30,6%	28,5%	60,9%	3%	7%	5%	7%	232	755	331	590
2050	11159	45867	21660	41552	24,0%	72,4%	34,4%	94,6%	4%	9%	8%	9%	319	1112	345	634

Table 10.3.3: Overview: renewable power generation, possible market shares, capacity factors, annual market growth rates and required annual manufacturing capacity. All factors interact with each other and influence the specific generation costs in cent/kWh over time significantly. Source: (Greenpeace and EREC, 2010) (IEA 2009, ReMind ReCIPE 2009, EMF22)

The expected role of CSP as another example is very different within all scenarios and has a wide range from 0.5% of the world's electricity production by 2050 in the IEA WEO 2009 and up to 17% under the ER 2010 scenario. While the ReMind case does not take this technology into account, the EMF 22 projects an electricity share from CSP of 2.5% by 2050. The ER 2010 assumes that annual manufacturing capacity will go up to over 65 GW/y by 2050, while all other scenarios assume an annual production capacity of less than 20 GW/y until 2030.

Both geothermal and bio-energy power plants – including combined-heat and power technologies – have very diverse technologies in the market and under development as well. However their annual market volume and therefore the required production capacity are low compared to the projections for solar and wind power technologies. The highest projection for the global geothermal power market by 2050 is with 21 GW/y in the ER 2010 on the level of the global wind power market in the year 2007 (19.7 GW/y). The expected yearly growth represents just 0.8% of the global technical potential for geothermal power generation.

The bio-energy share in all analyses is – relative to other technologies – low as well. The ReMind case estimates an annual market volume and a required manufacturing capacity of over 150 GW/a. However, similar to geothermal power generation, bio-energy power generation (excluding CHP) plays in most scenarios a rather low role and achieves an electricity share of maximum 9.3% by 2050 in the EMF 22.

Figure 10.3.1 summarizes the resulting range regarding the electricity generation of RE sources reflecting the selected scenarios distinguishing between the different technologies and compares it with the scenario demand projections for 2050. Solar photovoltaic, concentrated solar power (CSP) and wind power have the largest expected market potential beyond 2020. Hydro power remains on the same high level in almost all scenarios and the range of 10% to 15% by 2030 indicating a high correlation of projections. The total renewable power market potential in the lowest case (IEA WEO 2009) is 9% above the 2008 level with 24% by 2050. The highest renewable electricity shares are 94.6% (ER 2010) and 72% (ReMind) by 2050, while the EMF 22 scenario achieves a global renewable electricity share of 34%.

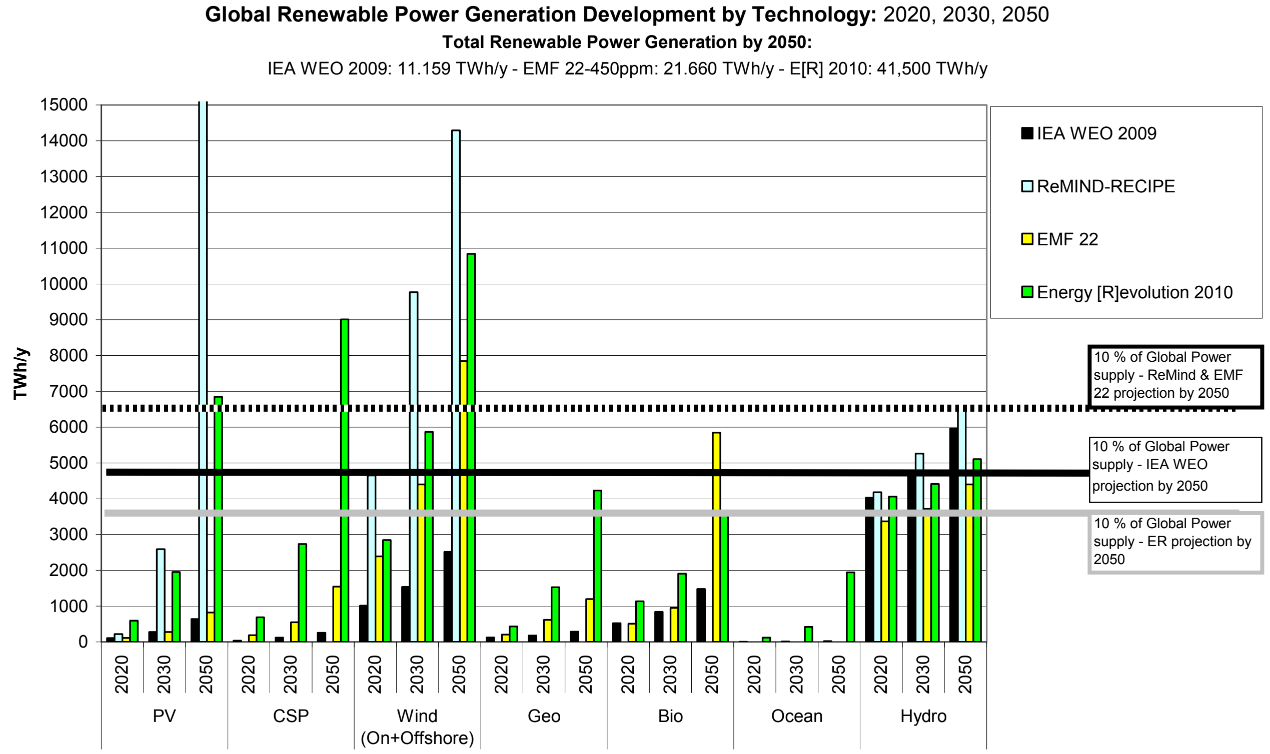

Figure 10.3.1: Global Renewable Power Development Projections by Technology

10.3.2.2. Market potential for the renewable heating and cooling sector

As the heating sector is one of the most dominant demand sectors, renewable heating technologies are already quite important. But, they can be used for cooling as well, which offers a huge new market opportunity for countries with Mediterranean, subtropical or tropical climate. RE for cooling can be applied for instance for air-conditioning and would in that context reduce electricity demand for electric air-conditioning significantly.

Factors for market development in the renewable power sector

None of the analysed scenarios provide detailed information about RE heating or cooling technologies. While the cost reduction potential for geothermal and bio energy share is relatively low as it is already an established technology, the cost reduction potential for solar heating is still significant (ESTIF, 2009). The influence of oil and gas prices, as well as building construction regulations, are huge incentives for the market development of RE heating and cooling technologies. Solar heating as well as some forms of bio-energy heating (e.g. wood pellets) and geothermal (ground heat pumps) have been already competitive in North Europe when oil and gas prices had been high in the first half of 2008. Therefore oil- and gas-price projections in scenarios will have a profound impact on the market potential.

Annual market potential for the RE heating and cooling

The RE heating sector shows much lower growth rate projections than outlined for the power sector. The highest growth rates are assumed for solar heating – especially solar collectors for water heating and space heating followed by geothermal heating. Geothermal heating includes heat-pumps, while geothermal co-generation plants are presented in section 10.3.2.1 under renewable power generation.

Both, the ReMind and EMF 22 scenario provide no information about solar and geothermal heating systems, which might be due to different reporting and/or categorisation. In the most ambitious scenario (ER 2010), solar heating systems show a significant increase. Nevertheless it will last until 2030 until today's bio-energy based heat production level will be reached. To achieve this, the market growth rates for solar collectors must exceed 35% until 2020 and a minimum of 10% afterwards throughout the end of the projection in the year 2050.

A shift from unsustainable traditional use of bio-energy for heating towards modern and more sustainable use of bio-energy heating such as wood pellet ovens are assumed in all scenarios. The more efficient use of biomass would increase the share of biomass heating without the necessity to increase the overall demand on biomass. However, none of the analysed scenarios provide information about the specific breakdown of traditional versus modern bio-energy use. Therefore it is not possible to estimate the real annual market development of the different bio-energy heating systems. Geothermal heating and cooling systems are expected to grow fast in the coming decade (until 2020) as well, and remain on a high level towards 2050.

The market potential for RE heating technologies such as solar collectors, geothermal heat pumps or pellet heating systems overlaps with the market potential analysis of the RE power sector. While the solar collector market is independent from the power sector, biomass cogeneration could be listed under the power sector or the heating/cooling sector. Geothermal heat pumps use power for their [TSU: was 'there'] operation and therefore increase the demand for electricity. RE heating and cooling is even more dispersed and decentralized than RE power generation, what explains to a certain extend that the statistical data are still quite poor and need further research.

Based on the energy parameters of the analysed scenarios, the required annual market volume has been calculated in order to identify the needed manufacturing capacities and how they relate to current capacities. Table 10.3.4 provides an overview about the annual market volumes but without including the additional needs for repowering. Even with relatively low growth rates in the scenarios manufacturing capacities for all RE heating and cooling technologies must be expanded significantly in order to realize the projected RE heat production in all analysed scenarios. The annual market volume for solar collectors until 2020 must be expanded from less about 35 PJ/y in

2008 to 100 PJ/y in 2020 in the IEA WEO 2009 case and up to 1162 PJ/y in the ER 2010. Due to the diverse technology options for bio- and geothermal energy heating systems and the low level of information in all analysed scenarios, it is not possible to provide here specific market size data by technology.

	Energy Parameter								Market Development							
	Generation [PJ/y]				% of global demand - based on demand projections of the scenarios				Annual Market growth [%/y]				Annual Market Volume [PJ/y]			
	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010
2020	157.623	192.000	134.603	151.716												
2030	173.749	193.000	144.593	156.289												
2050	205.190	184.955	150.776	153.913												
Solar Thermal 2020	844	0	NA	6.787	0,5%	0,0%	NA	4,5%	10%	NA	NA	39%	32		NA	409
Solar Thermal 2030	1.629	0	NA	18.963	0,9%	0,0%	NA	12,1%	8%	NA	NA	12%	100		NA	1162
Solar Thermal 2050	3.105	0	NA	51.278	1,5%	0,0%	NA	33,3%	7%	NA	NA	12%	187		NA	1568
Geothermal heating																
2010																
2020	631	115	NA	4.488	0,4%	0,1%	NA	3,0%	3%	NA	NA	28%	2		NA	58
2030	918	212	NA	10.865	0,5%	0,1%	NA	7,0%	4%	7%	NA	10%	13		NA	149
2050	1.635	4.568	NA	40.172	0,8%	2,5%	NA	26,1%	7%	41%	NA	16%	22		NA	283
bioenergy heating																
2020	36.224	15.760	40.381	41.823	23,0%	50,0%	30,0%	27,6%					28		104	130
2030	38.194	19.645	39.040	46.215	22,0%	60,2%	27,0%	29,6%	not available				678	385	686	811
2050	43.646	20.437	31.663	48.262	21,3%	66,7%	21,0%	31,4%					540	123	186	295
total renewables for power generation (incl. CHP)																
2020	37.699	15.875	40.381	53.098	23,9%	8,3%	30%	35,0%	1%	NA	1%	5%	62		104	597
2030	40.741	19.857	39.040	76.043	23,4%	10,3%	27%	48,7%	1%	3%	0%	4%	791		686	2122
2050	48.386	25.005	31.663	139.712	23,6%	13,5%	21%	90,8%	2%	3%	-2%	7%	749		186	2146

Table 10.3.4: Projected renewable heat production, possible market shares, annual growth rates and annual market volumes.

Within the heating sector, solar energy has the highest growth projections of all technologies followed by bio-energy and geothermal heating. Bio-energy has currently the highest share in global heat production, which is mainly due to the traditional use of biomass and in many cases not sustainable[8]. The total share of RE heating systems in all scenarios by 2050 varies significantly between 13.5% (ReMind) and 90% (ER 2010). Both, the IEA WEO 2009 and the EMF 22 project a RE market share of around 20% by 2050.

10.3.2.3. Market potential for RE sources in the transport sector

The quality and quantity of data submitted in the selected scenarios was not comprehensive enough to provide an overview about the estimated market potential in the transport sector. Generally there are two categories of RE used in the scenarios. First of all direct RE applications like bio-fuels or marine wind energy use (first and second generation sails) and secondly indirect RE options like electricity or hydrogen based on RE. In terms of the latter one a competition with stationary sector has to be considered.

10.3.2.4. Global RE primary energy contribution

Figure 10.3.2 provides an overview of the projected primary energy production (using the direct equivalent methodology) by source for the four selected scenarios for 2020, 2030 and 2050 and

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[8] See also Chapter 2.1.1.

compares the numbers as a numerical exercise with different global primary energy demands. Bio-energy has the highest market share in all scenarios, followed by solar energy. This is due to the fact, that bio-energy can be used across all sectors (power, heating & cooling as well as transport) while solar can be used for power generation and heating and cooling. As the residual material potential and available land for bio-energy is limited and competition with nature conservation issues as well as food production must be avoided, the sectoral use for the available bio-energy depends on where it is used most efficiently.

However solar energy can be used for heating and cooling and power generation as well, but solar technology starts from a relatively low level. The relatively low primary energy share for wind and hydro is due to its exclusive use in the power sector.

The total RE share in the primary energy mix by 2050 has a huge variation across all four scenarios. With only 15% by 2050 – about today´s level – the IEA WEO 2009 projects the lowest renewable primary energy share, while the ER2010 covers 80% of the worlds primary energy demand with RE. Both, the ReMind and EMF 22 projection are in the range of one quarter RE by 2030 and one third by 2050. It is worth to mention the resulting primary energy share would be higher in all cases if different accounting methodologies would be used instead of the direct equivalent methodology. The highest share of RE has been achieve with a combination of a high market development for RE and a successfully implemented energy efficiency strategy. While the ER 2010 is based on a RE share of 95% and 91% of global heating and cooling demand, the most difficult sector for RE to supply substantial shares is the transport sector.

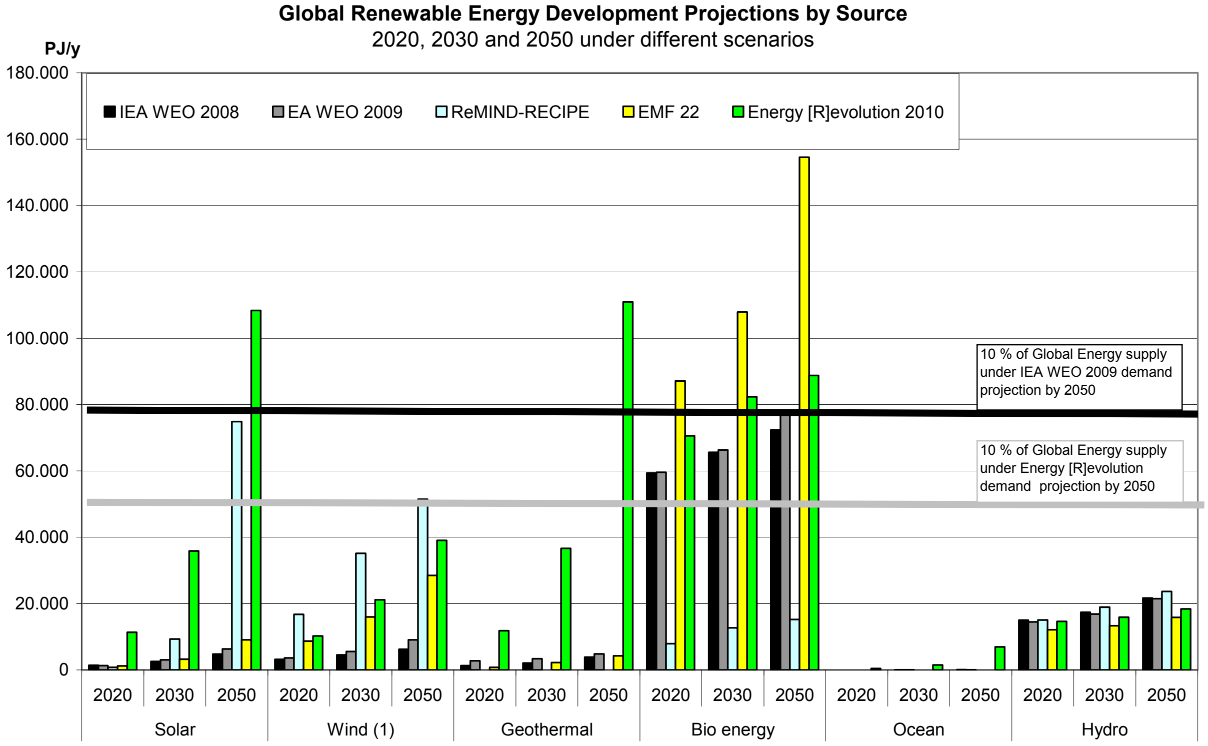

Figure 10.3.3: Global RE development projections by source and global renewable primary energy shares by source

10.3.3. Regional breakdown – technical potential versus market deployment

This section provides an overview about the market penetration paths given in the analysed scenarios versus the technical potential per region as well as an overview about the regional scenario data. The table compares the maximum value of the different scenarios with the technical potential in order to calculate the maximum deployment rate of the technical potential.

The quality of the regional data is not as comprehensive as it is the case for global scenario data. This is partly due to the fact that the number of scenarios providing a regional breakdown is very limited, especially for developing regions.

To give at least an impression about regional aspects, for illustrative purposes Tables 10.3.5 and 10.3.6 show the resulting market shares for the Energy [R]evolution 2010 scenario. Here data are available, furthermore it is amongst the selected scenarios the future path with the highest market projections for RE.

10.3.3.1. RE Power sector by Region

For the power sector the investigation shows that even if significant parts of the technical RE potential has to be deployed in the selected scenarios besides hydro power and geothermal energy the numbers are normally less than 10%. There are a few exemptions. In particular this is the case for wind energy where the deployment rates in China and India are even higher than the technical potential given in table 10.3.1. Obviously the ER 2010 scenario is based on other potential assumptions. Following an analysis by McElroy *et al*. (2009) for instance, it is estimated that China's wind potential could reach 640 GW by 2030, enough to cover the country's current electricity demand three times over.

Electricity: Technical Potential (TP) versus E[R] 2010 deployment in 2050 [EJ/y] - excluding biomass

	solar PV		solar CSP		hydro-power		wind (on + offshore)		ocean energy		geothermal electric		Total	
	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed
Africa	717	0,2%	4.348	0,1%	7	10,6%	29	3,7%	18	2,0%	4	20,0%	5.123	0,2%
China	98	5,6%	60	11,2%	5	100,0%	6	132,6%	7	32,2%	5	71,5%	180	17,0%
India	33	0,6%	106	4,7%	2	39,5%	2	163,5%	4	17,3%	15	13,6%	163	7,5%
Latin America	118	2,9%	299	1,7%	9	8,1%	47	7,5%	44	1,6%	5	43,3%	521	3,0%
Middle East	127	1,7%	1.153	0,5%	1	17,8%	5	24,3%	8	2,9%	1	72,7%	1.295	0,8%
OECD Europe	33	6,9%	4	39,7%	7	25,4%	31	15,6%	25	2,6%	2	89,4%	103	12,6%
OECD North America	84	5,0%	347	1,6%	6	56,9%	166	4,7%	46	2,2%	6	56,6%	655	3,9%
OECD Pacific	225	0,6%	1.513	0,1%	1	58,2%	57	5,8%	30	1,6%	4	11,7%	1.830	0,4%
Rest of Asia	137	2,0%	9	23,3%	6	15,8%	18	19,3%	150	0,6%	6	25,3%	326	3,6%
Transition Economies	116	0,4%	204	0,0%	5	28,4%	75	4,6%	13	1,2%	6	16,0%	418	1,5%
World	1.689	1,6%	8.043	0,5%	50	32,3%	436	9,1%	331	2,3%	45	37,5%	10.595	1,4%

Source RE Potential: DLR, Wuppertal Institute, Ecofys; Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply; Commissioned by the German Federal Environment Agency FKZ 3707 41 108, Marc

[TSU: The text in the footnote on sources is cut off.]

Table 10.3.5: Overview of relation between the market contribution of RE and the corresponding technical potential for different technologies and regions for 2050 and the power sector under the condition of the Energy [R]evolution 2010 scenario

For 2050, the highest deployment rate of the technical RE power potential per region has been found in China (17.0%), followed by OECD Europe (12.6%), India (7.5%), OECD North America (3.9%) and Developing Asia (3.6%). The other remaining regions have rates below 2.0%. On a global level, none of the analysed scenario exceeds a deployment rate of 1% of the total technical potential for renewable power generation.

Regional energy supply cost curves as "snapshots" of selected scenarios discussed in next sections are an alternative way (perspective) to present scenario results. The following curves (see Figures 10.3.4 to 10.3.6) can work as illustrative examples and represent a cross-section of three scenarios

(ReMIND Recipe, Energy Revolution 2008 (abbreviated as ER), and WEO 2008)[9]. They focus on a specific target year and relate the potentials for the deployment of certain renewable electricity technologies in the different regions to their cost levels in discreet steps.

The work alleviates two major shortcomings of the cost curve method (which are discussed in a more general and comprehensive way in section 10.4). First, recognizing the crucial determining role of carbon emission factors, energy pricing and fossil fuel policies in the ultimate shape of abatement cost curves, only RE cost curves are created (and not mitigation cost curves). Second, in order to capture the uncertainties in cost projections, several scenarios were reviewed. Using dynamic scenarios to create the curves as done here also prevents the problem of staticness [TSU: was ‘stactivness’].

Beyond the general issues about cost curves detailed in section 10.4, it is important to note a few points for the interpretation of the curves. First, the ER 2008 and the WEO 2008 scenario data were not as detailed for the costs, thus each technology in a region is represented by a single average cost in these scenarios. Average costs for a technology for a whole region mask the really cost-effective sub-technologies and sites into an average, compromised by the inclusion of less attractive sites or sub-technologies – thus not able to highlight the cheaper (and the more expensive) sites and sub-technologies. Second, it was not possible to deduct the presently existing capacity from the potentials by cost level, thus they include all capacity that can be installed in the target year allowed by the different constraints assumed. Due to the limited space available, but also caused by significant lack of data, curves for only three regions and the electricity sector are shown.

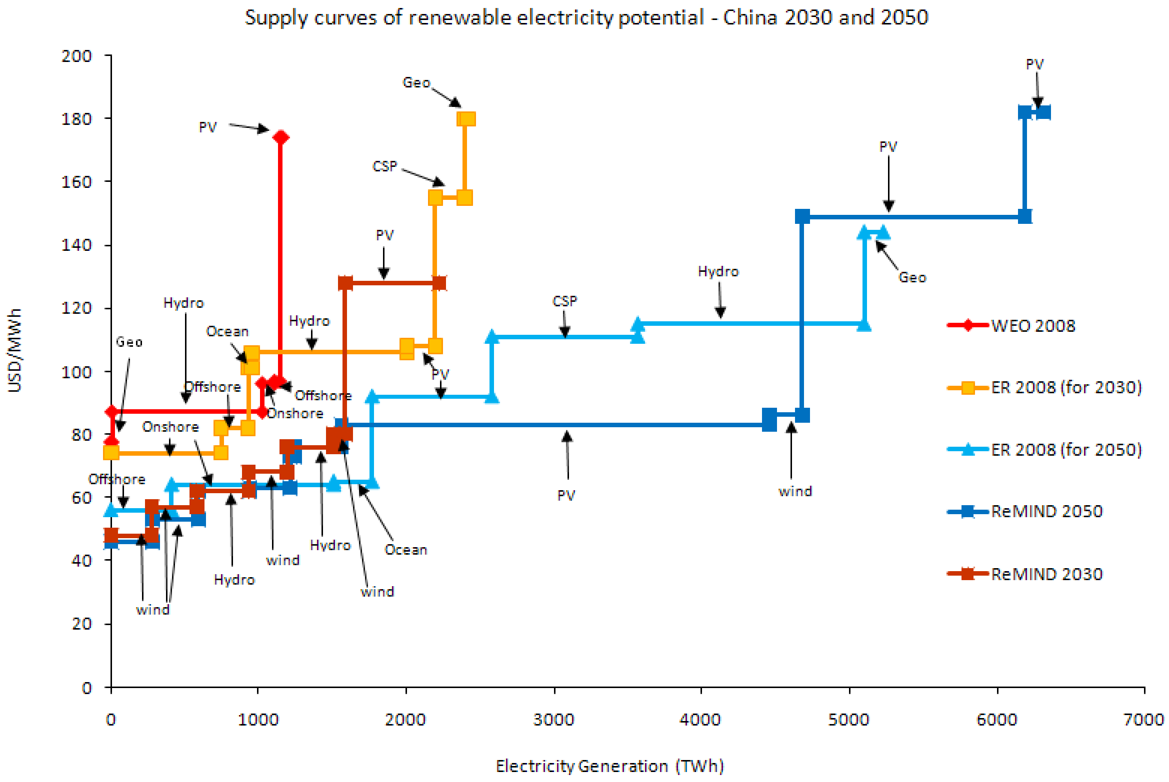

Figure 10.3.4: Renewable electricity supply curves for China for the year 2050.

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[9] For the SOD submission deadline data availability was limited. For the FD it is foreseen to use the same scenarios as been discussed before e.g. Energy Revolution 2010 and WEO 2009 instead of Energy Revolution 2008 and WEO 2008.

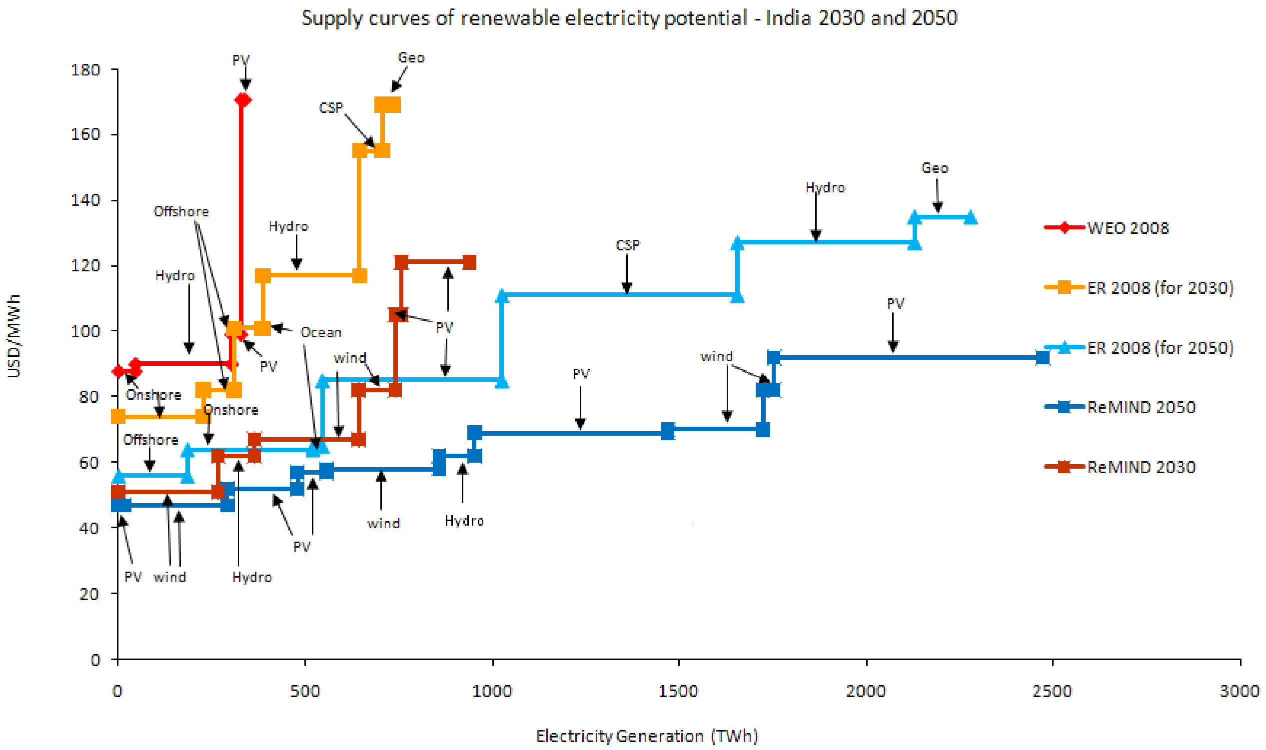

Figure 10.3.5: Renewable electricity supply curves for India for the year 2050.

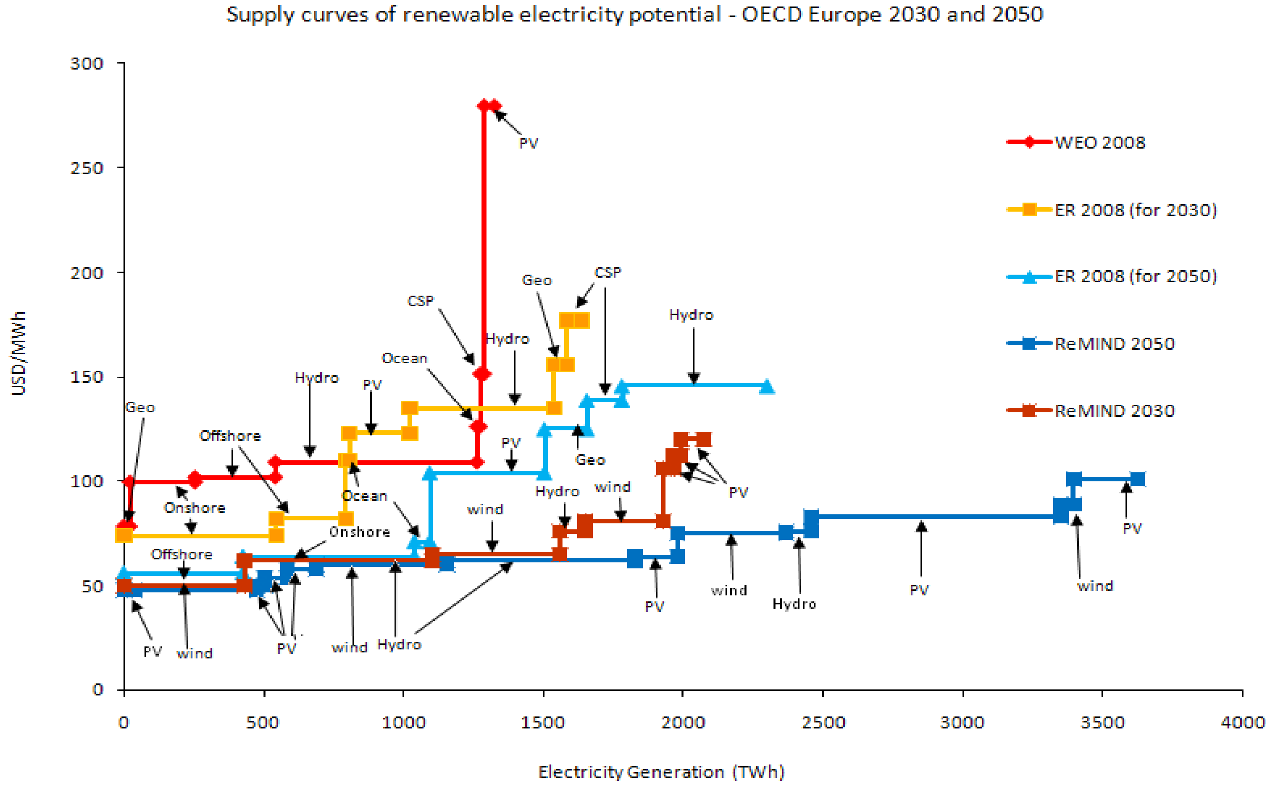

Figure 10.2.6: Renewable electricity supply curves for OECD Europe for the year 2050.

The figures illustrate several important trends. Perhaps the most important message they convey is the importance of a long-term vision when RE is considered. Potentials for deployment are consistently significantly larger for 2050 than for 2030 in all regions and scenarios, often doubling the potential at medium cost levels, except for OECD Europe. Even in this region, there is an important increase in the potential between these two years, but the ReMind scenario sees increase only at the larger cost options (still not very large since their 2050 curve does not go above USD100/MWh), and the ER scenario does not envision a larger than approximatelly 30% increase in the potential at most cost levels. On the other hand an over doubling of the potential in both China and India in both scenarios during this period can be seen.

When comparing the three models, the WEO 2008 projects the highest costs and lowest potentials in all three examined regions, while typically the ReMind scenario envisions the lowest cost levels and highest potentials[10]. While in some regions the curves from different models are close to each other and project similar potentials at similar cost levels, the technologies they consider the most promising are rather different. For instance, the ReMind scenarios see the largest promise in PV and in 2050 the lion's share of its cost-effective potential comes from this technology in all three examined regions. The ER scenario's projected potential consists of a balance of wind (on- and offshore), PV, CSP, hydropower and geothermal. WEO2008's projected potential in 2030 consists mainly of wind and hydro, and considers PV as a very expensive technology in all regions. This is the technology in which the different scenarios differ the most both in terms of costs and potentials. For instance, the ReMind's highest PV cost band for 2050 in OECD Europe is still lower than the average PV cost projected for this year by the ER scenario, and is approximately one-fourth of the average PV cost projected by WEO2008 by 2030, and the 2030 highest cost band is half.

The different scenarios see different roles and costs for CSP. This technology virtually does not play any role in the ReMind scenarios, while the ER scenarios see a larger role for CSP than for PV in both China and India in the longer term, albeit at a higher cost. Neither of the models attributes a major potential for geothermal, but they see its costs very differently. The costs of this power source in WEO2008 is approximately half of that in the ER scenarios for the same target year (2030), and even in 2050 the ER cost projections are significantly higher (highest among all technologies for India and China) for this technology than in the WEO2008 scenario in 2030 – although the potentials at this cost are several times higher than projected by the other scenarios, making a noticeable contribution to the total potential in 2050 in India and OECD Europe from among the examined regions. The ReMind scenarios do not consider geothermal power.

10.3.3.2. Primary energy by region, technology and sector

Following the same methodology, Table 10.3.6 compares the resulting primary energy contribution of RE in relation to the technical potential by region and technology. The maximum deployment share out of the overall technical potential for RE [TSU: was 'solar energy'] in 2050 was found in the illustrative scenario for China with a total of 6.7%. The second and third biggest deployment rates were found in scenarios for OECD Europe (5.6%) and India (5.0%). All other regions used less than 2.5% of the available technical potential for solar energy. Wind energy has been exploited to a much larger extend in all regions than solar energy. As indicated in Table 10.3.6, wind potential has been more than fully exploited in the scenario for India and China. This shows one more the complexity of scenario analysis, as the selected scenario here assumes a significant higher technical wind energy potential than the one expressed in Table 10.3.1. Geothermal energy does not play a mayor role in neither of the analysed scenarios. Both on a global and regional level the deployment

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[10] ReMIND assumes that RETs will be deployed at industrial scale at optimal sites and transported over large distances (up to continental scale) to demand centers. It implicitly assumes that bottlenecks, e.g. with respect to grid infrastructure, are avoided by early and anticipatory planning. This results in high capacity factors in ReMIND compared to other scenarios, which in turn has a strong effect on electricity generation costs and deployment levels.

rate of the available technical potential is far below 2.5%. The same is the case for ocean energy as a very young technology form.

Primary Energy: Technical Potential (TP) versus E[R] 2010 deployment in 2050 [EJ/y] - excluding biomass												
	Solar		Wind		Geothermal		Hydro		Ocean		Total	
	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	
Africa	5.076	0,2%	29	3,7%	1.015	0,1%	7	70,2%	18	2,0%	6.159	0,19%
China	175	10,7%	6	132,6%	420	1,9%	5	81,7%	7	32,2%	621	6,71%
India	146	5,8%	2	163,5%	144	1,4%	2	39,5%	4	17,3%	306	5,07%
Latin America	428	2,8%	47	7,5%	761	0,5%	9	8,1%	44	1,6%	1.348	1,52%
Middle East	1.298	0,9%	5	24,3%	180	1,0%	1	17,8%	8	2,9%	1.494	0,99%
OECD Europe	61	14,0%	31	15,6%	246	2,3%	7	25,4%	25	2,6%	386	5,61%
OECD North America	455	3,5%	166	4,7%	712	1,1%	6	56,9%	46	2,2%	1.421	2,52%
OECD Pacific	1.741	0,2%	57	5,8%	331	0,5%	1	58,2%	30	1,6%	2.170	0,47%
Rest of Asia	167	4,6%	18	19,3%	528	0,7%	6	15,8%	150	0,6%	878	1,92%
Transition Economies	325	0,8%	75	4,6%	657	0,8%	5	28,4%	1	11,5%	1.087	1,18%
World	9.856	0,9%	436	9,1%	5.000	0,9%	50	32,3%	331	2,3%	15.857	1,24%

Source RE Potential: DLR, Wuppertal Institute, Ecofys; Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply; Commissioned by the German Federal Environment Agency FKZ 3707 41 108, March 2009

Table: 10.3.6: Overview of the relation between the primary energy contribution of RE and the corresponding technical potential for different technologies and regions for 2050 under the condition of the Energy [R]evolution 2010 scenario

The established hydro power market potential on a global level covers roughly one third of the technical potential, in some countries the estimated capacity for 2050 is already very close to the maximum possible capacity for hydro power in these countries.

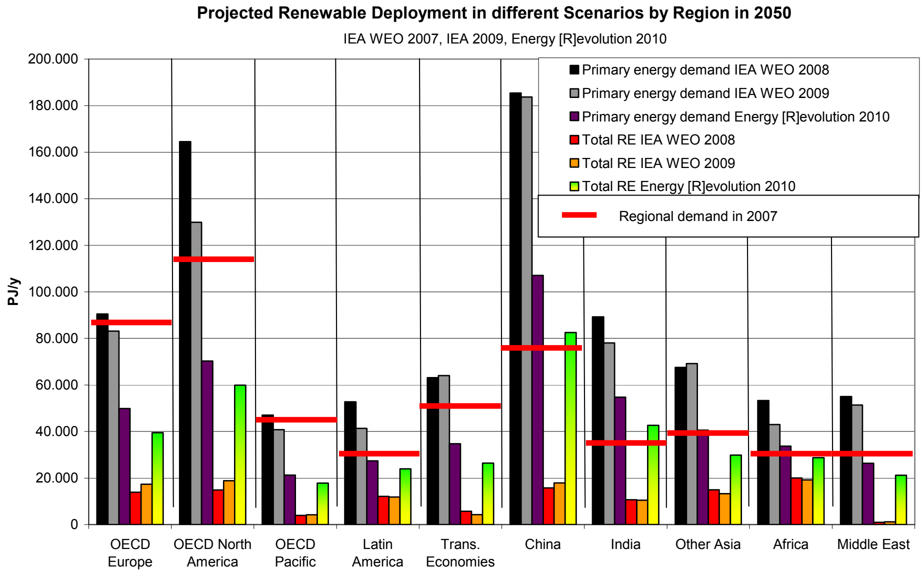

Figure 10.3.7: Regional breakdown from possible RE market potential: baseline (IEA WEO 2009) (>600 ppmv) versus Category II (<440 ppmv) ER 2010 scenario.

While the overall technical potential for RE exceeds current global primary energy by on order of magnitude (see section 10.3.2), even the ER 2010 scenario with the most aggressive growth rates for RE did not exceed 1.2 % (2050) of the given potential on a global level. Considering different regions the highest relation is given with 6.7% for China.

The analysed regional and global scenarios show a wide range of the RE shares in the future. Even if availability of regional data is poor, in order to show the different ranges of deployment rates for RE sources by sector and region, Figure 10.3.7 compares a baseline scenario (>600 ppm_v) with a category II (<440 ppm_v) scenario (Energy [R]evolution 2010 DLR/EREC/GPI). The data of the baseline scenario for 2040 and 2050 has been developed by the German Aerospace Agency (DLR).

Figure 10.3.7 shows different demand projects under the baseline and the ER 2010 scenarios, as well as total regional renewable market deployment compared to the energy demand in 2007. While the demand in the baseline for all OECD regions remains within the 2007 range, the demand for all other regions are projected to increase by an order of magnitude. The ER 2010, however, projects a drastic demand reduction in OECD regions and slower growth of energy demand in developing countries keeping the overall global demand on 2007 levels. While the RE shares of baseline scenario remain on 2007 levels and there cover only the additional demand, the ER 2010 projects to double or triples the renewable primary energy shares in all regions to well over 50%. The ER 2010 foresees for all OECD regions a RE share of 85% by 2050.

10.3.4. GHG mitigation potential of RE as the whole and as single options

Based on the results of the previous scenario survey and the identified market penetration rates projections for different RE technologies, the corresponding GHG mitigation potential has been calculated. For each sector, for each RE application a factor has to be identified addressing the kind of electricity generation or heat supply being substituted. This can not be done exactly without conducting own scenario analysis or complex power plant dispatching analysis. Therefore the following calculation is necessarily based on simplified assumptions and can only be seen as indicative. In that context RE applications are supposed to fully substitute fossil fuel use. In reality that may not be true as RE can compete for instance with nuclear energy as well. Also within the RE portfolio a competition is possible. To cover the uncertainties even in terms of fossil fuel substitution different factors have been chosen and uncertainty is marked in the following figures by arrow bars.

Behind that background for electricity generation the upper limit has been calculated on the basis of specific carbon emissions of coal fired power plants (0.79 kg CO_2 per kWh by 2020 and 0.63 kg CO_2 per kWh by 2050). The lower case has been calculated on the basis of specific carbon emissions of natural gas fired power plants (0.498 kg CO_2 per kWh by 2020 and 0.475 kg CO_2 per kWh by 2050). It is worth to mention that the lower limit is not far away from the specific emissions of the whole power plant mix under baseline conditions. For the power sector with the current global technology mix, the average specific carbon emission for 2007 is 0.539 kg CO_2 per kWh (IEA2009). For the future, the IEA 2009 baseline projection expects an increase of the specific emission factors to 0.495 kg CO_2 per kWh by 2020 and 0.478 kg CO_2 per kWh by 2030. For the heating sector, the average specific global carbon emission is 71 kt CO_2/PJ[11] with a chosen uncertainty range of +/- 15% while the upper range assumes a higher coal and oil use for heating and the lower an increased use of gas.

Figure 10.3.8 shows the annual CO_2 reduction potential per RE source for all analysed scenarios for 2020. The black line at 6 Gt CO_2/y identifies 20% of the global energy related CO_2 emissions (Base

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[11]

CO2 intensities heat [kt/PJ]	
District heating plants	95,1
Heat from CHP	187,3
Direct heating	59,1
Total	70,2
Total without CHP	60,8
Total direct only	59,1

year 2008), the grey line below represents 10%. Figure 10.3.9 shows the same sample of results for 2050. The red line here indicates 50% of total energy related CO_2 emissions (Basis 2008 [TSU: was 2007]).

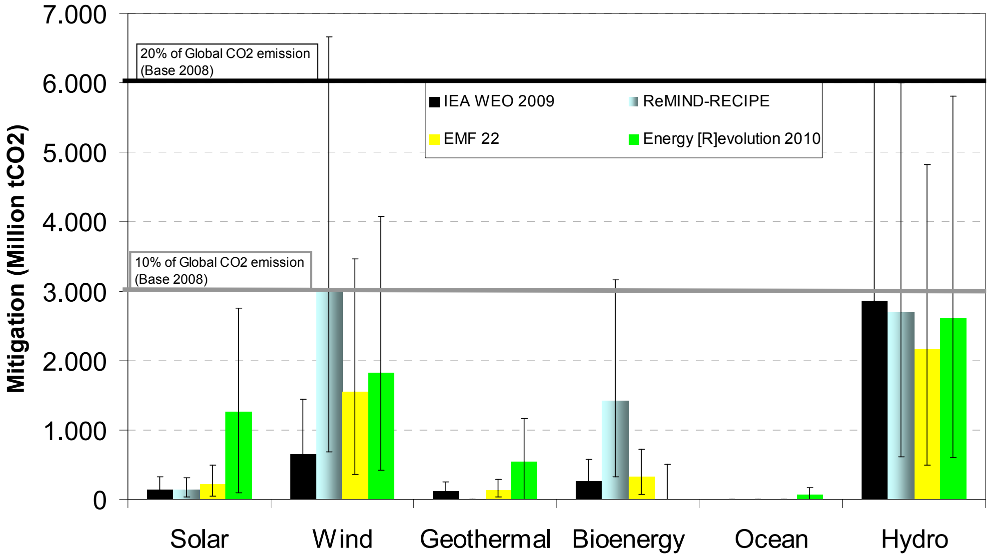

Figure 10.3.8: Annual Global CO2 savings from RE for different scenario based deployment paths for 2020 (NOTE: this is excluding transport and biomass used for direct heating)

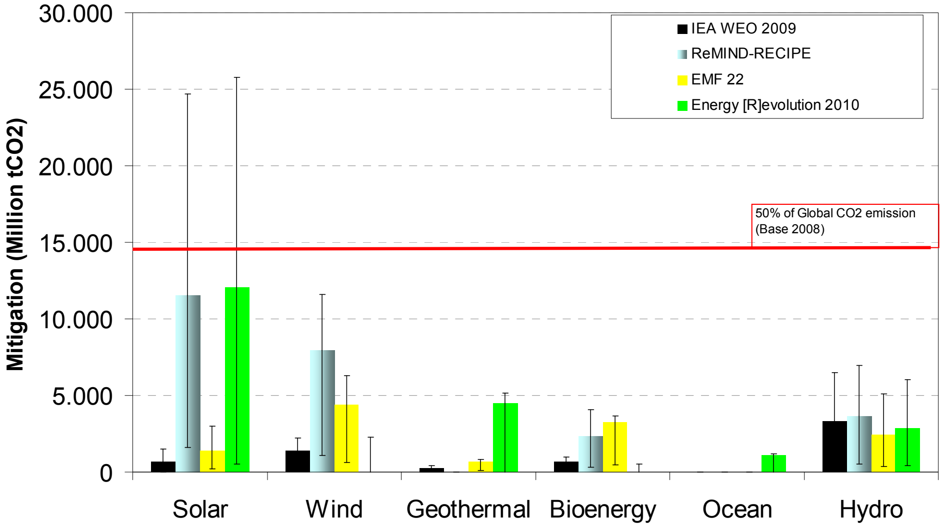

Figure 10.3.9: Annual Global CO2 savings from RE for different scenario based deployment paths for 2050 (NOTE: this is excluding transport and biomass used for direct heating)

Following the given assumptions and the scenario results hydro energy has the highest CO_2 reduction contribution of all scenarios by 2020, followed by wind energy. By 2050, solar has the highest mitigation potential followed by wind and hydro.

In this analysis, bio-energy contributes between 1,169 million tonnes CO2/a in the low case and 6,695 million tonnes CO2/a in the high case by 2050. But one has to keep in mind that, in practice, the uncertainties are significantly higher than for all other technologies. The use of non-renewable bio-fuels or solid biomass would reduce this amount significantly and could even result into higher CO_2 emissions compared to fossil fuels[12] (Crutzen et al., 2007). In addition, all analysed scenario

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[12] Sattler, C., Kachele, H. & Verch, G. 2007. Assessing the intensity of pesticide use in agriculture. Agriculture, Ecosystems and Environment 119: 299-304. and Crutzen, P.J., Mosier, A.R., Smith, K.A. & Winiwarter, W. 2007.

did not identify the share of modern biomass versus modern biomass in the `direct heating category`, therefore the biomass used for direct heating has been excluded from the CO2 reduction emission calculation.

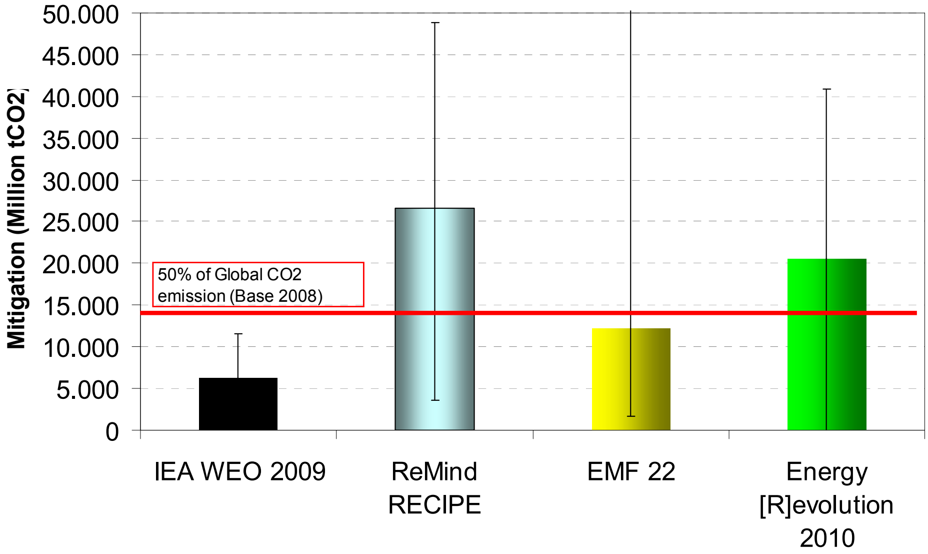


Figure 10.3.10: Annual Global CO2 savings from RE for different scenario based deployment paths for 2050 (NOTE: this is excluding transport and biomass used for direct heating)

Based on the analysed scenarios, the total annual CO_2 reduction potential varies significantly between all analysed scenarios. While the low case abatement potential for RE is the IEA WEO 2009 with 6.3 Gt CO_2/a by 2050, which represents the business-as-usual pathway, the medium case (EMF22) achieves a total of 12.2 Gt CO_2/a by 2050. The highest contribution represented by ReMind (ER 2010) [TSU: correct reference?] is marked by CO_2 savings by 2050 of 26.5 Gt CO_2/ a (20.5 Gt CO_2/a) which is equal to approximately 75% reduction of energy related CO_2-emission of the analysed baseline scenarios. However, the error bars in Figure 10.3.8 indicate that there are very high uncertainties.

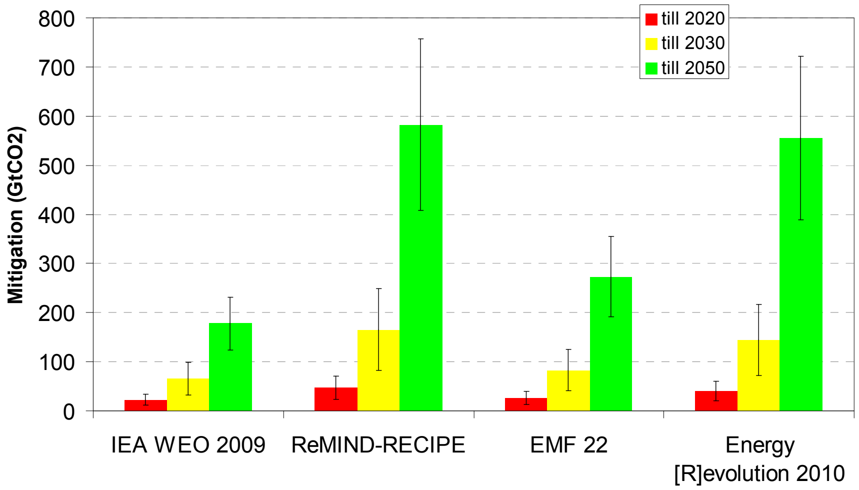


Figure 10.3.11: Global cumulative CO2 savings between 2020 and 2050

N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics Discussions 7: 11191-11205. and Scharlemann, J.P.W. & Laurance, W.F. 2008. How green are biofuels? Science 319: 43-44.

Cumulative CO2 reduction potentials from RE sources until 2020, 2030 and 2050 have been calculated on the basis of the annual average CO_2 savings shown in Figures 10.3.8 and 10.3.9. Based on this, the analysed scenarios would have a cumulated reduction of 178 Gt CO2 under the IEA WEO 2009 baseline conditions, 273 Gt CO2 in the EMF 22 case, 555 Gt CO2 in ER 2010 case and 583 Gt CO2 under the ReMind scenario (see Figure 10.3.11) [added by TSU]. Again, these numbers exclude transport and biomass used for direct heating.

10.3.5. Comparison of the results of the in depth scenario analysis

All analysed scenarios assume an increase of RE sources across all sectors. However, the power sector is in the forefront of all sectors and the sharpest increase of RE capacity is projected. Hydropower is believed to play the dominant role in the RE sector up until 2030 in all four analysed scenarios. Wind is believed in 3 out of 4 scenarios to overtake hydro by 2030. The results for all other technologies are far more diverse. Two scenarios see solar photovoltaic as an important player in the power sector after 2030, with a share of more than 10% by 2050, while the baseline scenario projects photovoltaic remains at marginal levels. In 3 out of 4 scenarios the foreseen role for geothermal energy remains low at levels well below 5% of the global power supply. The heating and cooling sector offers an even more diverse picture, which might be caused not only be uncertainties and distinguished assumptions but partly scenario results are not by 100% comparable because of different accounting methods, e.g. for geothermal heat pumps. In terms of primary energy share, bio-energy plays the most important contribution – especially in the heating sector. Wind and solar are projected to become an important player after 2030.

As already stressed in the comprehensive scenario survey, there are many reasons why the investigated scenarios come to different results. Each of the in-depth analysed scenarios follows a different strategy. Significant differences in the demand projections, a move towards electricity within the transport and/or heating sector or not has a significant impact on the selected technologies and their deployment rates. Besides that, other mitigation technologies, such as CCS and/or nuclear, have an impact on the resulting role of RE sources in the energy mix. Also system aspects play an important role. A high share of relatively inflexible "base load" power plants – such as coal- or lignite power plants - will reduce the technical and economic "space" of variable renewable power generation like solar photovoltaic and wind.

While under the baseline scenario the renewable primary energy production almost doubles to 120 EJ/y by 2050, the category I+II scenario EMF 22 projects tripling to 210 EJ/y. The ER 2010 projects the highest RE primary energy production up to 372 EJ/y – more than 5 times the 2007 level.

10.3.6. Knowledge gaps

Following knowledge gaps can be identified:

- New RE technologies, such as ocean energy, are not represented in most of the current energy scenarios.
- The interaction of the chosen technology pathways with the effects on deployment costs are not well reflected in most scenarios.
- The reporting system, e.g. for geothermal heat pumps, is very different in all scenarios and sometimes not transparent, which makes it difficult to compare the results
- More generally, there is a severe lack of data for the heating and transport sector especially for the sectoral or regional basis.

10.4. Regional Cost Curves for mitigation with RE sources

10.4.1. Introduction

Governments and decision-makers face limited financial and institutional resources and capacities for mitigation, and therefore tools that assist them in strategising how these limited resources are prioritised have become very popular. Among these tools are abatement cost curves – a tool that relates the mitigation potential of a mitigation option to its marginal cost. Recent years have seen a major interest among decision- and policy-makers in abatement cost curves, witnessed by the proliferation in the number of such studies and institutions/companies engaged in preparing such reports (e.g. Next Energy, 2004; Dornburg *et al.*, 2007; McKinsey&Company, 2007; International Energy Agency, 2008; McKinsey&Company, 2008a; McKinsey&Company, 2009c; McKinsey&Company, 2009b) (Creyts et al. 2007) [AUTHORS: Reference missing in bibliography]. However, while abatement curves are very practical and can provide important strategic overviews, it is pertinent to understand their use for decision-making has many limitations.

The aims of this section are to: (a) review the concept of abatement cost curves briefly and appraise their strengths and shortcomings; (b) review the existing literature on regional abatement cost curves as they pertain to mitigation using RE; and (c) review the literature on (regional) RE technology resource cost curves.

10.4.2. Abatement and energy cost curves: concept, strengths and limitations

10.4.2.1. The concept

The concept of supply curves of carbon abatement, energy, or conserved energy all rest on the same foundation. They are curves consisting typically of discreet steps, each step relating the marginal cost of the abatement measure/energy generation technology or measure to conserve energy to its marginal cost; and rank these steps according to their cost. As a result, a curve is obtained that can be interpreted similarly to the concept of supply curves in traditional economics.

Supply curves of conserved energy were first introduced by Arthur Rosenfeld (see Meier *et al.*, 1983) and became a popular concept in the 1980s (Stoft, 1995) [AUTHORS: Reference missing in bibliography]. The methodology has since been revised and upgraded, and the field of its application field extended to energy generation supply curves including RE cost curves; as well as carbon abatement from the 1990s (Rufo, 2003). One of the benefits of the method was that it provided a framework for comparing otherwise different options, such as the cost-effectiveness of different energy supply options to energy conservation options, and therefore was a practical tool for some decision-making approaches, such as integrated resource planning. Although Stoft (1995) explains why the supply curves used in the studies by Meier et al. cannot be regarded as "true" supply curves, including the fact that markets associated with the different types of options depicted in them, such as energy efficiency and energy supply markets, differ in many aspects; he maintains that they are useful for their purpose.

Despite the widespread use of supply curves and their advantages discussed above, there are some inherent limitations to the method that have attracted criticism from various authors that are important to review before we review the literature on them or present the regional cost curves.

10.4.2.2. Limitations of the supply curve method

The concept of abatement, energy and conservation supply curves have common and specific limitations. Much of criticism in the early and some later literature focuses on the notion of options with negative costs. For instance, the International Energy Agency (IEA) (2008b) raises an objection based on the perfect market theory from neoclassical economics, arguing that it is not possible to have negative cost options as under perfect market conditions someone must have realized those options complying with rational economic behaviour. The existence of untapped "profitable" (i.e. negative cost) potentials themselves represent a realm of debates ongoing for decades between different schools of thought (e.g. see Carlsmith *et al.*, 1990; Sutherland, 1991; Koomey, 1998; Gumerman *et al.*, 2001). Those accepting negative cost potentials argue, among others, that certain barriers prevent those investments from taking place on a purely market basis, but policy interventions can remove these barriers and unlock these profitable potentials. Therefore the barriers prevailing in RE markets, detailed in other sections of this report, such as insufficient information, limited access to capital, uncertainty about future fuel prices (for example in the case of fossil fuels or biomass) or misplaced incentives (e.g. fossil fuel subsidies for social or other reasons) hinder a higher rate of investments into RE technologies, potentially resulting in negative cost options (Novikova, 2009).

A further concern about supply curves is raised by EEEC (2007) [AUTHORS: Reference missing in bibliography], criticizing that the methodology simplifies reality. In their view, the curves do not reflect the real choices of actors, who accordingly do not always implement the available options in the order suggested by the curve. Both EEEC (2007) and (International Energy Agency (IEA), 2008b) agree that there is the problem of high uncertainty in the use of supply curves for the future. This uncertainty is true both from economic and technological perspectives. Additional uncertainty rising from the methodology is the sensitivity of mitigation curves relative to the baseline assumption of the analysis (Kuik, 2009). Baker *et al.* (2008) have demonstrated that aggregation may also trigger significant uncertainty in MACCs. For any given hour with given load and fuel prices, the expected monotonically rising (although not necessarily convex) relationship between price and abatement can be observed. However, when hours are aggregated into days, weeks, months, and years, the constancy of the relationship will be completely lost. Perhaps one of the key shortcomings of the cost curves are that they consider and compare mitigation options individually, whereas typically a package of measures are applied together, therefore potentially missing synergistic and integrational opportunities, or potential overlaps. Optimised, strategic packages of measures may have lower average costs than the average of the individual measures applied using a piecemeal approach. Conversely, some measures may be more expensive or even become unviable when other measures are implemented. Any measures that compete against each other are substitutable, in some part or entirely (Sweeney and Weyant, 2008).

For GHG abatement cost curves, a key input that largely influences the results is the carbon intensity, or emission factor, of the country or area to which it is applied, and the uncertainty in projecting this into the future. This may lead to a situation where the option in one locality is shown to be a much more attractive mitigation measure as compared to an alternative than in another one simply as a result of the differences in emission factors (Fleiter *et al.*, 2009). As a result, a carbon abatement curve for a future date may say more about expected policies on fossil fuels than about the actual measures analysed by the curves, and the ranking of the individual measures is also very sensitive to the developments in carbon intensity of energy supply.

There are some concerns emerging in relation to abatement cost curves that are not yet fully documented in the peer-reviewed literature. For instance, the costs of a RE technology in a future year largely depends on the deployment pathway of the technology in the years preceding – i.e. the policy environment in the previous decades. The abatement cost of a RE option heavily depends also on the prices of fossil fuels which is also very uncertain to predict.

Economic data, such as technological costs or retail rates, are derived from past and current economic trends that may obviously not be valid for the future, as sudden technological leaps, policy interventions, or unforeseeable economic changes may occur – as has often been precedented in the field of RE technology proliferation. These uncertainties can be mostly alleviated through the use of scenarios, which may result in multiple curves, such as for example in Van Dam *et al.*, (2007), and as presented in the previous sections (10.2 and 10.3). Some of the key uncertainty factors are the discount rates used and energy price developments assumed. The uncertainty about discount rates does not only stem from the fact that it is difficult to project them for the future, but because it is difficult to decide what discount rate to use, i.e. social vs. market discount rates. A number of studies (see e.g. Nichols, 1994) have discussed that in the case of investments in energy efficiency or RE, individual companies or consumers often use higher discount rates than would be otherwise expected for other types of e.g. financial investments. On the other hand, as Fleiter *et al.* (2009) note, society faces a lower risk in the case of such investments, therefore a lower discount rate could be considered appropriate from that perspective. Kuik *et al*. (2009) demonstrated that depending on the method used to construct them, MACCs are affected by policies abroad. Essentially, policies abroad create a shift in the baseline for a country through changes in prices in energy markets as well as in price developments in RE technologies.

While several of these shortcomings can be addressed or mitigated to some extent in a carefully designed study, including those related to cost uncertainty, others cannot, and thus when cost curves are used for decision-making, these limitations need to be kept in mind while discussing regional cost curves reviewed from the literature in the following section as well as regarding the regional cost curves out of the scenario results in section 10.3.

10.4.3. Review of regional energy and abatement cost curves from the literature

10.4.3.1. Introduction

This section reviews the key studies that have produced national or regional cost curves for RE and its application for mitigation. First, we review work that look at RE cost curves, followed by a review of the role of RE in overall abatement cost curves – since designated cost curves for renewable alone are rare.

10.4.3.2. Regional and global RE cost curves

In an attempt to review the existing literature on regional cost curves, a number of studies were identified, as summarized in **Error! Reference source not found.**. As discussed in the previous section, the assumptions used in these studies have a major influence on the shape of the curve, ranking of options and the total potential identified by the curves, the table also reviews the most important characteristics and assumptions of the models/calculations as well as their key findings.

In general, it is very difficult to compare data and findings from different RE supply curves, as there have been very few studies using a comprehensive and consistent approach and detail their methodology, and most studies use different assumptions (technologies reviewed, target year, discount rate, energy prices, deployment dynamics, technology learning, etc.). Therefore, country- or regional findings in **Error! Reference source not found.** need to be compared with caution, and for the same reasons findings for the same country can be very different in different studies.

Table 10.4.1: Summary of regional/national literature on RE supply curves, with the potentials grouped into cost categories (Baseline refers to the expected projection of the energy type whose potential is described in the “notes” by the target year; most typically the projected TPES for the particular country, unless otherwise noted in the Notes)

Country/region		Cost ($ / MWh)	Total RES (TWh/yr)	% of base-line	Dis-count rate (%)	Notes	Source
Global		< 100	200,000-300,000	>100	10	- Combined potential of Onshore Wind, solar PV and Biomass given land usage constrains and technology scenarios - Sources of uncertainty considered	de Vries et al. (2006), baseline: World Energy Council, 2001 and Hoogwijk, 2004 [AUTHORS: Reference missing in bibliography].
Global (Biomass)		<100	97,200	N/A	10	- Study claims biomass production under this price can exceed present electricity consumption multiple times	(Hoogwijk *et al.*, 2003) Target year not specified
Global	Wind	<100 <80 <60 <40	42,000 39,000 23,000 2,000	133 123 72 6	10	- Liquid transport fuel and electricity from biomass, onshore wind, PV - Capacity calculated for the whole world, grid connections, supply-demand relationships etc. not incorporated - Global technical potential for electricity generation - High technology development scenario (A1) with stabilizing world population and fast and widespread yield improvements.	RES data: (de Vries *et al.*, 2007) Target year: 2050 Baseline data: (International Energy Agency (IEA), 2003)
	Biomass	<60	59,000	187			
	PV	<100 <80	1,850,000 400,000	5,868 1,268			
Global		<70 <100	21,000 53,000	600-700	10	- Technical potential for onshore wind based on wind strength and land use issues, grid availability, network operation and energy storage issues are ignored - baseline refers to 2001 world electricity consumption	Hoogwijk et al. (2004), Reference year: 2004 baseline IEA 1996
	Former USSR	<70 <100	2,000 7,000	160 550			
	USA	<70 <100	3,000 13,000	80 350			
	East Asia	<70 <100	0 50	0 3			
	Western Europe	<70 <100	1,000 2,000	40 80			
Global		<50	121,805	N/A	10	- Biomass energy from short-rotation crops at abandoned cropland and restland - four IPCC CRES [TSU: should probably read: SRES] land-use scenarios for the year 2050 - land productivity improvement over time, cost reductions due to learning and capital-labour substitution - Present world electricity consumption (20 PWh/yr) may be generated at costs below $45/MWh (A1 B1 scenarios) and 50 $/MWh (A2 B2 scenarios) in 2050	(Hoogwijk *et al.*, 2009) Target year: 2050
	Former USSR		23,538				
	USA		9,444				
	East Asia		17,666				
	OECD Europe		3,194				

Central and Eastern Europe	<100	3,233	74	N/A	- Biomass only, best scenario with willow being the selected energy crop (highest yield) - Countries: BG, CZ, EST, HU, LV, LT, PL, RO, SK - Baseline data includes Slovenia, however, its share is rather low, therefore resulting distortion is not so high.	RES data: van Dam et al. (2007) Target year: 2030 Baseline data: (Solinski, 2005)
Czech Republic	<100	101	20	4	- Only biomass production - Best case scenario where future yields equal the level of the Netherlands	RES data: (Lewandowski *et al.*, 2006) Target year: 2030 Baseline data: (International Energy Agency (IEA), 2005a)
Germany	<100	160	24	N/A	- Only Wind and PV are included - PV only enters above 200 USD	RES data: Scholz (2008) Baseline data: McKinsey and Company (2007)
	<200	177	27			
	<300	372	56			
India	<200	90	5.6	10	- wind - Grid availability not expected to be a serious concern - baseline refers to 2005 electricity consumption	Pillai et al. (2009) Target year: 2030
	<100	56	3.4		- small hydro - Grid availability not expected to be a serious concern - baseline refers to 2005 electricity consumption	
Netherlands	<100	22	2.1	N/A	- Included: onshore and offshore wind, PV, biomass and hydro; - Interest rate is not available, however, this option is a scenario where sustainable production is calculated. Therefore they use 5% IRR assuming that there are governmental support; - Baseline is TPES forecast for 2020 by IEA;	RES data: Junginger et al. 2004 Reference year: 2020 Baseline data: IEA (2006)
	<200	23	2.2			
	<300	24	2.3			
UK	<100	81	22	7.9	- Included: "Low-cost technologies" (landfill gas, onshore wind, sewage gas, hydro); - Costs: capital, operating and financing elements; - Baseline is all electricity generated in the UK forecasted for 2015;	RES data: Enviros (2005) Baseline data: UK SSEFRA (2006)
	<200	119	33			
United States	<100	3,421	15	N/A	- Wind energy only	RES data: Milligan (2007) Baseline data: EIA (2009)
United States (WGA)	<100	177	0.77	N/A	- Only the WGA region - CSP, biomass, and geothermal; - Geothermal reaches maximum capacity under 100 $/MWh; - CSP has a large potential, but full range is between 100 and 200 $/MWh	RES data: Mehos and Kearney (2007), Overend and Milbrandt (2007), Vorum and Tester (2007) Baseline data: EIA (2009)
	<200	1,959	8.5			
	<300	1,971	8.6			
United States (AZ 2025)	<100	0.28	N/A	Biomass and PV: 7.5 Rest: 8	- State of Arizona, United States - RES: wind, biomass, solar, hydro, geothermal Interest rates vary between energy sources	RES data: Black & Veatch Corporation (2007)
	<200	10.5	N/A			
	<300	20	N/A			

The weakness of many regional or technology studies is that they usually do not account for the competition for land and other resources, such as capital among the various energy sources (except for probably the various plant species in the case of biomass). In studies that do take this into account (such as de Vries *et al.*, 2007), potentials substantially decline in case of exclusive land use, with solar PV suffering the worst losses both in technical and economic potentials.

10.4.3.3. Regional and global carbon abatement cost curves

One general trend can be observed based on this limited sample of studies. Abatement curve studies tend to find lower potentials for mitigation through RE than those focusing on RE for energy supply. Even for the same country these two approaches may find very different potentials.

One factor contributing to this general trend is that RE supply studies typically examine a broader portfolio of RE sources technologies, while the carbon mitigation studies reviewed focus on selected resources/technologies to keep models and calculations at reasonable complexity. For instance, remaining with the UK example, the CBI (2007) [AUTHORS: Reference missing in bibliography] study does not take into consideration other RE sources presented by (Enviros Consulting Ltd., 2005) as low-cost options, such as landfill gas, sewage gas and hydropower.

The highest figure in carbon mitigation potential share by the deployment of RE, as demonstrated by Table 10.4.2, is for Australia: 13.4% under 200 USD/t CO_2e by 2030. This has to be seen in contrast with the much higher shares as a percentage of national TPES reported in the previous section (data from McKinsey&Company, 2008a). Besides Australia, countries with the most promising abatement potentials through RE sources identified in the sample of studies are China and Poland – all having high emission factors.

10.4.4. Review of selected technology resource cost curves from the literature

The energy and abatement cost curves discussed above are based on technology specific findings. For selected technologies this section ends with the discussion of illustrative examples of resource cost curves. In this context some studies are highlighted which were already part of the general overview in section 10.4.3. Additionally, this section is linked with the discussion of the energy and cost aspects in the various technology chapters (Chapters 2-7).

Summary of biomass resource cost curves. The analysis of biomass resource cost curves in the literature use typically different land-use scenarios (de Vries *et al.*, 2007; Hoogwijk *et al.*, 2009) (Figure 10.4.1). They take into account geographical potential (crop productivity and land availability) as well as capital and labour input. Hoogwijk et al. (2009) find that biomass can supply about 40-70% of the present primary energy consumption (130-270 EJ/year) by 2050 at costs below USD 2/GJ/year, which is the present lower limit of the cost of coal.

Table 10.4.2 summarises the findings and characterises the assumptions in the studies reviewed that construct regional carbon abatement cost curves through the deployment of renewable technologies. They have a different focus, goal and approach as compared to RE supply curve studies, and are broader in scope, examining RE within a wider portfolio of mitigation options.

Table 10.4.2: Summary of carbon abatement cost curves literature (cells including grey literature are coloured in grey)

Country/region	Year	Cost (\$/tCO$_2$e)	Mitigation potential (million tonnes CO_2)	% of baseline	Discount rate (%)	Notes	Source
Global	2050	<200	46,195	85	N/A	- Key sensitivities: lower potential for wind, hydro or CCS, lower uranium resources raise abatement costs by 2-5%	Syri et al. (2008) [AUTHORS: Reference denoted: 2002]. Baseline model: global ETSAP/TIAM Baseline Scenario: WEO 2009
Global	2030	<100	6,390	9.1	4	- Scenario A (Maximum growth of RE and nuclear) - Scenario B (50% growth of RE and nuclear)	(McKinsey&Company, 2009b)
		<100	4,070	5.8			
Annex I	2020	<100	2,818	20	N/A	- Different abatement allocations analysed depending (equal marginal cost, per capita emission right convergence, equal percentage reduction) - CO_2 equivalent emissions six Kyoto GHGs, but exclude LULUCF - Costs in 2005 USD	Elzen et al. (2009) [AUTHORS: Reference missing in bibliography] Baseline Scenario: WEO 2009
Australia	2020	<100	74	9.5	N/A		(McKinsey&Company, 2008a)
Australia	2030	<100	105	13			
Australia (NSW Region)	2014	<100	8.1	1.0	N/A	- New South Wales region - Includes governmental support for RES	Abatement data: Next Energy (2004) Baseline data: McKinsey&Company (2008a)
		<300	8.5	1.1			
China	2030	<100	1,560	11	4		(McKinsey&Company, 2009a)
China	2030	<50	3,484	30	N/A	- Storylines do not describe all possible development (eg. disaster scenarios, explicit new climate policies) - Main abatement (half of total) is efficiency, the rest is renewable and fuel switch from coal	Van Vuuren et al. (2003) [AUTHORS: Reference missing in bibliography] Baseline scenario: IPCC SRES (2000) Baseline Scenario: WEO 2009

Country/region	Year	Cost ($\$/tCO_2e$)	Mitigation potential (million tonnes CO_2)	% of baseline	Discount rate (%)	Notes	Source
China	2030	<100	2,323	20	N/A	- Main factor influencing abatement cost is constraints on the rollout of nuclear power - Baseline seems to be underestimated as 2010 power consumption is 40% below fact.	Chen, 2005 [AUTHORS: Reference missing in bibliography] Baseline Scenario: IEA 2009
Czech Republic	2030	<100	9.3	6.2	N/A	- Scenario with maximum use of RE sources	(McKinsey&Company, 2008b)
		<200	11.9	8.0			
		<300	16.6	11			
Germany	2020	<100	20	1.9	7	- Societal costs (governmental compensation not included)	(McKinsey&Company, 2007)
		<200	31	3.0			
		<300	34	3.2			
Poland	2015	<100	50	11	6	- Only biomass - Best case scenario	Abatement data: (Dornburg *et al.*, 2007) Baseline data: EEA (2007)
		<200	55.90	12			
Switzerland	2030	<100	0.9	1.6	2,5	- Base case scenario	(McKinsey&Company, 2009c)
South Africa	2050	<100	83	5.2	10	- Renewable electricity to 50% scenario	(Hughes *et al.*, 2007)
Sweden	2020	<100	1.26	1.9	N/A		(McKinsey&Company, 2008c)
United States	2030	<100	380	3.7	7		Creyts et al. (2007) [AUTHORS: Reference missing in bibliography]
United Kingdom	2020	<100	4.38	0.46	N/A		CBI (2007) [AUTHORS: Reference missing in bibliography]
		<200	8.76	0.93			

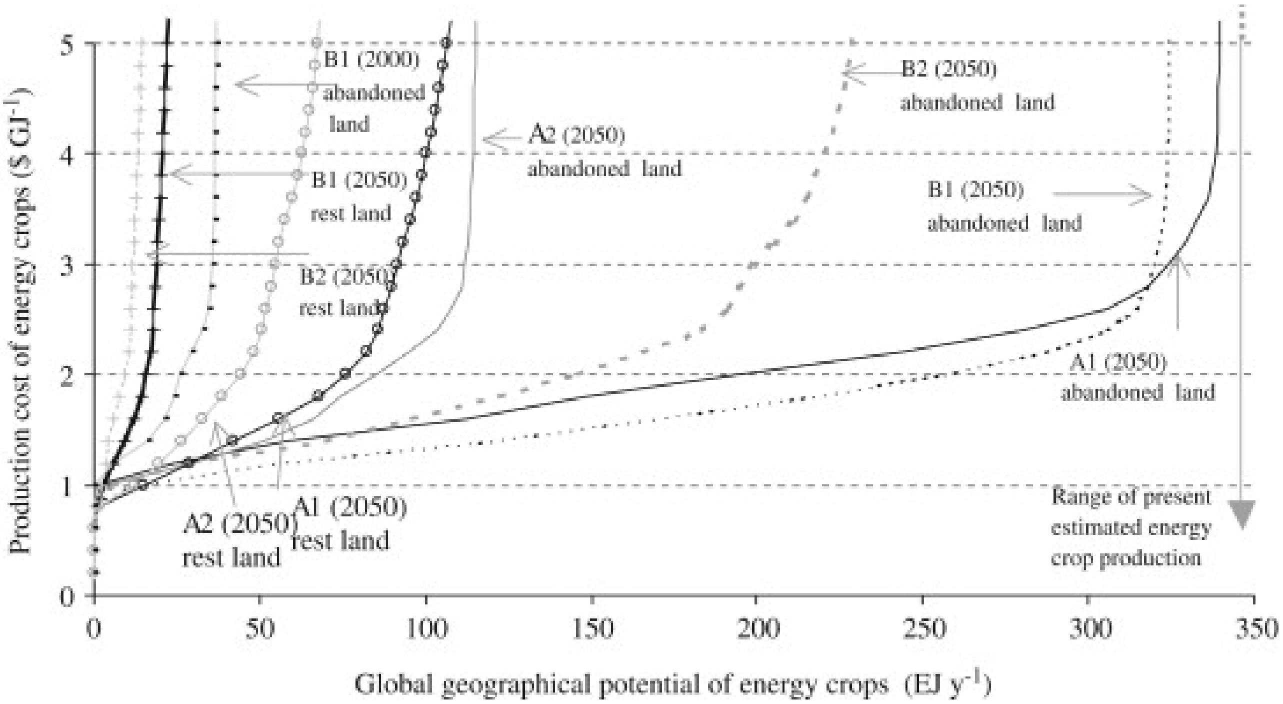


Figure 10.4.1: The global average cost-supply curve for the energy production potential from energy crops for four SRES scenarios for the year 2050 (Hoogwijk et al., 2009).

Regions of low production cost and relatively high potential are the former USSR, Oceania, Eastern and Western Africa and East Asia. Cost reductions are due to land productivity improvements over time, learning and capital-labour substitution. Biomass-derived electricity costs are at present slightly higher than electricity base-load costs. The present world electricity consumption of around 20 PWh/year may be generated in 2050 at costs below USD 45/MWh in two scenarios, while below USD 55/MWh in two others. At costs of USD 60/MWh, about 18 to 53 PWh/year of electricity can be produced in 2050. The global curve that sums all regional curves is found to be relatively flat until 300 EJ/year potential, land rental costs and the substitution of capital for labour represent highest sensitivity.

In the study of de Vries *et al.* (2007), another trade-off is addressed: the food vs. energy one. The authors assess four land-use scenarios, each corresponding to different levels of food-trade, technology development and population. Low potential estimate in the A2 scenario is a direct consequence of more people, hence higher food demand and lower yield (improvement) hence more land demand for food production (Figure 10.4.2).

The price of biomass energy as of 2000 is 50-100 USD/MWh, representing 7 PWh of technical potential in year 2000, while the projected cost ranges between 30-100 USD/MWh, supplying 59 PWh by 2050. Electricity production from biomass is significantly costlier: 100 USD/MWh in 2050, contributing 30–85PWh/year by 2050. Land availability and management factor plays a key part in the evolution of uncertainties.

Summary of PV resource cost curves. De Vries *et al.* (2007) estimate PV electricity generation potential at 4,105 PWh/year in 2050 at the cost of 60-250 USD/MWh. Since the potential for the year 2050 depends primarily on cost reducing innovations: for a cut-off cost level of 100 USD/MWh, a non-zero potential emerges only in scenarios with high economic growth vs. low population growth, or medium economic and population growth (Figure 10.4.3).

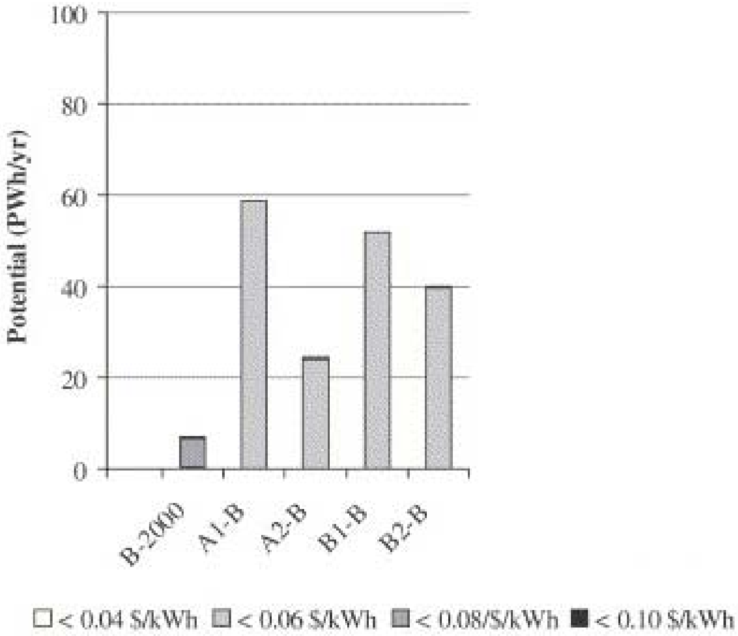


Figure 10.4.2: The global technical potential for electricity from biomass in the year 2000 and in the four scenarios for the year 2050 for four production categories (de Vries *et al.*, 2007).

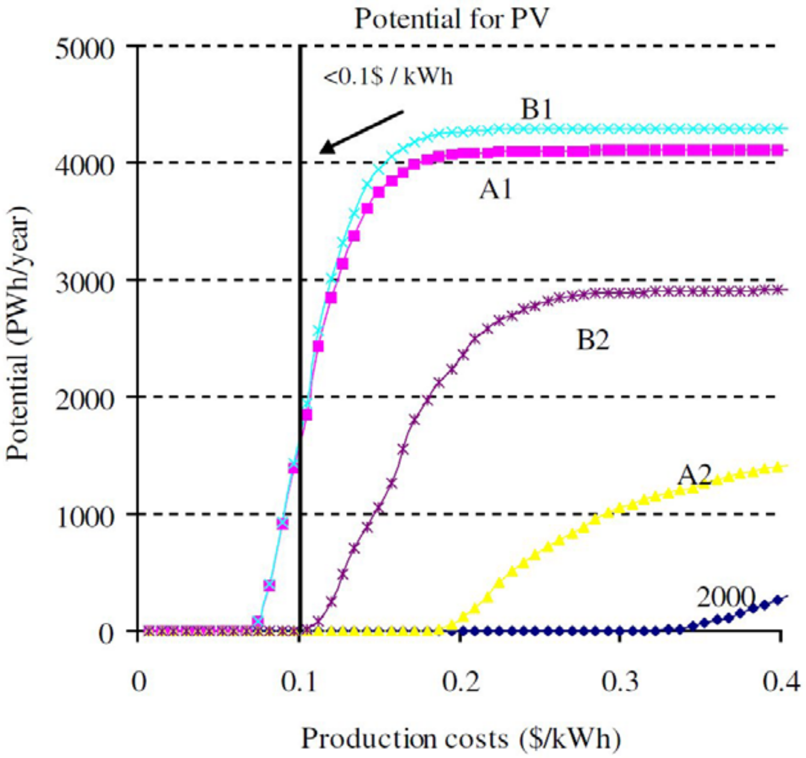


Figure 10.4.3: Resource supply cost curve for PV for four IPCC scenarios in 2050. The figure also shows the 0.1 USD/kWh line used in the paper as cut-off cost in determining the economic potential (de Vries et al., 2007).

Solar PV is extremely sensitive to competition for land, its technical and economic potentials are very sensitive to the cost determinants. If the technological breakthroughs do not take place, a large part of the major potential is unlikely to become economic. Its capital-intensive nature makes it also sensitive for changes in the interest rate, for the same reason. High or low exclusion factors also affect the solar-PV potential, but land does not seem to be the constraint here: even with the high exclusion factor, the potential is over 20 times the 2000 world electricity demand (de Vries *et al.*, 2007).

Summary of onshore wind cost curves. Papers assessing wind potential usually base their data on climatic models of wind speeds (de Vries et al., 2007; Hoogwijk et al., 2004; Changliang and Zhanfeng, 2009). Hoogwijk *et al.* (2004) have made explicit assumptions about the average turbine availability, wind farm array efficiency and spacing, and, relatedly, power density; this has not differentiated across grid-cells i.e. one global parameter has been used. The estimated global technical potential for wind in 2000 is 43 PWh/year, which is expected to increase to 61 PWh/year by 2050, but largely confined to three proliferous regions (**Figure** 10.4.4). These are the USA, the Former USSR and Oceania (16 PWh/yr, 8 PWh/yr and 4 PWh/yr, respectively), which is estimated to reach 22 PWh/yr, 11 PWh/yr and 11 PWh/yr for the three regions (Hoogwijk et al., 2004; McElroy et al., 2009). When analysing scenarios taking into consideration socio-economic aspects, it is found that the strongest increase in potential for wind by a stabilizing of population and therefore a decreased need for agricultural land. Compared to current costs (50 – 130 USD/MWh), wind power might even be generated at costs below 40 USD/MWh in scenarios assuming either high economic growth vs. low population growth, or medium economic and population growth.

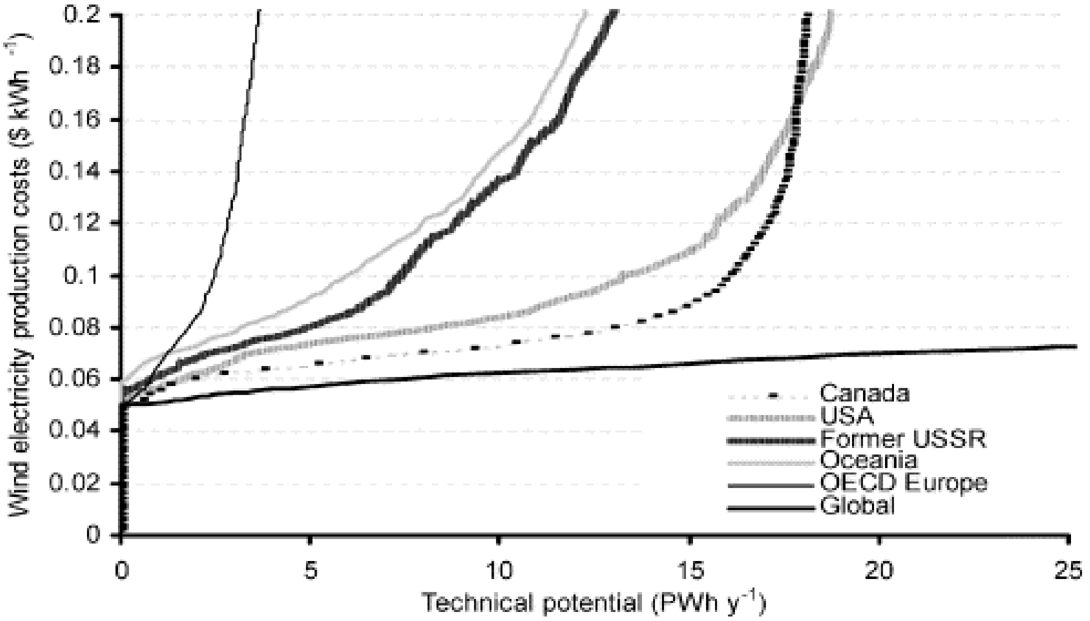
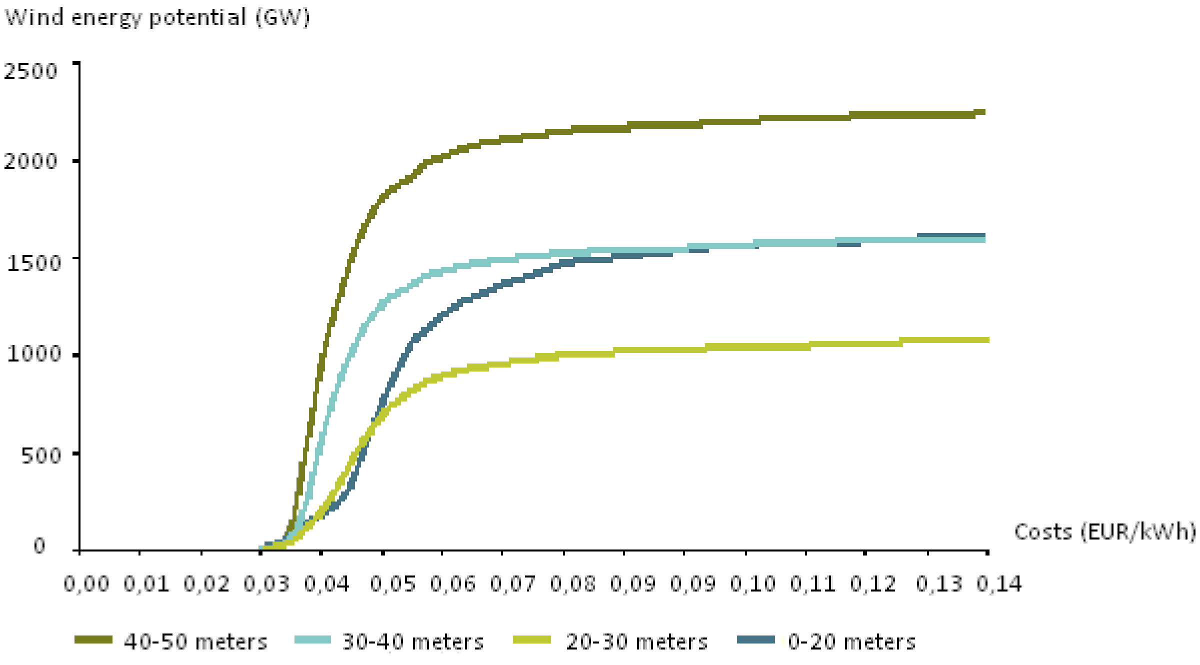


Figure 10.4.4: Regional cost-supply curve for wind energy (USD/kWh vs. PWh/yr) for *D=4* MW km^2. For comparison, the global cumulative curve is also presented (Hoogwijk *et al.*, 2004).

The same study demonstrates that competition for land with total exclusion of more than one option can for wind bring down the technical and economic potential with over one third. Nevertheless, none of the wind resource assessments consider grid stability and energy storage issues that are crucial for economic viability of wind installations. Wind remains in all cases an important contributor to the worldwide economic potential at less than 100 USD/MWh, with a potential between 8 and 43PWh/year — or 50–300% of the 2000 world electricity demand (de Vries *et al.*, 2007).

Summary of offshore wind cost curves. For offshore wind, the available potential and costs are strongly determined by the distance of the installation from the shore. In a recent study of EEA

(2009), the lower limit of wind speed at hub height has been set to 5.0 m/s to consider the windmill economically viable. At an average production cost of 6.9 eurocents (2005 prices)/kWh in 2030, 5,800 GW of offshore wind power could be developed in Europe. This figure however corresponds to an unrestricted potential (**Figure** 10.4.5).



Source: EEA, 2008

Figure 10.4.5: Potential for offshore wind energy generation at different water depths in 2030 for Europe (EEA, 2009).

Various studies have assessed the technical potential for offshore wind. Nevertheless, only Fellows (2000) presents the assessments on a global level (except Norway and Canada), including cost estimates for the timeframe to 2020. Hoogwijk and Graus (2008) have added values for Canada and corrected the data for the technological development for 2020 to 2050. High potentials are found in OECD Europe, and Latin America, this latter having high shares of low cost potentials unexplored. A capacity of 1,2 PWh/year for OECD Europe and Latin America is found at costs lower than 100 USD/MWh. At costs < 50 USD/MWh, 0,3 PWh/year is available in OECD Europe, while 550 PWh/year in Latin America. Lowest potentials are found in the Middle East, where even at <100USD/MWh only 0,18 PWh/year capacity is available (Hoogwijk and Graus, 2008).

Summary of technology resource cost curves. This section has reviewed selected resource cost curves for selected RE technologies for which such were found. It is important to emphasise that such studies are comparable only to limited extent due to the use of different methodologies and potentially conflicting assumptions (such as related to land use), thus they should not be directly used for potential summation or comparison purposes. These results also significantly differ from the integrated technology cost curves produced based on scenarios presented in Section 10.3, since these present potentials for deployment taking into account much more constraints than these resource potential/cost studies.

10.4.5. Gaps in knowledge

There is a major gap in knowledge for renewable non-electric energy potentials on a regional basis, especially as a function of cost. Additionally, the real benefit of the cost curve method, i.e. to identify the really cost-effective opportunities, in practice cannot be fully utilized with the given datasets. Average costs for a technology for a whole region mask the really cost-effective potentials and sites into an average, compromised by the inclusion of less attractive sites or sub-technologies. Therefore, significant, globally coordinated further research is needed for refining these curves into sub-steps by sites and sub-technologies in order to identify the most attractive opportunities broken out of otherwise less economic technologies (such as more attractive wind sites, higher productivity biomass technologies/plants/sites, etc.).

10.5. Cost of commercialization and deployment (investments, variable costs, market support, RDD&D)

RE sources are expected to play an important role in achieving ambitious climate protection goals, e.g., those consistent with a 2°C limit on global mean temperature change compared to preindustrial times (International Energy Agency (IEA), 2010b). Although some technologies are already competitive, e.g., large hydropower, combustible biomass (under favorable conditions) and larger geothermal projects (>30 MW_e), many innovative technologies in this field are still on the way to becoming mature alternatives to fossil fuel technologies (International Energy Agency (IEA), 2008b). Currently and in the mid-term, the application of these technologies therefore will result in additional *private* costs compared to energy supply from conventional sources.[13] Starting with a review of present technology costs, the remainder of this subchapter will focus on expectations on how these costs might decline in the future, for instance, due to extended R&D efforts, technological learning associated with increased deployment, or spill-over effects (cf., IPCC, 2007d, Chapter 2.7. and Chapter 11.5.1.). In addition, historic R&D expenditures and future investment needs will be discussed.

10.5.1. Introduction: Review of present technology costs

In the field of RE, energy supply costs are mainly determined by investment costs. Nevertheless, operation & maintenance costs (OMC), and – if applicable – fuel costs (in the case of biomass), may play an important role as well. The respective cost components were discussed in detail in Chapters 2 to 7. The current section intends to provide a summary of technology costs in terms of specific investment costs (expressed in US$/kW installed capacity) and levelized costs of energy (LCOE, expressed in terms of US$/MWh, see Appendix A II). Both values will be given for the generation of electricity, heat and transport fuel (see Table 10.5.1).

On a global scale, the values of both cost terms are highly uncertain for the various RE technologies. As recent years have shown, the investment costs might be considerably influenced by changes in material (e.g., steel) and engineering costs as well as by technological learning and mass market effects. Levelized costs of energy (LCOE, also called levelized unit costs or levelized generation costs) are defined as 'the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent' (International Energy Agency (IEA), 2005b). LCOE therefore capture the full costs (i.e., investment costs, operation and maintenance costs, fuel costs and decommissioning costs) of an energy conversion installation and allocate these costs over the energy output during its lifetime.

As a result, levelized costs heavily depend on RE resource availability (e.g., due to different full load hours) and, as a consequence, are different at different locations (Heptonstall, 2007; International Energy Agency (IEA), 2010a). Optimal conditions can yield lower costs, and less favorable conditions can yield substantially higher costs compared to those shown in Table 10.5.1. The costs given there are exclusive of subsidies or policy incentives. Concerning LCOE, the actual

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[13] Within this subchapter, the external costs of conventional technologies are not considered. Although the term "private" will be omitted in the remainder of this subchapter, the reader should be aware that all costs discussed here are *private* costs in the sense of subchapter 10.6. Externalities therefore are not taken into account.

global range might be wider than the best guess range given in Table 1, as discount rates, investment cost, operation and maintenance costs, capacity factors and fuel prices are site dependent. Table 10.5.1 contains data which was compiled by the authors of SRREN Chapter 2-7 (this report). Additional information on the derivation of these numbers is given in Appendix 3 (Cost Table).

Technology	Typical characteristics	Typical current investment costs[1] (USD$_{2005}$/kW)	Typical current energy production costs[1] (USD/MWh)	References
POWER GENERATION				
Hydropower				
	Plant size: 10–18 000 MW	1 000–5 500	30–120	IEA, 2008a
	Plant size: 1–10 MW	2 500–7 000	60–140	IEA, 2008a
	Plant size: < 0.1–20 000 MW	1 000–3 000	20–110	IPCC, 2011
Wind				
Onshore wind	Turbine size: 1–3 MW	1 200–1 700	70–140	IEA, 2008a
	Plant size: 5–300 MW	1 200–2 100	50–150	IPCC, 2011
Offshore wind	Turbine size: 1.5–5 MW	2 200–3 000	80–120	IEA, 2008a
	Plant size: 20– 120 MW	3 200–4 600	120–200	IPCC, 2011
Bioenergy[2]				
Biomass combustion for power (solid fuels)	Plant size: 10–100 MW	2 000–3 000	60–190	IEA, 2008a
Biomass co–firing	Plant size: 5–100 MW (existing), > 100 MW (new plant)	120–1 200 + power station costs	20–50	IEA, 2008a
Geothermal power				
Hydrothermal	Plant size: 1–100 MW; Types: binary, single– and double–flash, natural steam	1 700–5 700	30–100	IEA, 2008a
	Plant size: 10–100 MW Type: condensing-flash plant	1 800–3 600	40-130	IPCC, 2011
	Plant size: 2–20 MW Type: binary-cycle plants	2 100–5 200	50–170	IPCC, 2011
Enhanced geothermal system (EGS)	Plant size: 5–50 MW	5 000–15 000	150–300 (projected)	IEA, 2008a
Solar energy				
Solar PV	Power plants: 1–10 MW Rooftop systems: 1–5 kWp	5 000–6 500	200–800[3]	IEA, 2008a; REN21, 2008
	Rooftop (residential) 0.004–0.01 MW	6 400–7 300	400–850	IPCC, 2011
	Rooftop (commercial) 0.02–0.5 MW	5 500–6 800	340–790	IPCC, 2011
	Utility scale (fixed tilt) 0.5–100 MW	3 700–4 500	220–420	IPCC, 2011
	Utility scale (1-axis) 0.5– 100 MW	4100–5000	190–470	IPCC, 2011
Concentrating solar power (CSP)	Plant size: 50–500 MW	4 000–9 000 (trough)	130–230 (trough)[4]	IEA, 2008a
	Plant size: 50–250 MW	6 400–7 300	200–310	IPCC, 2011
Ocean energy				
Tidal and marine currents	Plant size: Several demonstration projects up to 300 kW capacity;	7 000–10 000	150–200	IEA, 2008a
Wave energy[5]		7 700–16 100	210 - 790	IPCC, 2011
Tidal current[5]		8 600–14 300	160-320	IPCC, 2011
OTEC[5]		8 000–10 000	160-200	IPCC, 2011

Technology	Typical characteristics	Typical current investment costs[1] (USD$_{2005}$)	Typical current energy production costs[1,2]	References
HEATING/COOLING				
Biomass heat (excluding CHP)	Size: 5–50 kWth (residential)/ 1–5 MWth (industrial)	120 /kW$_{th}$ (stoves); 380–1 000 /kW$_{th}$ (furnaces)	10–60 USD/MWh	IEA, 2008a; REN21, 2008
Solar hot water/ heating	Size: 2–5 m^2 (household); 20–200 m^2 (medium/ multi–family); 0.5–2 MW$_{th}$ (large/ district heating); Types: evacuated tube, flat–plate	400–1 250 /m^2	20–200 USD/MWh (household); 10–150 USD/MWh (medium); 10–80 USD/MWh (large)	IEA & RETD 2007, REN21, 2008
Geothermal heating/cooling	Plant capacity: 1–10 MWth Types: ground-source heat pumps, direct use, chillers	250–2450 /kW$_{th}$	5–20 USD/MWh	IEA & RETD 2007, REN21, 2008
Geothermal (building heating)	0.1 – 1 MW$_{th}$	1590–3940 /kW$_{th}$	100–240 MWh	IPCC, 2011
Geothermal (district heating)	3.8–35 MW$_{th}$	570–1560 /kW$_{th}$	50–120 MWh	IPCC, 2011
Geothermal (greenhouse)	2–5.5 MW$_{th}$	500–1000 /kW$_{th}$	30–60 MWh	IPCC, 2011
Geothermal (Aquaculture ponds)	5–14 MW$_{th}$	50–100 /kW$_{th}$	30–40 MWh	IPCC, 2011
Geothermal heat pumps (GHP)	0.01–0.35 MW$_{th}$	940–3750 /kW$_{th}$	70–210 MWh	IPCC, 2011
BIOFUELS (1ST GENERATION)				
Ethanol	Feedstocks: sugar cane, sugar beets, corn, cassava, sorghum, wheat (and cellulose in the future)	0.3–0.6 billion per billion litres/ year of production capacity for ethanol	0.25–0.3 USD/litre gasoline equivalent (sugar); 0.4–0.5 USD/litre gasoline equivalent (corn)	REN21, 2008
Biodiesel	Feedstocks: soy, oilseed rape, mustard seed, palm, jatropha, tallow or waste vegetable oils	0.6–0.8 billion per billion litres/ year of production capacity	0.4–0.8 USD/litre diesel equivalent	REN21, 2008

Notes:

1. Using a 10% discount rate. *Current* costs relate to costs either in 2005 or 2006 in case that the reference is made to IEA (2008a), RETD (2007), or REN21 (2008). For cross references to chapers in this report (IPCC, 2011), *current* cost data refer to costs in 2008 (expressed in USD$_{2005}$).

2. Wide ranges due to plant scale, maturity of technology, detailed design variables, type and quality of biomass feedstocks, feedstock availability, regional variations, etc. Costs of delivered biomass feedstock vary by country and region due to factors such as variations in terrain, labour costs and crop yields.

3. Typical costs of 20–40 UScents/kWh for low latitudes with solar insolation of 2,500 kWh/m2/year, 30–50 UScents/kWh for 1,500 kWh/m2/year (typical of Southern Europe), and 50–80 UScents for 1,000 kWh/m2/year (higher latitudes).

4. Costs for (parabolic) trough plants. Costs decrease as plant size increases. Plants with integrated energy storage have higher investment costs but also enjoy higher capacity factors. These factors balance each other out, leading to comparable generation cost ranges for plants with and without energy storage.

5. Highly uncertain projected costs. Underlying assumptions (discount rate and lifetime) are not known (see Chapter 6, IPCC, 2011, this report). Studies older than 2006 showed larger investment cost ranges.

Table 10.5.1: Current specific investment and levelized costs of energy (LCOE).

Source: The table is based on Table 5 in IEA, 2008b (p. 80 – 83) extended by cost data collected for the IPCC SRREN (this report, for details see Appendix 3 (Cost Table).

A comparison of LCOE of RE technologies with those of conventional technologies (nuclear, gas, and coal power plants) shows that RE sources are often not competitive with conventional sources, especially if they both feed into the electricity grid (see Figure 10.5.1). Under favorable conditions, exceptions include biomass, hydro, and geothermal power. If the respective technologies are used in a decentralized mode, their production cost must be compared with the retail consumer power price, which is much higher. In this case, important niche markets already exist that facilitate the market introduction of new technologies. The same holds true for applications in remote areas, where often no grid based electricity is available.

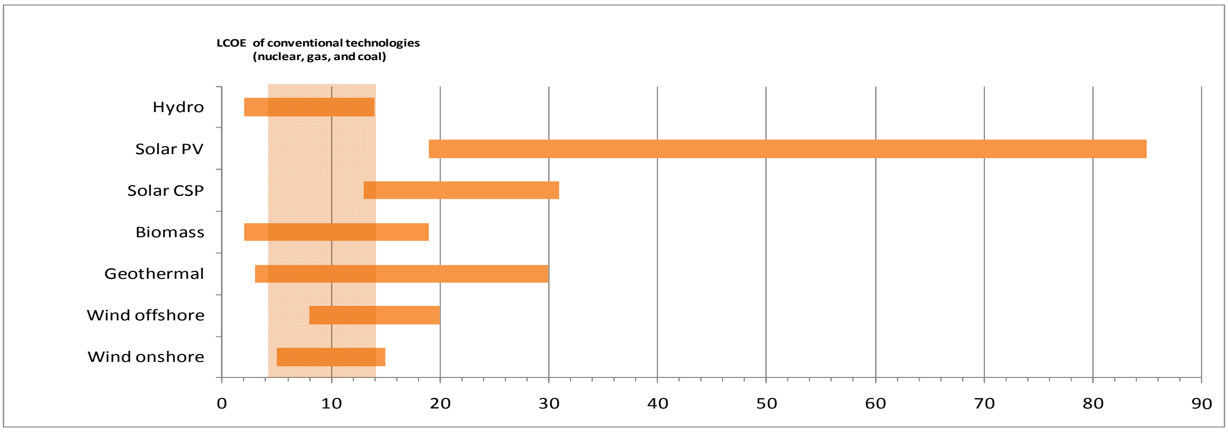


Figure 10.5.1: Cost-competitiveness of selected renewable power technologies. The figure is based on (International Energy Agency (IEA), 2007) and updated by cost data (see Table 10.5.1) collected for the IPCC SRREN (this report). The LCOE are given in US-cent/kWh. LCOE of conventional technologies depict the range valid for North America, Europe, and Asia Pacific (IEA, 2010). For OECD countries a future carbon price of US$ 30/t CO2 is assumed.

As RE technologies are often characterized by high shares of investment costs relative to OMC and fuel costs, the applied discount rate has a prominent influence on the LCOE (see Figure 10.5.2). The attractiveness of RE projects obviously depends on the requested internal rate of return. Projects that are not competitive for utilities might, nevertheless, be interesting from a private investor’s point of view.

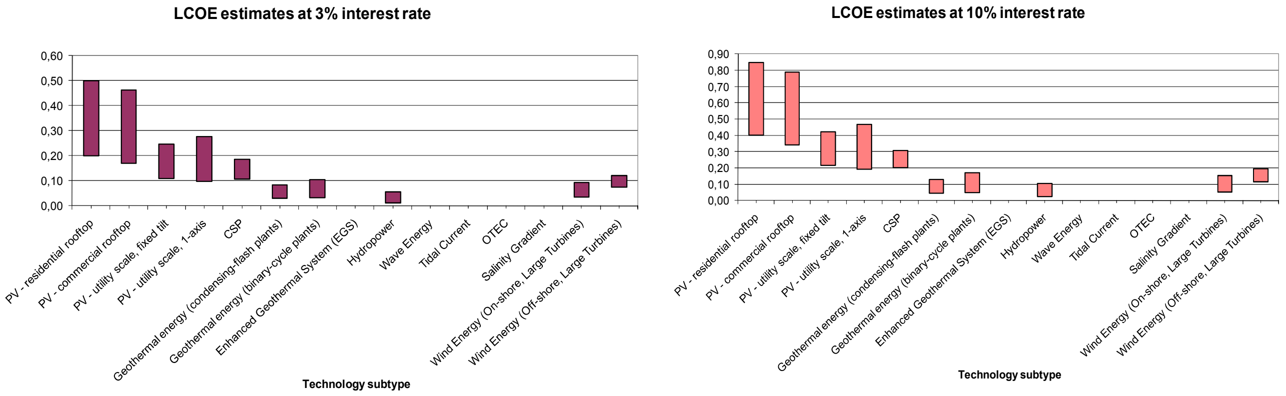


Figure 10.5.2: Cost-competitiveness of selected RE power technologies using different discount rates. The levelized costs of electricity production are given in US$2005/kWh. Source: Chapter 2-7, IPCC SRREN (this report, for details see Appendix 3 (Cost Table)). Note that the scale of the y-axes are different.

10.5.2. Prospects for cost decrease

Most technologies applied in the field of RE (and some other climate protection technologies, e.g., CCS power plants) are innovative technologies. As a consequence, large opportunities often exist to improve the energy efficiency of the technologies, and/or to decrease their production costs. Together, these two effects are expected to decrease the levelized cost of energy of many RE sourcing technologies substantially in the future. According to Junginger *et al.* (2006), the list of the most important mechanisms causing cost reductions comprises:

- *Learning by searching*, i.e. improvements due to Research, Development and Demonstration (RD&D) – especially, but not exclusively in the stage of invention,
- *Learning by doing* (in the strict sense), i.e. improvements of the production process (e.g., increased labor efficiency, work specialization),
- *Learning by using* (i.e. improvements triggered by user experience feedbacks) occur once the technology enters (niche) markets,
- *Learning by interacting (or "spillovers",* (cf. Clarke *et al.*, 2006; IPCC, 2007a), i.e. the reinforcement of the above mentioned mechanism due to an increased interaction of various actors in the diffusion phase,
- *Upsizing of technologies* (e.g. upscaling of wind turbines),
- *Economies of scale* (i.e., mass production) once the stage of large-scale production is reached.

The various mechanisms may occur simultaneously at various stages of the innovation chain. In addition, they may reinforce each other. As a consequence of the aforementioned mechanisms, many technologies applied in the field of RE sources showed a significant cost decrease in the past (see Figure 3). This empirical observation is highlighted by *experience (or "learning") curves,* which describe how costs decline with accumulated experience and corresponding cumulative production or (ever) installed capacity (International Energy Agency (IEA), 2000; International Energy Agency (IEA), 2008a).

For a doubling of the (cumulatively) installed capacity, many technologies showed a more or less constant percentage decrease of the specific investment costs (or of the levelized costs or unit price, depending on the selected cost indicator). The numerical value describing this improvement is called *learning rate (LR)*. It is defined as the percentage cost reduction for each doubling of the cumulative capacity. A summary of observed learning rates is provided in Table 2. Frequently, the *progress ratio (PR)* is used as a substitute for the learning rate. It is defined as PR = 1- LR (e.g., a learning rate of 20% would imply a progress ratio of 80%). Frequently, energy supply costs (e.g. electricity generation costs) and the cumulative energy (ever) supplied by the respective technology (e.g., the cumulative electricity production) are used as substitutes for capital costs and the cumulative installed capacity, respectively (cf. Figure 10.5.3c).

If the learning rate is time-independent, the empirical experience curve can be fitted by a power law. In this case, plotting costs versus cumulative installed capacity in a figure with double logarithmic scales shows the experience curve as a straight line (see Figure 3). As there is no natural law that costs *have* to follow a power law (Junginger *et al.*, 2006), care must be taken if historic experience curves are extrapolated in order to predict future costs (Nemet, 2009). Obviously, the cost reduction cannot go *ad infinitum* and there might be some unexpected steps in the curve in practice (e.g. caused by technology breakthroughs). In order to avoid implausible results, projections that extrapolate experience cost curves in order to assess future costs therefore should constrain the cost reduction by appropriate *floor costs* (cf. Edenhofer *et al.*, 2006).

Unfortunately, *cost* data are not easily obtained in a competitive market environment. Indicators that are intended to serve as a substitute, e.g., product *prices* do not necessarily reveal the actual improvement achieved. Instead, they might be heavily influenced by an imbalance of supply and demand. This refers to both the final product itself (e.g., if financial support stipulates a high demand) and the cost of product factors, which might be temporarily scarce (e.g., steel prices due to supply bottlenecks). A deviation from price-based experience curves as observed for photovoltaic modules and wind energy converters in the years between 2004 and 2008 (see Figure 3a and 3b), therefore does not necessarily imply that a fundamental cost limit has been reached. Instead, it might simply indicate that producers were able to make extra profits in a situation where, for instance, feed-in tariff systems led to a demand that transgressed the production capabilities of the respective manufacturers.

As these extra profits can be increased by further cost reduction efforts, there is an incentive for producers to proceed in doing so. The fundamental incentive scheme of the feed-in-tariff system therefore is still working in the background even in the high price phases recently observed. However, the actual cost reductions are not passed to consumers in that phase.

According to some researchers (Junginger et al., 2006), the cost reduction achieved in the background might reveal itself after the supply and production bottlenecks are removed or the market power of the prime producer was destroyed in the so-called “shakeout” phase. In this case, the deviation from the long-term experience curve might be largely removed. Short term deviations that can be explained by supply bottlenecks, for instance, or by typical effects of demand or supply driven markets therefore should not immediately lead to a corresponding decrease of the learning rates that are used, for instance, for projections of future energy costs.

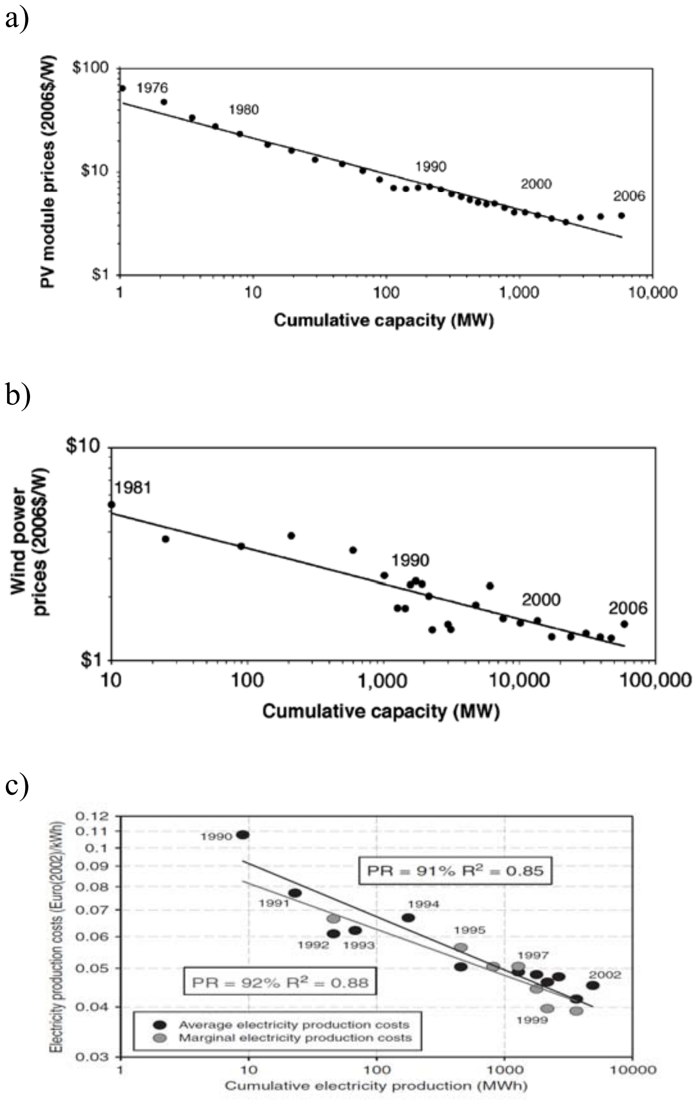


Figure 10.5.3: Illustrative experience curves for a) photovoltaic modules, b) wind turbines and c) Swedish bio-fuelled combined-heat and power plants. Source: Nemet, 2009; Junginger et al., 2006.

A summary of observed learning rates is provided in Table 10.5.2 Learning rates referring to investment costs (or turnkey investment costs) are often lower than those derived from electricity generation costs. Although the cost reduction in the specific investment costs of wind turbines, for instance, might be small, the scale-up results in higher hub-heights and an associated significant increase in full load hours (and consequently in the amount of energy delivered). In order to assess the success of policy support programs learning rates referring to LCOE therefore should be used. Learning rates referring to single countries vary widely. Especially in countries with high market

Table 10.5.2: Observed learning rates for various electricity supply technologies. Source: IEA, 2008a, p. 205, extended and updated by learning rates collected for the IPCC SRREN (this report).

Technology	Source	Country / region	Period	Learning rate (%)	Performance measure	IPCC SRREN cross reference
Onshore wind						
	Neij, 2003	Denmark	1982-1997	8	Price of wind turbine (USD/kW)	
	Durstewitz, 1999	Germany	1990-1998	8	Price of wind turbine (USD/kW)	
	IEA, 2000	USA	1985-1994	32	Electricity production cost (USD/kWh)	
	IEA, 2000	EU	1980-1995	18	Electricity production cost (USD/kWh)	
	Kouvaritakis, et al., 2000	OECD	1981-1995	17	Price of wind turbine (USD/kW)	
	Junginger, et al., 2005a	Spain	1990-2001	15	Turnkey investment costs (EUR/kW)	
	Junginger, et al., 2005a	UK	1992-2001	19	Turnkey investment costs (EUR/kW)	
	Jamasb, 2007	Global	1980-1998	13	Investment costs (USD/kW)	
	Neij, 1997	Denmark	1982-1995	4	Price of wind turbine (USD/kW)	Table 7.6.
	Mackay and Probert, 1998	USA	1981-1996	14	Price of wind turbine (USD/kW)	Table 7.6.
	Neij, 1999	Denmark	1982-1997	8	Price of wind turbine (USD/kW)	Table 7.6.
	Wene, 2000	USA	1985-1994	32	Electricity production cost (USD/kWh)	Table 7.6.
	Wene, 2000	European Union	1980-1995	18	Electricity production cost (EUR/kWh)	Table 7.6.
	Miketa and Schrattenholzer, 2004 *	Global	1971-1997	10	Investment costs (USD/kW)	Table 7.6.
	Klaassen et al., 2005 *	Germany, Denmark, and UK	1986-2000	5	Investment costs (USD/kW)	Table 7.6.
	Kobos et al., 2006 *	Global	1981-1997	14	Investment costs (USD/kW)	Table 7.6.
	Jamasb, 2006 *	Global	1980-1998	13	Investment costs (USD/kW)	Table 7.6.
	Söderholm and Sundqvist, 2007	Germany, Denmark, and UK	1986-2000	5	Turnkey investment costs (EUR/kW)	Table 7.6.
	Söderholm and Sundqvist, 2007 *	Germany, Denmark, and UK	1986-2001	4	Turnkey investment costs (EUR/kW)	Table 7.6.
	Neij, 2008	Denmark	1980-2000	17	Electricity production cost (USD/kWh)	Table 7.6.
	Kahouli-Brahmi, 2009	Global	1979-1997	17	Investment costs (USD/kW)	Table 7.6.
	Kahouli-Brahmi, 2009 *	Global	1979-1997	27	Investment costs (USD/kW)	Table 7.6.
	Nemet, 2009	Global	1981-2004	11	Investment costs (USD/kW)	Table 7.6.
	* Indicates a two-factor learning curve that also includes R&D; all others are one-factor learning curves					
Offshore wind						
	Isles, 2006	8 EU countries	1991-2006	3	Installation cost of wind farms (USD/kW)	
	Jamasb, 2006	Global	1994-2001	1	Investment costs (USD/kW)	
Photovoltaics (PV)						
	Harmon, 2000	Global	1968-1998	20	Price PV module (USD/Wpeak)	
	IEA, 2000	EU	1976-1996	21	Price PV module (USD/Wpeak)	
	Williams, 2002	Global	1976-2002	20	Price PV module (USD/Wpeak)	
	ECN, 2004	EU	1976-2001	20-23	Price PV module (USD/Wpeak)	
	ECN, 2004	Germany	1992-2001	22	Price of balance of system costs	
	van Sark, et al., 2007	Global	1976-2006	21	Price PV module (USD/Wpeak)	
	Kruck, 2007	Germany	1977-2005	13	Price PV module (EUR/Wpeak)	
	Kruck, 2007	Germany	1999-2005	26	Price of balance of system costs	
	Nemet, 2009	Global	1976-2006	15-21	Price PV module (USD/Wpeak)	
Concentrated Solar Power (CSP)						
	Enermodal, 1999	USA	1984-1998	8-15	Plant capital cost (USD/kW)	
	Jamasb, 2006	Global	1985-2001	2	Investment costs (USD/kW)	
Biomass						
	IEA, 2000	EU	1980-1995	15	Electricity production cost (USD/kWh)	
	Goldemberg, et al., 2004	Brazil	1985-2002	29	Prices for ethanol fuel (USD/m^3)	
	Junginger, et al., 2006	Denmark	1984-1991	15	Biogas production costs (EUR/Nm^3)	
	Junginger, et al., 2006	Denmark	1992-2001	0	Biogas production costs (EUR/Nm^3)	
	Junginger, et al., 2005b	Sweden and Finland	1975-2003	15	Forest wood chip prices (EUR/GJ)	
	Van den Wall Bake et al.; 2009	Brazil	1975-2003	32	Sugarcane production costs (USD/t sugarcane)	Table 2.7.4
	Hettinga et al., 2009	USA	1975-2005	45	Corn production costs (USD/t corn)	Table 2.7.4
	Junginger et al., 2006a		1984-1998	12	Biogas plants (€/m^3 biogas/day)	Table 2.7.4
	Van den Wall Bake et al., 2009	Brazil	1975-2003	19	Ethanol from sugarcane (USD/m^3)	Table 2.7.4
	Goldemberg et al., 2004	Brazil	1980-1985	7 / 29	Ethanol from sugarcane (USD/m^3)	Table 2.7.4
	Van den Wall Bake et al., 2009	Brazil	1975-2003	20	Ethanol from sugarcane (USD/m^3)	Table 2.7.4
	Hettinga et al., 2009	USA	1983-2005	18	Ethanol from corn (USD/m^3)	Table 2.7.4
	Junginger et al., 2006a	Sweden	1990-2002	8-9	Biomass CHP power (EUR/kWh)	Table 2.7.4
	Junginger et al., 2006a	Denmark	1984-2001	0-15	Biogas production costs (EUR/Nm^3)	Table 2.7.4

growth rates country specific learning can be low, because learning is a global phenomenon and – compared to the global average – the cumulative capacity installed in these countries is higher (Neij, 2008) ; Schaeffer et al, 2009) [AUTHORS: Reference missing in bibliography].

10.5.3. Deployment cost curves and learning investments

According to the definition used by the IEA (2008b), "*deployment costs* represent the *total* costs of cumulative production needed for a new technology to become competitive with the current, incumbent technology." As the innovative technologies replace operation costs and investment needs of conventional technologies, the *learning* investments are considerably lower. The *learning investments* are defined as the *additional* investment needs of the new technology. They are therefore equal to the deployment costs minus (replaced) cumulative costs of the incumbent technology.

Although not directly discussed in IEA, 2008 – to give the full picture – the cost difference could be extended to take into account variable costs as well (Figure 10.5.4). Because of fuel costs, the latter is evident for conventional technologies, but this contribution should also be taken into account if the RE usage implies considerable variable costs – as in the case of biomass. Once variable costs are taken into account, avoided carbon costs contribute to a further reduction of the *additional* investment needs. Figure 10.5.4 shows a schematic presentation of experience curves, deployment costs and learning investments. The deployment costs are equal to the integral below the experience curve, calculated up to the break-even point.

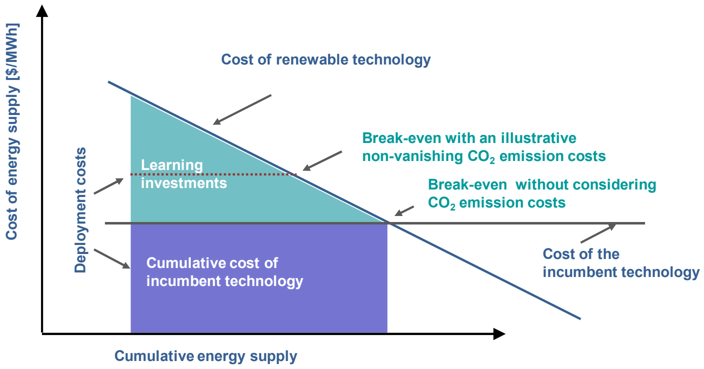


Figure 10.5.4: Schematic representation of experience curves, deployment costs and learning investments (modified version of the diagram depicted in (International Energy Agency (IEA), 2008b).

In the beginning of the deployment phase, additional costs are expected to be positive ("expenditures"). Due to technological learning (in the broadest sense) and the possibility of increasing fossil fuel prices, additional costs could be become negative after some decades. A least cost approach towards a decarbonized economy therefore should not focus solely on the additional costs that are incurred until the break-even point with conventional technologies has been achieved (learning investments). After the break-even point, the innovative technologies considered are able to supply energy with costs lower than the traditional supply. As these costs savings occur then (after the break-even point) and indefinitely thereafter, their present value might be able to compensate the upfront investments (additional investment needs). Whether this is the case depends on various factors (inter alia the discount rate and the perceived climate policies and associated future carbon prices).

Innovative integrated assessment models – i.e., those which model technological learning in an endogenous way – are capable of assessing the overall mitigation burden associated with a cost optimal application of RE sources within the context of ambitious climate protection goals (Edenhofer *et al.*, 2006). The results obtained from these modeling exercises indicate that – from a macroeconomic perspective – significant upfront investments in innovative RE technologies are often justified if the respective technologies are promising with respect to their renewable resource potential and their learning capability.

The least cost (dynamically efficient) climate protection strategies proposed by these integrated assessment models are not necessarily adopted in reality. Due to the imperfect performance of liberalized energy markets, incentives for private investments in climate-friendly technologies might be artificially low. In fact, several private sector innovation market failures distort private sector investments in technological progress (Jaffe *et al.*, 2005). The main problem in this case is that private investors developing new technologies might not be able to benefit from the huge cost savings that are related with the application of these technologies in a couple of decades. Furthermore, as long as external environmental effects are not completely internalized, the usage of fossil fuels appears to be cheaper than justified.

An optimal strategy therefore has to combine two complementary approaches that address the two market failures mentioned above (externalities due to environmental pollution and the market failures associated with the innovation and diffusion of new technologies). Together these market failures provide a strong rationale (see Chapter 11) for a portfolio of public policies that foster emissions reduction (e.g. by emission trading or carbon taxes) as well as the development and deployment of environmentally beneficial technologies (e.g., by economic incentives like feed-in tariffs or direct subsidies, (Jaffe *et al.*, 2005; Montgomery and Smith, 2007; van Benthem *et al.*, 2008) .

10.5.4. Time-dependent expenditures

The most comprehensive survey on past investments in clean energy technologies is published by the United Nations Environment Programme UNEP in collaboration with New Energy Finance Ltd. on an annual basis (UNEP, 2009). The reported global new investment in sustainable energy projects include: all biomass, geothermal and wind generation projects over 1 MW, all hydroelectric projects between 0.5 and 50 MW, all solar projects over 0.3 MW, all marine energy projects, all bio-fuel projects with a capacity of 1 million liters or more per year, and all energy efficiency projects that involve financial investors.

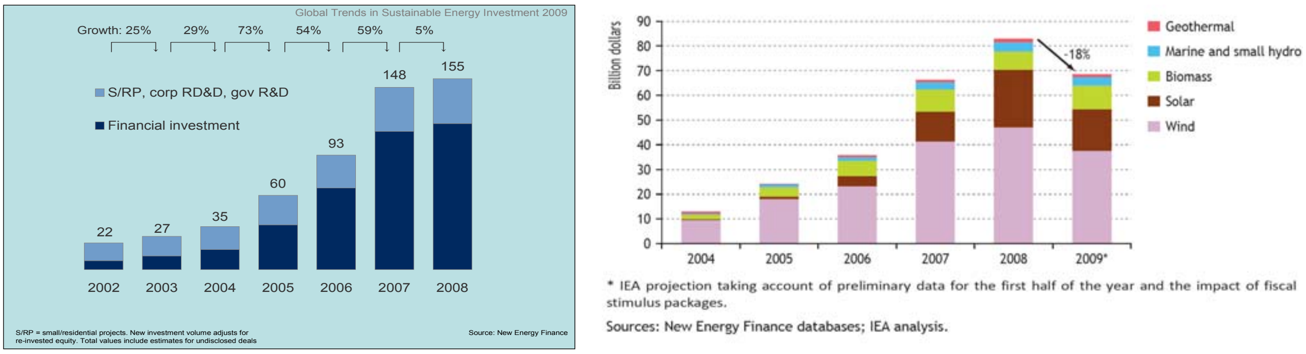
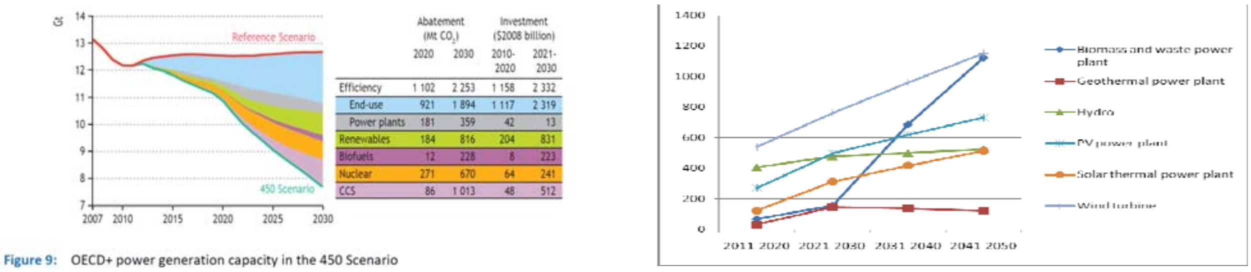


Figure 10.5.5: a) Global new investment in sustainable energy, 2002-2008, in billion US$ (UNEP, 2009). b) Global investments in new RE-based power generation assets (International Energy Agency (IEA), 2009).

As Figure 10.5.5 clearly shows, the global RE market has shown significant growth over the last decade. Although the absolute share of RE sources in the provision of energy is still small from a global perspective, all RE (including large hydroelectric) attracted more power sector investment (~ 140 billion US$) than fossil-fuelled technologies (~ 110 billion US$) for the first time in 2008 (UNEP, 2009). Due to the financial crises, the growth in 2008 (5%/yr) was small compared to growth rates that exceeded 50%/yr in the years before.

In the following, *future* deployment cost estimates are shown for the different emission mitigation scenarios discussed in Section 10.3. As discussed before, deployment costs indicate how much money will be spent in the sector of RE sources once these scenarios materialize. The given numbers therefore are important for investors who are interested in the expected market volume. Data on energy delivered by the corresponding scenarios can be found in Sections 10.3 and 10.4.

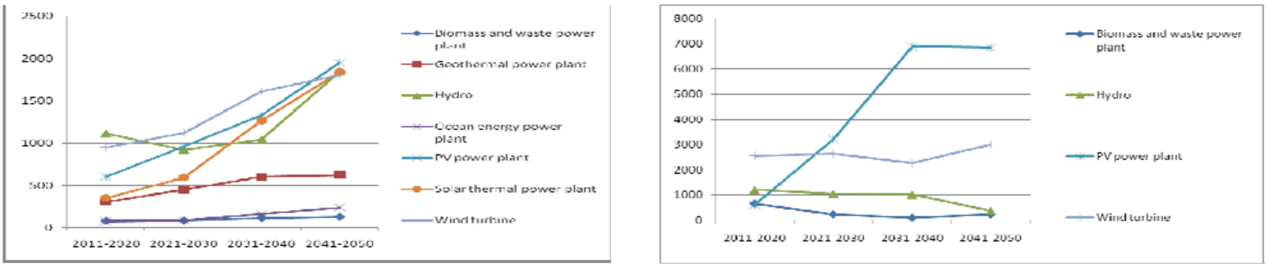


	Abatement (Mt CO_2)		Investment ($2008 billion)	
	2020	2030	2010-2020	2021-2030
Efficiency	1 102	2 253	1 158	2 332
End-use	921	1 894	1 117	2 319
Power plants	181	359	42	13
Renewables	184	816	204	831
Biofuels	12	228	8	223
Nuclear	271	670	64	241
CCS	86	1 013	48	512

Figure 9: OECD+ power generation capacity in the 450 Scenario

a) IEA WEO (450 ppmv), PLACE-HOLDER
Source: IEA 2009 Copenhagen excerpt

b) MiniCam (450 ppm$_v$ CO_2-equiv., nuclear and carbon capture technologies are permitted). Source: ???



c) Energy [R]evolution (450 ppm$_v$ CO_2-equiv., nuclear and carbon capture technologies are not permitted). Source: (Greenpeace and EREC, 2008).

d) REMIND (450 ppm$_v$ CO_2, nuclear power plants and carbon capture technologies are not permitted). Compared to the other scenarios, the PV share is high as concentrating solar power has not been considered. Source: (Luderer *et al.*, 2009).

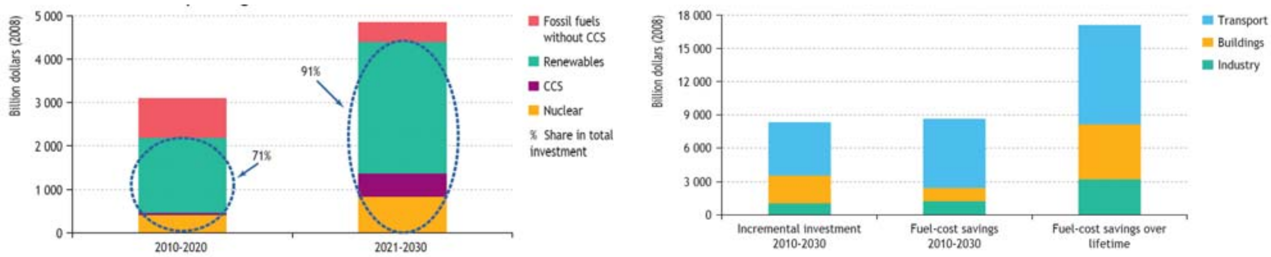
Figure 10.5.6: Illustrative global decadal investments (in billion US $2005) needed in order to achieve ambitious climate protection goals (according to different least costs and 2nd best scenarios).

Figure 10.5.6 depicts the decadal investment needs associated with RE deployment strategies that are broadly compatible with a goal to constrain global mean temperature change to less than 2 °C compared to preindustrial levels. In order to achieve this goal, CO_2 concentrations are stabilized at 450 ppm$_v$. From an investor's perspective, and depending on the technology, the given numbers indicate a future global market volume on the order of several 100 billion US$ per year.

Specific investment costs of RE sources are typically higher than those of conventional energy supply technologies. In order to assess the *additional* costs arising from using RE sources, two effects must be taken into account: Due to the so-called non-vanishing capacity credit, investing in RE sources reduces investment needs for conventional technologies (see Chapter 8). In addition, fossil fuel costs (and OMC) will be reduced as well. As a consequence, deployment costs do not indicate the actual mitigation *burden* societies face if these scenarios materialize. In calculating this burden, replaced conventional investments and avoided variable costs must be considered as well. As the latter are dependent on the development of fossil fuel prices, the overall net cost balance could be positive from a mid-term or long-term perspective (for a national study, see Winkler *et al.*, 2009).

Only a few scenarios considered in Section 10.2 provide data on the total avoided investments in conventional plants, and the overall avoided fuel costs. However, no global scenario exercise currently attributes the *avoided costs* to distinguished technologies. Although this information would be extremely useful in order to carry out a fair assessment of learning investments or (net) deployment costs, up to now (and in contrast to emissions wedges that are quite usual nowadays), it is not standard to calculate the associated "avoided fuel cost wedges".

Due to the lack of the aforementioned *technology specific* assessments, illustrative results of a specific scenario (IEA, 2009) will be presented here (see Figure 10.5.7b). Note that these results do not only take into account investments into RE sources. In addition, other low carbon technologies (energy efficiency improvements, nuclear energy, carbon capture and storage) are considered as well (cf. Figure 10.5.7a). Nevertheless, the results highlight the importance of comparing investment needs on the one hand and associated avoided (investment and operation) costs of the substituted technologies on the other.



Notes: The changes in power-generation investment and fuel costs are included in the electricity prices charged to the sectors shown in this graph. Costs are not discounted.

Figure 10.5.7: a) Total global investment in RE, nuclear, CCS and fossil fuels for power generation in the 450 Scenario. b) Incremental investment needs and fuel-cost savings[14] for industry, buildings and transport in the WEO 2009 450 ppm_v scenario relative to the WEO 2009 reference scenario. Source: IEA, 2009 (Fig. 7.5, p. 264 and Fig. 7.15 p. 288).

Relative to the reference scenario, the global undiscounted fuel-cost savings that are associated with achieving the ambitious 450 ppm_v goal amount to over 8,600 billion US$ (in the period of 2010 to 2030). Over the lifetime of the investments, the undiscounted fuel-cost savings even exceed 17 000 billion US$. The associated net savings over the lifetime are 3 600 billion US$ for a discount rate of 3% and 450 billion US$ for 10%, respectively (IEA, 2009). From a global macro-economic perspective, avoided fuel costs reduce consumer bills. As the profits of the producers are reduced as well, the "real" reduction of the burden of introducing RE sources is obviously lower than fuel cost savings might imply.

10.5.5. Market support and RDD&D

Whereas the list in 10.5.2 summarizes different *causes* for technological progress and associated cost reductions, an alternative nomenclature focuses on how these effects can be triggered. Following this kind of reasoning, Jamasb (2007) [AUTHORS: In Bibliograpy Jamasb 2006 – need to check which is correct] distinguishes:

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[14] Note that fuel cost saving reduce consumer expenditures. As the revenues of producer are reduced as well, fuel cost savings are not identical with "economy-wide" savings.

- *Learning by research* triggered by research and development (R&D) expenditures which intend to achieve a *technology push* and
- *Learning by doing* (in the broader sense) resulting from capacity expansion promotion programs that intend to establish a *market (or demand) pull*

Figures 10.5.8a and 10.5.8b depict the historic support for RE research in relation to other technologies. Note that for fossil and nuclear technologies, the large-scale government support in the early stages of their respective innovation chain (i.e., well before the 1970s) is not shown.

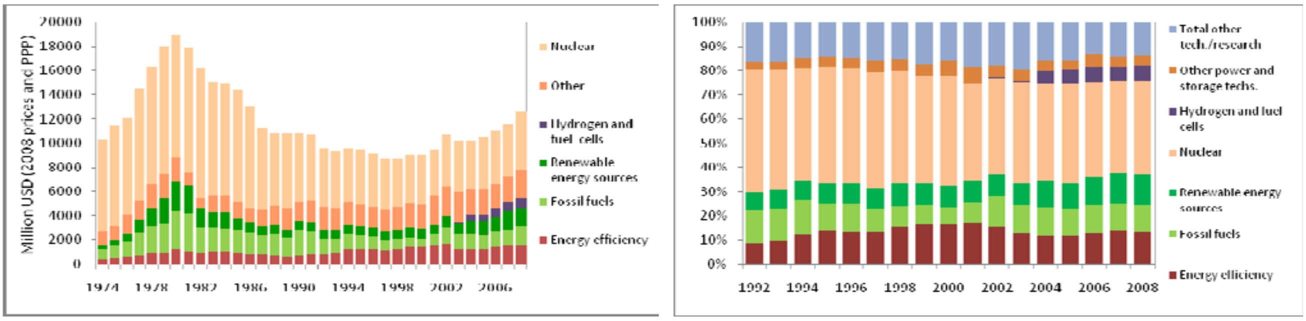

Figure 10.5.8: a) Government budgets on energy RD&D of IEA countries and b) technology shares of government energy RD&D expenditures in IEA countries (cf. (International Energy Agency (IEA), 2008b), p. 172-173, updated with data from http://wds.iea.org/WDS/ReportFolders/ReportFolders.aspx, accessed 29/09/2009).

Whereas RD&D funding is appropriate for infant technologies, market entry support and market push programs (e.g., via norms, feed-in tariff, renewable quota schemes, tax credits, bonus and malus systems) are the appropriate tools in the deployment and commercialization phase (Foxon, 2005; González, 2008). A detailed description of these programs can be found in Chapter 11.

On a global scale, comprehensive assessments on the total expenditures spent by market support programs (e.g., feed-in tariffs, direct subsidies, or tax credits) and on the additional costs that are associated with programs stipulating RE energies by other means (e.g., norms and quotas) are not available. However, the historic and future investment needs discussed in Section 10.5.4. can be used to assess at least the order of magnitude.

10.5.6. *Knowledge gaps*

Experience curves nowadays are used to initiate decisions that involve billions of dollars of public funding. Unfortunately, small variations in the assumed learning rates can have a significant influence on the results of models that use experience curves. Empirical studies therefore should strive to provide error bars for the derived learning rates (van Sark *et al.*, 2007). In addition, a better understanding of the processes that result in cost reductions would be extremely valuable (cf. van den Wall-Bake *et al.*, 2009). Furthermore, there is a severe lack of information which is necessary to decide whether short-term deviations from the experience curve can be attributed to supply bottlenecks, or whether they already indicate that the cost limit (in the sense of floor costs) is reached.

If available at all, cost discussions in the literature mostly focus on investment needs. Unfortunately, many global studies neither display total cost balances (including estimates about operational costs and cost savings) nor externalities like social, political and environmental costs (e.g. side benefits like employment effects or the role of RE sources in reducing the risks associated with fossil fuel price volatility, (cf. Awerbuch, 2006; Gross and Heptonstall, 2008). Although some assessments of externalities have taken place at a national level (cf., Chapter 9 and Chapter 10.6), a comprehensive global investigation and an associated costs benefit analysis is highly recommended.

In addition, as Chapter 8 shows, there is a severe lack of reliable and comprehensive assessments of the additional costs arising from integrating RE sources into existing and future energy systems (cf., Gross and Heptonstall, 2008).

10.6. Social, environmental costs and benefits [TSU: Heading lacks "(investments, variable costs, market support, RDD&D)"]

10.6.1. Background and objective

Energy production typically causes direct and indirect costs and benefits for the energy producer and for society. Energy producers for instance incur private costs, such as plant investment and operating costs, and receive private benefits, such as income from sold energy. Private costs and benefits are defined as costs or benefits accounted by the agents responsible for the activity. The operations of energy producers often cause external impacts, which may be beneficial or detrimental but which are not covered by the energy producers. The costs and benefits due to external impacts are called external costs or external benefits, correspondingly (for the definition, see Glossary). The external costs are usually indirect and they arise, for example, from pollutant emissions. The reduction of detrimental impacts caused by pollutant emissions can be seen as an external benefit when RE replaces some more detrimental energy sources. Additionally external benefits might occur if energy production and consumptions results in positive effects for the society (e.g. job creation in the energy sector). The social costs are assumed to include here both private costs and external costs (Ricci, 2009a; Ricci, 2009b), although other definitions have also been used in the past (e.g. Hohmeyer, 1992). Figure 10.6.1 below shows a possible illustrative representation of the different definitions of costs and benefits.

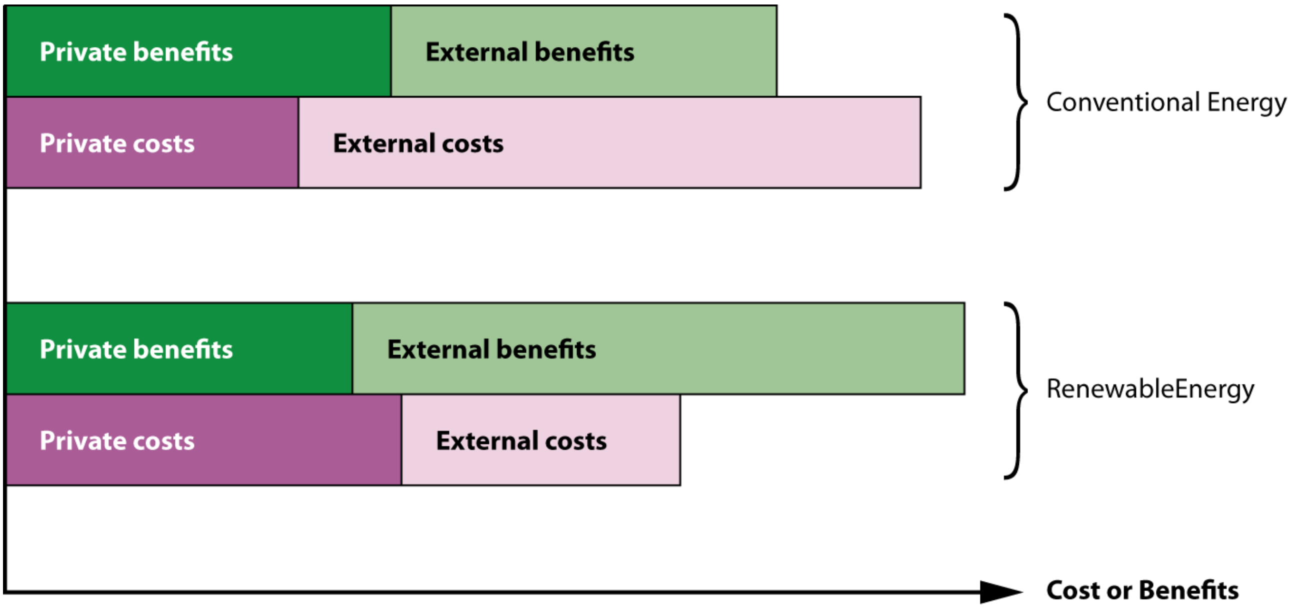

Figure 10.6.1: Simple illustrative representation of cost and benefits in the context of conventional and RE sources. [TSU: No Source]

In conventional non-RE production, private costs are usually lower than the private benefits, which means that the energy production is normally profitable. On the other hand, the external costs can be high, on occasions exceeding the total (social) benefits. Energy derived from RE technologies on the other hand can often be unprofitable for the energy producer if not supported by incentive schemes. If the external costs (including environmental costs) are taken into account, the production of RE can, however, as a whole be more profitable from a social point of view than conventional energy production (Owen, 2006).

Typical factors causing external costs include the atmospheric emissions of fossil-fuel-based energy production. The emissions can, among other things, consist of GHGs, acidifying emissions and particulate emissions. These types of emissions can often but not always be lowered if RE is used to replace fossil fuels (Weisser, 2007)[15]. Increasing the share of RE often contributes positively to access to energy[16], energy security and the trade balance and it limits the negative effects from fluctuating prices of fossil-based energy (Berry and Jaccard, 2001; Bolinger *et al.*, 2006; Chen *et al.*, 2007). Further, increasing RE may also contribute to external benefits, e.g. by creating jobs especially in rural areas (e.g. in the fuel supply chain of bioenergy). However, various types of RE have their own private and external costs and benefits, depending on the energy source and the technology utilised.

Costs and benefits can be addressed in cost-benefit analyses to support decision-making. However, the value of RE is not strictly intrinsic to renewable technologies themselves, but rather to the character of the energy system in which they are applied (Kennedy, 2005). The benefits of an increased use of RE are to a large part attributable to the reduced use of non-RE in the energy system.

The coverage and monetarisation of the impacts in general is very difficult. Especially the long time spans associated with climate change and its impacts are difficult to consider in cost-benefit analyses (Weitzman, 2007; Dietz and Stern, 2008). Further, many environmental impacts are so far not very well understood or very complex and new for people and decision-makers, and their consideration and monetary valuation is difficult. This might limit the use of cost-benefit analysis and require other approaches, such as public discussion process and direct setting of environmental targets and cost-benefit or cost-effectiveness analyses under these targets. (Krewitt, 2002; Soderholm and Sundqvist, 2003; Grubb and Newbery, 2007).

The production and use of energy can be considered from the viewpoint of sustainable development. (see Chapter 9) Sustainable development is often divided into three aspects, namely environmental, economic and social sustainability. RE often has synergistic effects with the aspects of sustainable development. However, this is not necessarily always the case. For example, biomass, if extended widely, can be controversial as an energy source because of competition on land use. The land used to produce energy crops is not available for other purposes, e.g. food production and conservation of biodiversity (Haberl *et al.*, 2007) although other references indicate that both food and fuel demand can be met in many cases at some reasonable level (Sparovek *et al.*, 2009). On the other hand, managed areas not favourable for food production may be used for some energy crops with social and environmental benefits. Futhermore, the use of biomass can result in non-negligible or even relatively high GHG emissions (through various means, like production of fertilizers, energy use for harvest and processing, N_2O-emissions from agricultural land and land use changes). If used in a non-suitable manner the land clearing for biofuel production can cause in some cases considerable emissions ("biofuel carbon debt") the compensation of which with biofuel use replacing fossil fuel can take long time spans (Adler *et al.*, 2007; Fargione *et al.*, 2008; Searchinger *et al.*, 2008). However, it is necessary to analyze case by case, avoiding the misjudgement of general biomass production based on hypothetical case.

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[15] One has to keep in mind that in particular biomass applications can also cause particulate emissions.

[16] There are still about 1 to 2 billion people without access to energy services (IEA), the renewable energy sources due to their distributed character can at least to some extent help to alleviate this problem.

When the response to climate change is considered, RE can be linked to the changing climate in regard to both climate change mitigation and adaptation (IPCC, 2007a; IPCC, 2007b). On the other hand, climate change can have a great impact on RE production potentials and on costs. Examples include biomass, wind and hydropower. The potential of biomass depends on climate changes affecting biomass growing conditions like temperature and soil humidity, the potential of wind power depends on wind conditions, and the potential of hydro on precipitation conditions, specially in the case of run-of-river (Venäläinen *et al.*, 2004; Bates *et al.*, 2008; de Lucena *et al.*, 2009).

The greatest challenges for energy systems are guaranteeing the sufficient supply of energy at fair price and the reduction of the environmental impacts and social costs, including the mitigation of climate change. RE can markedly contribute to the response to these challenges. The understanding of these possible contributions is crucial for transformation in cost terms.

Behind that background, the objective of this Section is to make a synthesis and discuss external costs and benefits of increased RE use in relation to climate change mitigation and sustainable development. The results are presented by technology at global and regional levels. Therefore the section defines the cost categories considered and identifies quantitative estimates or qualitative assessments for costs by category type, by RE type, and as far as possible also by geographical area. (regional information is still very sparse).

This section has links to the other chapters of SRREN, such as Chapter 1 (Introduction to Renewable Energy and Climate Change) and to Chapter 9 (Renewable Energy in the Context of Sustainable Development). Parts of this section (10.6) consider the same topics, but from the viewpoints of social costs and benefits.

10.6.2. Review of studies on external costs and benefits

Energy extraction, conversion and use cause significant environmental impacts and social costs. Many environmental impacts can be lowered by reducing emissions with advanced emission control technologies (Amann, 2008).

Although replacing fossil-fuel-based energy with RE can reduce GHG emissions and also to some extent other environmental impacts and social costs caused by them, RE can also have environmental impacts and external costs, depending on the energy source and technology (da Costa *et al.*, 2007). These impacts and costs should be lowered, too and of course should be considered if a comprehensive cost assessment is requested.

This section considers studies by cost and benefit category and presents a summary by energy source as well. Some of the studies are global in nature, and to some extent also regional studies will be quoted which have been made mostly for Europe and North America. The number of studies concerning other parts of the world is still quite limited. Many studies consider only one energy source or technology, but some studies cover a wider list of energy sources and technologies.

In the case of energy production technologies based on combustion, the impacts and external costs, in particular the environmental costs arise mainly from emissions to air, especially if the greenhouse impact and health impact are considered. The life-cycle approach, including impacts via all stages of the energy production chain, is, however, necessary in order to recognise and account for total impact. This holds true also in the case of non-combustible energy sources (WEC, 2004; Kirkinen *et al.*, 2008; Ricci, 2009a; Ricci, 2009b).

The assessment of external costs is often, however, very difficult and inaccurate. As a result, the cost-benefit analysis of some measure or policy, where the benefit arises from decreases in some environmental or external impacts, is often very contentious. On the other hand, the difference between benefits and costs can be made clear even though the concrete numbers of the cost and benefit terms are uncertain. The benefits and costs can often be distributed unevenly among stakeholders, both at present and over time. Discounting of impacts over long time-horizons is at least to some extent problematic. Also, there are usually no compensation mechanisms which could balance costs and benefits between different stakeholders. (Soderholm and Sundqvist, 2003)

10.6.2.1. Climate change

Carbon dioxide is the most important anthropogenic GHG. The growth of its concentration in the atmosphere causes the greatest share of radiative forcing (Butler, 2008). The damage due to changing climate is often described by linking carbon dioxide emissions with the social costs of their impacts, sc. social costs of carbon (SCC), which is expressed as social costs per tonne of carbon or carbon dioxide released. A number of studies have been published on this subject and on the use of SCC in decision-making. Recent studies have been made e.g. by (Anthoff, 2007; Grubb and Newbery, 2007; Watkiss and Downing, 2008).

The monetary evaluation of the impacts of the changing climate is difficult, however. To a large extent the impacts manifest themselves slowly over a long period of time. In addition, the impacts can arise very far from a polluter in ecosystems and societies which are very different from the ecosystems and the society found at the polluter's location. It is for this reason that, for example, the methods used by the Stern review (2006) for damage cost accounting on a global scale are criticised but they can also be seen as a choice for producing reasonable estimates for results. Besides the question about discount rate which is quite relevant considering the long term impacts of GHG emissions there is considerable uncertainty in areas such as climate sensitivity, damages due to climate change, valuation of damages and equity weighting (Watkiss and Downing, 2008).

A German study dealing with external costs uses the values of US$ 17, 90 and 350 per metric tonne of CO_2 (14, 70 and 280 €/tCO_2) for the lower limit, best guess and upper limit for SCC, respectively, referring to (Downing *et al.*, 2005; Watkiss and Downing, 2008) assess that the range of the estimated social costs of carbon values covers three orders of magnitude, which can be explained by the many different choices possible in modelling and approaches in quantifying the damages. As a benchmark lower limit for global decision-making, they give a value of about US$ 17/tCO_2 (£35/tC). They do not give any best guess or upper limit benchmark value, but recommend that further studies should be done on the basis of long-term climate change mitigation targets.

The price of carbon can also be considered from other standpoints, e.g. what price level of carbon dioxide is needed in order to limit the atmospheric concentration to a given target level, say 450 ppm_v. Emission trading gives also a price for carbon which is linked to the total allotted amount of emission. Another way is to see the social costs of carbon as an insurance for reducing the risks of climate change (Grubb and Newbery, 2007).

RE sources have usually quite low GHG emissions per produced energy unit (WEC, 2004; IPCC, 2007a; Krewitt, 2007), so the impacts through climate change and the external costs they cause are usually low. On the other hand, there can also be exceptions, e.g. in the case of fuels requiring long refining chains like transportation bio-fuels produced under unfavourable conditions (Hill *et al.*, 2006; Soimakallio *et al.*, 2009b). Land use change for increasing bio-fuel production can, in some circumstances, release carbon from soil and vegetation and in practice increase net emissions for decades or even longer time spans (Edwards *et al.*, 2008; Searchinger *et al.*, 2008), but there is not yet much empirical information on that. In some cases the organic matter at the bottom of hydro power reservoirs can cause methane emissions, which can be significant (Rosa *et al.*, 2004; dos Santos *et al.*, 2006). However in many cases no significant GHG emissions are emitted (see section 5.6 of this special report).

Increasing the use of RE sources often displaces fossil energy sources which have relatively high greenhouse gas emissions and external costs (Koljonen *et al.*, 2008). This can be seen to cause negative external costs, or positive external benefits if the whole system is considered. In other words, the positive impacts of the increase of the RE depend largely on the properties of the original energy system (Kennedy, 2005).

10.6.2.2. Health impacts due to air pollution

Combustion of both renewable fuels and fossil fuels often cause emissions of particulates and gases which have health impacts (Krewitt, 2002; Torfs *et al.*, 2007; Amann, 2008; Smith *et al.*, 2009; Committee on Health *et al.*, 2010). Exposure to smoke aerosols can be exceptionally large in traditional burning, e.g. in cooking of food in developing countries (Bailis *et al.*, 2005). Also, emissions to the environment from stacks can reach people living far from the emission sources. The exposure and the number of health impacts depend on the physical and chemical character of the particulates, their concentrations in the air, and population density (Krewitt, 2007). The exposure leads statistically to increased morbidity and mortality. The relationships between exposure and health impacts are estimated on the basis of epidemiological studies (e.g. Torfs *et al.*, 2007). The impact of increased mortality is assessed using the concept of value of life year lost. The monetary valuation can be done e.g. by using the willingness-to-pay approach.

The results depend on many assumptions in the modelling, calculations and epidemiological studies. Krewitt (2002) describes how the estimated external costs of fossil-based electricity production have changed by a factor of ten during the ExternE project period between the years 1992 and 2002. ExternE is a major research programme launched by the European Commission at the beginning of the 1990s to provide a scientific basis for the quantification of energy related externalities. The cost estimates have been increased by extension of the considered area (more people affected) and by inclusion of the chronic mortality. On the other hand, the cost estimates have been lowered by changing the indicator for costs arising from deaths and by using new exposure-impact models. It can be argued that the results include considerable uncertainty (Torfs *et al.*, 2007).

The specific costs per tonne of emissions have been assessed in reference (Krewitt and Schlomann, 2006) to be for SO_2 about US$ 3,800 per tonne (3000€/t), for NO_x about $ 3,800 (3,000€/t), for Non-Methane VOC about $ 250 (200€/t) and for particulates PM_{10} about $ 15,000 (12,000€/t). The NMVOC emissions contribute to the formation of ground-level ozone, which has detrimental effects on health. Sulphur dioxide and nitrogen oxide emissions form sulphate and nitrate aerosols which also have detrimental health impacts.

When RE is used to replace fossil energy, the total social costs of the total energy system due to health impacts usually decrease, which can be interpreted to lead to social benefits linked to the increase of RE. However, this is not always the case as discussed in this subchapter but requires a more detailed analysis.

10.6.2.3. Impacts on waters

Thermal condensing power plants usually need water, e.g. from a river. This causes thermal loading of the river on a local scale. If the thermal load is too big, cooling towers, although more expensive than the use of river water, can be used so that the heat is discharged to the atmosphere. In terms of RE sources cooling water demand is relevant in particular for biomass combustion plants or concentrated solar thermal power plants. However, the unit size of bio-energy plants is usually small which may limit the thermal loading peaks.

Hydropower plants, especially if the water must be stored or regulated, can have detrimental impacts on fishing and other water-based livelihoods. The detrimental impacts can be lowered and mitigated (see section 5.6 of this special report) by compensating measures such as fish passes and plantations (Larinier, 1998).

The environmental and social impacts of hydropower projects vary considerably from case to case, leading to variable external costs and benefits. Environmental Impact Assessment (EIA) requirements defined in many national legislations of countries can be used as a tool for assessing the impacts on environment and society of a planned hydropower station (Wood, 2003; UNEP, 2007). The International Hydropower Association's Hydropower Sustainability Assessment Protocol and its current cross-sectional review is the leading initiative at the international level.

10.6.2.4. Impacts on land use, soil, ecosystems and biodiversity

Reservoir hydropower can have an impact on land use depending on the geographic location. In contrast, run-of-river schemes have less social and environmental impacts. Reservoirs are useful not only for hydropower projects but also for the management of fresh water systems for both potable water supply and irrigation. Thus hydropower schemes using reservoirs can have a multipurpose role. A run-of-river hydropower plant draws the energy for electricity production mainly from the available flow of the river. Such hydropower plants generally include some short-term storage, allowing for adaptations to demand and supply. The reservoirs can in some cases cover settlements, agricultural land and land used for other livelihoods as can be glimpsed from Section 5.6 of this Special Report.

The use of bio-energy can be increased by utilising residues from agriculture and forestry as well as by energy plantations. A large increase in bio-energy use, however, requires an increase in the land area designated to energy crops, resulting besides given options for using set-aside lands in competition with other activities like food, fodder and fibre production as well as with land use for biodiversity conservation and settlement. (Haberl *et al.*, 2007).

On the other hand, many residues from agriculture or forestry or even energy crop plantations, such as straw and slash, can be used to maintain or improve the quality of the soil. In contrast, excessive harvesting of forest residues for example can lower the nutrient and carbon content of the soil (Korhonen *et al.*, 2001; Palosuo, 2008).

Sulphur dioxide and nitrogen oxide emissions from energy production can also cause acidification and eutrophication of ecosystems. Air pollutants such as nitrogen dioxides and NMVOC emissions (which may result from the use of some RE options) can have impacts on the productivity of agriculture and on materials used in man-made structures. The external costs of these impacts are considerably lower than the costs of health impacts, according to Krewitt and Schlomann (2006).

10.6.2.5. Other socio-economic impacts

Benefits of energy sources include the facilitation of many services like illumination, heating and cooling of room space, food storage and cooking, the possibility to use information and communication technologies, and benefits in industries and other sources of livelihood. A secure access to energy is crucial for the functioning of modern societies and for a high standard of living. The world population is increasing (United Nations Population Division, 2008). By 2050 it is expected to be about 9 billion. There will likely be strong growth in demand for energy primarily in the developing economies.

The depletion of the limited energy reserves of fossil fuels (WEC, 2007; Similä, 2009) and bottlenecks in the energy infrastructure as well as a high centralization of resources can cause wide fluctuations in the price of energy and also risks in the availability of energy. Therefore, many countries are striving to improve energy security and promote the use of domestic energy sources. These challenges can often be responded to by increasing the share of RE (Koljonen *et al.*, 2009; Similä, 2009).

Generally, long-term measures to increase energy security focus on diversification, reducing dependence on any one source of imported energy, increasing the number of suppliers, exploiting indigenous fossil fuel or RE resources, and reducing overall demand through energy conservation. RE sources, as part of a cleaner energy mix, are growing in importance. Furthermore, RE sources cover a wide spectrum of energy sources, e.g. wind, solar, hydropower, geothermal, biomass, and ocean energy that contribute to security of energy supply.

Increasing the production and use of RE creates jobs in R&D and manufacturing (Monni *et al.*, 2002; Bundesministerium fuer Umwelt Naturschutz und Reaktorsicherheit (BMU), 2006). The supply of bioenergy fuels has also important role in the creation of jobs. The supply of local and domestic energy also has an impact on the economy of the area and even the country and its trade balance (Berry and Jaccard, 2001; Bergmann *et al.*, 2006; Lehr *et al.*, 2008). Moreover there is not only a possible employment effect due to the production process of RE sources, but a general possibility that access to energy and in particular RE enables the creation of new jobs especially in rural areas (e.g. business opportunities in small scale commercial applications).

On the other hand, the number of new jobs associated with some RE technologies can be quite small after the construction period. And the changes in energy system can result in loss of jobs in the fossil sector and in loss of jobs in the overall economy due to the effects of higher energy prices on other parts of the economy (Soimakallio *et al.*, 2009a). However, the net impact on jobs is often positive under a variety of circumstances, especially if export of technologies is accounted (Lehr *et al.*, 2008).

The biggest impacts of RE sources on the built environment (on landscape aspects) might be caused by wind power, hydro dams and large biomass plantations which may even have an impact on property prices in the neighbourhood. The production units for RE are mostly small and quite discrete, except for wind turbines and possibly some constructions needed for big hydropower plants (in the future maybe as well for centralized photovoltaics plants and solar thermal plants). Older wind power plants may also cause some noise in their vicinity. On the other hand, wind power can offer some positive image values (Moller, 2006). Biomass plantations might not be as visible from far away as wind mills are, but they require a large amount of land and are often in the form of monocultures, and can lead to negative impacts on biodiversity if not properly planned.

10.6.3. Social and environmental costs and benefits by energy sources and regional considerations

Most of the studies covered in this section consider North America (Gallagher *et al.*, 2003; Roth and Ambs, 2004; Kennedy, 2005; Chen *et al.*, 2007; Committee on Health *et al.*, 2010; Kusiima and Powers, 2010) and Europe (Groscurth *et al.*, 2000; Bergmann *et al.*, 2006; Krewitt and Schlomann, 2006; Ricci, 2009b), while some are more general without a specific geographical area.

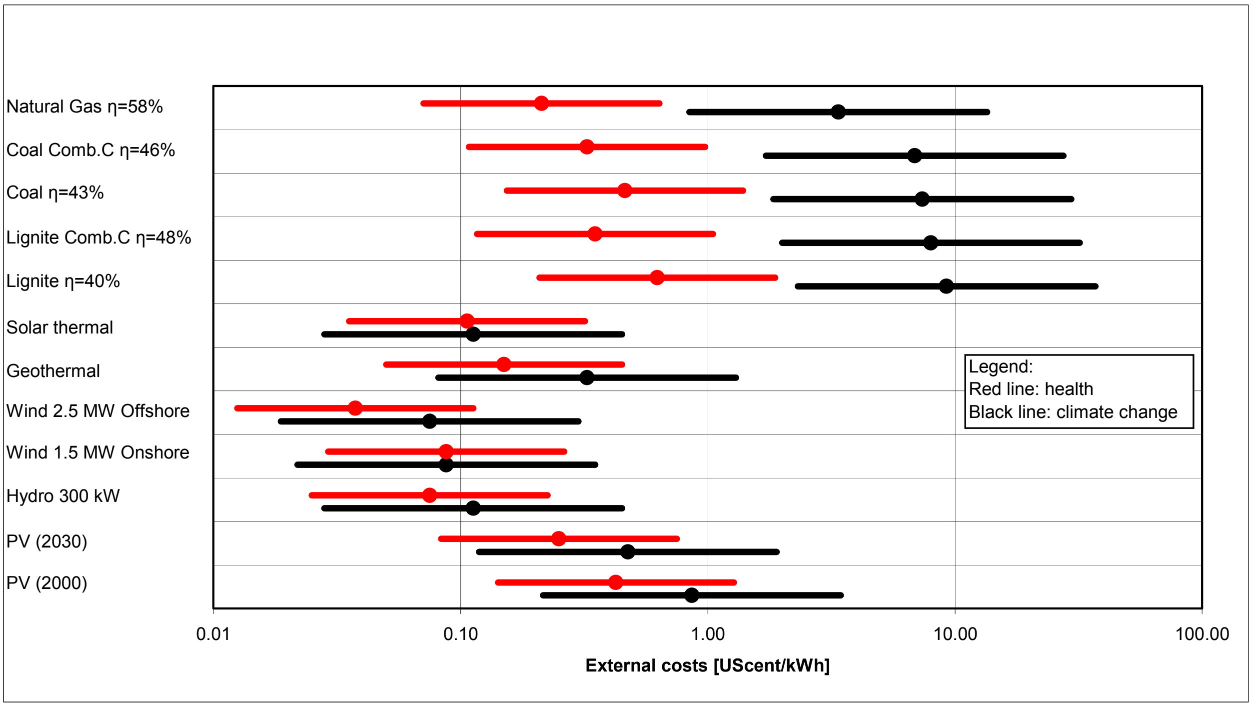
Some studies consider developing countries, especially Brazil. Da Costa *et al.* (2007) discuss social features of energy production and use in Brazil. Fearnside (1999; 2005) and Oliveira & Rosa (2003) study big hydropower projects and the energy potential of wastes in Brazil, respectively. Sparovek *et al*. (2009) investigate the impacts of the extension of sugar cane production in Brazil. Bailis *et al.* (2005) consider biomass- and petroleum-based domestic energy scenarios in Africa and their impacts on mortality on the basis of particulate emissions. Spalding-Fecher and Matibe (2003) study total external costs of coal-fired power generation in South Africa. Amann (2008) study cost-effective emission reduction of air pollutants and greenhouse gas emissions in China.

Studies concerning different areas of the globe are still sparse. More studies, articles and reports are needed to provide information on social costs and their possible variation in the ecosystems and societies of different geographical areas.

Table 10.6.1: External costs (US cents/kWh) due to electricity production based on renewable energy sources and fossil energy. Valuation of climate change is based on an SCC value of 90 \$/tCO$_2$. (Krewitt and Schlomann, 2006).

	PV (2000)	PV (2030)	Hydro 300 kW	Wind 1,5 MW Onshore	Wind 2,5 MW Offshore	Geothermal	Solar thermal	Lignite η=40%	Lignite Comb.C η=48%	Coal η=43%	Coal Comp.C η=46%	Natural Gas η=58%
Climate change	0.86	0.48	0.11	0.09	0.08	0.33	0.11	9.3	8.0	7.4	6.9	3.4
Health	0.43	0.25	0.075	0.09	0.04	0.15	0.11	0.63	0.35	0.46	0.33	0.21
Ecosystems	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡
Material damages	0.011	0.008	0.001	0.001	0.001	0.004	0.002	0.019	0.010	0.016	0.01	0.006
Agricultural losses	0.006	0.004	0.001	0.002	0.0005	0.002	0.001	0.013	0.005	0.011	0.006	0.005
Large accidents	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Proliferation	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Energy security	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
Geopolitical effects	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
	~1.3	~0.74	~0.19	~0.18	~0.12	~0.49	~0.22	>9.9	>8.4	>7.9	>7.2	>3.6

🟢 ”green light”: no important impacts
🟡 ”yellow”: some impacts arise
🔴 ”red light”: important impacts in conflict with sustainability
Comb.C: combined gas turbine and steam cycles



Comb.C: Combined gas turbine and steam cycles

Figure 10.6.2: Illustration of external costs due to electricity production based on RE and fossil energy. Note the logarithmic scale of the figure! The black lines in dictate the external cost due to climate change and the red lines indicate the external costs due to health effects. External costs due to climate change dominate in fossil energy. Valuation of external costs due to climate change is based on the SCC value of 90 \$/tCO$_2$ and its lower limit of 17 and upper limit of 350 \$/tCO$_2$. The uncertainty for the external costs of health impacts is assumed to be a factor of three (Based on Krewitt & Schlomann 2006; Krewitt 2002. Typical household consumer price of electricity varied in 2008 e.g. in EU countries from 7 (Bulgaria) to 19 (Ireland) US cents per kilowatt-hour (Eurostat 2009).

To calculate the net impact in terms of social costs of an extension of RE sources two things have to be done. First, (a) the external costs and benefits can be assessed on the basis of the life-cycle approach for each technology in the conditions typical for that technology so that only the direct impacts of that technology are taken into account (Pingoud *et al.*, 1999; Roth and Ambs, 2004; Krewitt and Schlomann, 2006; Ricci, 2009b). The other thing (b) is to consider the RE technologies as parts of the total energy system and society, when the impacts of a possible increase in the use of the RE technologies can be assessed as causing decreases in the use and external costs of other energy sources. These decreases of external costs can be seen as external benefits of the RE technologies for the society (Kennedy, 2005; Loulou *et al.*, 2005; Koljonen *et al.*, 2009).

An assessment of external costs in Central European conditions is presented in Table 10.6.1 (Krewitt & Schlomannn, 2006) and in Figure 10.6.2. It can be seen that the social costs due to climate change and health impacts dominate in the results in Table 10.6.1. The other impacts make a lesser contribution to the final results having in mind that not all impacts are quantifiable. Even if a lower value of social costs of carbon of \$17/tCO_2 is used in Table 10.6.1 instead of \$90 /tCO_2, the climate impact still dominates in the total social costs of fossil-based technologies, but for renewable technologies the health impacts would be dominant. Figure 10.6-2 show the large uncertainty ranges of two dominant external cost components of Table 10.6.1, namely climate related and health related external costs. A recent extensive study made for the conditions in USA (Committee on Health *et al.*, 2010) arrives at almost similar results than Krewitt & Schlomann (2006) for natural gas based electricity production but clearly higher external cost level for coal based production due to higher non-climate impacts. Other external costs due to energy security and geopolitical concerns are not covered by the study but depend e.g. on geographic area and available domestic resources.

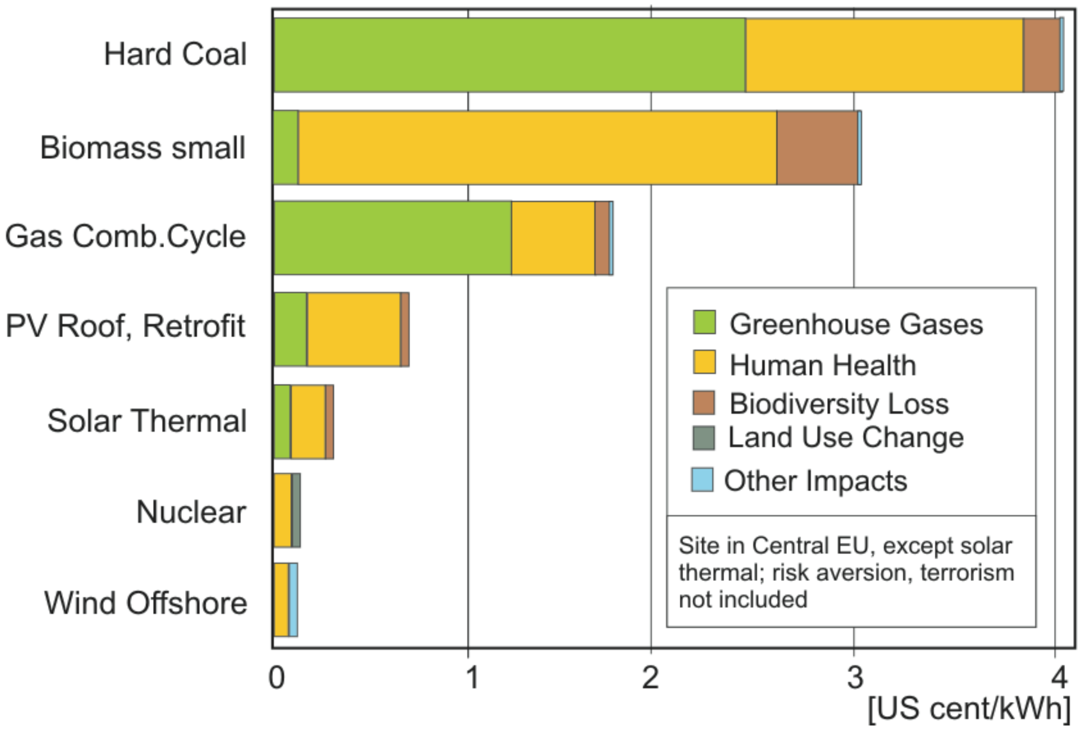


Figure 10.6.3: Quantifiable external costs for some electricity generating technologies. Estimation of external impacts and their valuation include considerable uncertainties and variability(Ricci, 2009a; Ricci, 2009b).

Results of an other study in Figure 10.6.3 show somewhat lower external costs for different technologies (Ricci, 2009a; Ricci, 2009b) than shown in Table 10.6.1. However, the results are within the uncertainty ranges given in Figure 10.6.4. Small scale biomass fired CHP plant

considered in the study causes relatively high external costs due to health effects via particulate emissions, however, inexpensive technical solutions can lower particulate emissions considerably in plants of moderate size classes. Nuclear energy and offshore wind energy cause smallest external cost in this study. The nuclear alternative does not include external cost impacts due to proliferation nor due to risks due to terrorism. Inclusion of these impacts could raise the external cost level of nuclear power.
As only costs of individual technologies are shown in Table 10.6.1 and Figures 10.6.2 and 10.6.3, benefits can be derived when assuming that one technology replaces another one. RE sources and the technologies using them have mostly lower external costs per produced energy than fossil-based technologies. However, case-specific considerations are needed as there can also be exceptions.

When the share of RE sources is increased in the energy system and when the use of fossil energy is decreasing, the external costs of the energy system per unit of energy usually decrease and the external benefits increase.

In most cases the environmental damages and related external costs decrease when fossil fuels are replaced by RE. Also the social benefits from the supply of RE usually increase. In some cases, however, there can be trade-offs between RE expansion and some aspects of sustainable development. Therefore, it is important to carry out Environmental Impacts Assessment (EIA) studies on RE projects in consideration in order to be sure that sufficient requirements for the implementation of the projects are met.

10.6.4. Synergistic strategies for limiting damages and social costs

Many environmental impacts and external costs follow from the use of energy sources and energy technologies that cause greenhouse gas emissions, particulate emissions and acidifying emissions – fossil fuel combustion being a prime example. Therefore, it is quite natural to consider the reduction of the impacts due to emissions with combined strategies (Amann, 2008)(Bollen et al., 2009) [AUTHORS: Reference missing in bibliography, only Bollen 2007 in bibliography].

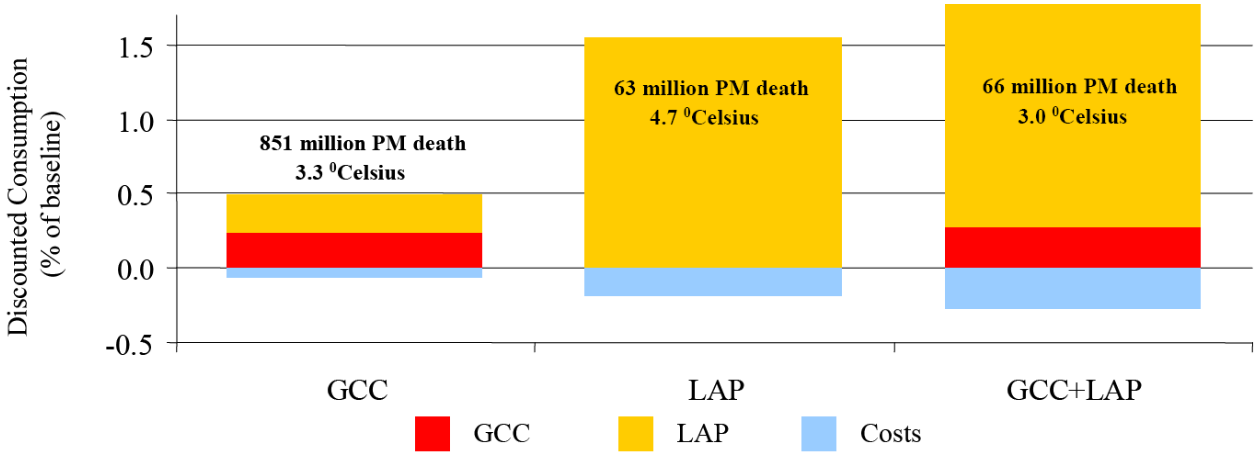


Figure 10.6.4: Changes in costs, benefits and global welfare for three scenarios (GCC, LAP, GCC+LAP), expressed as percentage consumption change (welfare increase) in comparison to the baseline. In the scenario GCC the social costs of Global Climate Change (GCC) have been internalised, in the scenario LAP the social costs of Local Air Pollutants (LAP) have been internalised, and in the scenario GCC+LAP both social cost components have been internalised. For each scenario the number of deaths due to particulate matter (PM) emissions and temperature rise due to greenhouse gas emissions is shown in the Figure. In the baseline the number of particulate matter (PM) deaths due to air pollutants would be 1000 million and the temperature rise 4.8 C.

Bollen et al. (2009) have made global cost-benefit studies using the MERGE model (Manne and Richels, 2005). In their studies the external costs of health effects due to particulate emissions and impacts of climate change were internalised. According to the study (Figure 10.6.4), the external benefits were greatest when both external cost types were internalised, although the mitigation costs were high as they work in a shorter time frame. The discounted benefits from the control of particulate emissions are clearly larger than the discounted benefits from the mitigation of climate change. The difference is, according to a sensitivity study, mostly greater by at least a factor of two, but of course depends on the specific assumptions (in particular on the discount rate chosen). The countries would therefore benefit from combined strategies quite rapidly due to reduced external costs stemming from the reduced air pollution health impacts.

Amann (2008) have reached quite similar conclusions in a case study for China. According to the study, the reduction of GHG emissions in China causes considerable benefits when there is a desire to reduce local air pollution. Also a study (Syri *et al.*, 2002) considering the impacts of the reduction of greenhouse gas emissions in Finland stated that particulate emissions are also likely to decrease.

A study by Spalding-Fecher & Matibe (2003) is one of the few cases of such for developing countries. They found that, in South Africa, the total external costs of coal-fired power generation are 40 and 20 percent of industrial and residential charges for electricity. They concluded also that a reduction in GHG emissions lessen air-borne particulates which lead to respiratory disorders and other diseases.

10.6.5. Knowledge gaps

There are considerable uncertainties in the assessment and valuation of external impacts of energy sources. The assessment of physical, biological and health damages includes considerable uncertainty estimates based typically on calculational models, the results of which are often difficult to validate. The damages or changes have seldom market values which could be used in cost estimation but indirect information or other approaches must be used for damage valuation. Further, many of the damages will take place far in the future which complicates the considerations. All these factors contribute to the uncertainty of external costs.

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Box 10.2. Moving Beyond Top-Down vs. Bottom-Up?

In previous IPCC reports (e.g. Herzog et al., 2005; Barker et al., 2007)) quantitative scenario modelling approaches were broadly separated into two groups: top-down and bottom-up. Although this classification may have made sense in the past, recent developments make it decreasingly appropriate. Most importantly, (i) the transition between the two categories is continuous, and (ii) many models, although rooted in one of the two traditions (e.g. macro-economic or energy-engineering models), incorporate aspects from the other approach and thus belong to the class of so-called hybrid models (Hourcade et al., 2006; van Vuuren et al., 2009).

In addition, the terms top-down and bottom-up can be misleading, because they are context dependent: they are used differently in different scientific communities. For example, in previous IPCC assessments, all integrated modelling approaches were classified as top-down models regardless of whether they included significant technology information (van Vuuren et al., 2009). On the other hand, the interpretation of both terms depends on the aggregation level that is typically addressed by the respective scientific community. In the energy-economic modelling community, macro-economic approaches are traditionally classified as top-down models and energy-engineering models as bottom-up. However, in engineering sciences, even the more detailed energy-engineering models that represent individual technologies such as power plants, but essentially treat them as “black boxes”, are characterized as top-down models as opposed to a component-based view which is considered to be bottom-up.

Box 10.3 Storylines of the four illustrative scenarios

IEA WEO 2009: This scenario is a typical baseline scenario or Business-as-usual approach. As such, it calculates the possible energy pathway without any substantial change in government policy (IEA WEO 2009, p 44) and under the assumption of a moderate fossil fuel cost raise. The WEO 2009 baseline does not include specific GHG emissions targets. As the IEA's projection only covers a time horizon up to 2030 for this scenario exercise, an extrapolation of the scenario has been used which was provides by the German Aerospace Agency (DLR) by extrapolating the key macroeconomic and energy indicators of WEO 2009 forward to 2050 (Publication filed in June 2010 to Energy Policy).

ReMind-Recipe: This scenario describes a mitigation path aiming at a stabilization of atmospheric CO_2 concentrations at 450 ppm. It was generated with the energy-economy-climate model ReMIND-R, which computes welfare-optimized transformation trajectories under full where-flexibility (emission reductions are performed where it is cheapest), when-flexibility (optimal timing of emission reductions) and what-flexibility (cost-optimal technology choice). Another crucial assumption is perfect foresight: Investment decisions fully account for future changes of prices and technology developments. Due to its idealized assumptions, it can be regarded as a benchmark scenario of future developments under perfect institutional settings. ReMIND accounts for a variety of renewable energy sources (wind, solar, biomass, hydro, geothermal) and conversion technologies. Wind power and solar photovoltaic are parameterized as learning technologies. RETs can be deployed at industrial scale at optimal sites and transported within world regions (up to continental scale) to demand centers, whereby the model implicitly assumes that bottlenecks, e.g. with respect to grid infrastructure, are avoided by early and anticipatory planning. (according to Luderer *et al.*, 2009)

EMF 22: The MiniCAM EMF 22 scenario was developed as part of Energy Modelling Forum study 22, looking at possible approaches to long-term climate goals. The scenario was generated using the MiniCAM integrated assessment model, the precursor to the GCAM integrated assessment model. The scenario is an overshoot scenario that reaches 450 ppmv CO_2-e (Kyoto gases) by 2100, after peaking at 525 ppmv CO_2-e (Kyoto gases) in 2050, and assuming full international participation in emissions reductions. The underlying characteristics of the scenario include global population growth that peaks at approximately 9.0 billion people in 2070 and then declines to 8.7 billion people in 2100; a transition in economic production, and the preponderance of associated CO_2 emissions, from the developed regions to the developing regions; and the availability of a wide range of energy supply options, including major renewable energies, nuclear power, and both fossil energy and bioenergy equipped with carbon capture and storage (CCS) technology. The presence of bioenergy with CCS is particularly important in the scenario, because it allows for the option to create negative emissions, primarily in electricity production. (according to Clarke *et al.*, 2009)

Energy [R]evolution 2010: The ER 2010 (Greenpeace and EREC, 2010; Teske *et al.*, 2010) is based on the socio-economic assumptions of the IEA WEO 2009, but projects increase fossil fuel costs and a price for carbon from 2010 onwards. The scenario has a key target to reduce worldwide carbon dioxide emissions down to a level of around 3.5 Gt per year by 2050. To achieve its targets, the scenario is characterised by significant efforts to fully exploit the large potential for energy efficiency, using currently available best practice technology and to foster the use of RE. In all sectors, the latest market development projections of the renewable energy industry have been taken into account. To accelerate the market penetration of RE, various additional measures have been assumed. For instance a speedier introduction of electric vehicles, combined with the implementation of smart grids and faster expansion of super grids shall allow a higher share of fluctuating renewable power generation (photovoltaic and wind) to be employed.

INTERGOVERNMENTAL PANEL ON climate change

Chapter 11

Policy, Financing and Implementation

Chapter:	11	
Title:	Policy, Financing and Implementation	
(Sub)Section:	All	
Author(s):	CLAs:	Catherine Mitchell, Janet L. Sawin, Govind Raj Pokharel, Daniel Kammen, Zhongying Wang
	LAs:	Solomone Fifita, Mark Jaccard, Ole Langniss, Hugo Lucas, Alain Nadai, Ramiro Juan Trujillo Blanco, Eric Usher, Aviel Verbruggen, Rolf Wüstenhagen, Kaoru Yamaguchi
	CAs:	Doug Arent, Greg Arrowsmith, Lori Bird, Alex Bowen, Sylvia Breukers, Elisabeth Clemens, Peter Connor, Felix Creutzig, Peter Droege, Chris Greacen, Renata Grisoli, Kirsty Hamilton, Cameron Hepburn, Suzanne Hunt, Jochen Harnisch, Birger Madsen, Lars J. Nilsson, Anis Radzi, Tormod Andre Schei, Sergio Trindade, Dan Van Der Horst, Saskia Vermeylen, Charles Wilson
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COMMENTS ON TEXT BY TSU TO REVIEWER

Yellow highlighted – original chapter text to which comments are references

Turquoise highlighted – inserted comment text from Authors or TSU e.g. [AUTHOR/TSU:…]

Chapter 11 has been allocated a total of 85 pages in the SRREN. The actual chapter length (excluding references & cover page) is 113 pages: a total of 28 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened in terms of text and/or figures and tables.

Financing and Implementation

CONTENTS

EXECUTIVE SUMMARY

Government policies are required for the substantial increase in deployment of RE required to help mitigate climate change. Market signals, through the current structure of energy markets, even when incorporating carbon pricing, have not been sufficient to trigger significant RE growth.

Multiple success stories from around the world demonstrate that policies can have a substantial impact on RE development and deployment. Where renewable deployment has been successful, specific policies in support of RE have been put in place. Only rarely has deployment occurred without specific policies in support of renewables, for example geothermal in Iceland; solar thermal in China. At the same time, not all RE policies have proven effective and efficient.

To be effective and efficient, policies must be specifically targeted to RE in order to address and overcome the numerous challenges that currently limit uptake and investment in RE capacity, in research and development of RE technologies, and in the infrastructure necessary for integrating RE into the existing energy system. After more than 30 years of policy experience, there is now a clear understanding of what works and what does not. This understanding is particularly clear with policies to promote power generation; while a wide variety of approaches exist in the transport and heating sectors, thus far none stand out.

Instrument design is key for policies to be effective and efficient. Policy instruments are most effective if tailored to the requirements of individual RE technologies and to local political, economic, social and cultural needs and conditions. Due to an energy system's long-term nature, the necessary investments in RE plants, in manufacturing facilities, in infrastructure for integration and R&D rely on stable and predictable policies and frameworks deliberately conceived and covering the energy sector more generally. Clear, long-term, consistent signals and well-designed policies are crucial to reduce the risk of investment sufficiently to enable high rates of deployment, the evolution of low-cost applications, and an environment conducive to innovation and change. Successful policy ultimately will be successful only if efforts on R&D and new technology development are finally deployed in the marketplace and become part of the energy system, thereby exploiting the cost reduction potential through learning by doing and economies of scale.

Well-designed policies are more likely to emerge in an enabling environment, and they will be more effective in rapidly scaling up RE. An enabling environment combines technological, social, institutional and financial dimensions. It is characterised by the readiness of society and stakeholders, including decision-makers to create an environment in which RE development and deployment can prosper. This readiness is motivated by a wide range of drivers, including the low climate and environmental impacts associated with most RE resources and technologies, and RE's potential to enhance energy security, to provide energy access for the world's poorest people, and to create new job opportunities.

The intertwined requirements to achieve the needed rate of deployment involve a systemic and evolutionary process. Thus, coordination is essential among policies—both RE policies and those in other related sectors such as agriculture, transportation, construction—and among the sub-components of the enabling environment, whether economics, technology, law, institutional, social and cultural.

The global dimension of climate change and the need for sustainable economic development call for a global partnership on deploying RE that recognizes diversity of countries, regions and business models. Deployment of RE provides opportunities for international cooperation, while wide-scale integration of RE will demand it. New finance mechanisms and creative policies on all levels are needed to stimulate technology transfer, investment and deployment of RE. For a problem as vast as climate change, an enabling environment is effective only if the private sector in its broadest form—meaning from small to large enterprises—is supported and is a partner in the process.

Policies to promote RE can begin in a simple manner to provide initial incentives for investing in RE. To achieve higher shares of RE, more comprehensive policies are required that address specifically the various barriers hindering RE deployment. For the efficient integration of RE into the energy system, the interaction among all energy carriers and energy efficiency options must be optimised (See Chapter 8). Today's energy system was designed primarily for fossil and/or nuclear energy carriers, and a transformation is required to reflect the characteristics of RE technologies. In the longer term, a structural shift is needed for low-carbon dioxide emitting RE to meet the energy service needs of people in developed and developing countries. This implies important changes in societal activities, practices, institutions and social norms, and government policy has a critical role to play in driving this transformation. Political will and effective policies to promote RE deployment in concert with decreasing energy intensity are integral to this transition.

The now-required energy transition differs from previous ones in two ways: the available time span is restricted to a few decades, while in much of the world RE must develop and integrate into a system—including in some cases policies and regulations—that was constructed to suit fossil fuels and nuclear power. As such, combinations of strategic and directed policies to meet interim and long-term targets and advance infrastructure will be critical, alongside long-standing political commitment and the flexibility to learn from experience and adapt as situations change.

11.1 Introduction

This report explores the potential for low-carbon dioxide (CO_2) emitting renewable energy (RE) technologies to meet the energy service needs of people in both developed and developing countries. Capturing the potential of the globe's RE resources depends on a wide spectrum of factors. In order to achieve a transition of the scale required and the speed in which it must occur to avoid catastrophic climate change, it will be important to systematically implement policies on a wide-scale to overcome the barriers to RE discussed earlier in this report.

The previous chapters have explained the state of technological understanding, barriers and policy issues specific to individual technologies, and have described the required issues of integration. Chapter 10 has reviewed over a hundred scenarios and undertaken detailed studies of the potential from different rates of technological learning. It shows that there are large uncertainties in the future development of RE since it depends on external factors, such as economic growth, as well as the degree to which well-designed RE policies are put in place to overcome barriers and feed into a virtuous cycle of lowering costs and further increasing deployment.

This chapter sets out the issues surrounding the policies, financing and implementation of RE to enable this virtuous cycle to develop. It lays out the general RE policy options, including financing, that are available for rapidly increasing the uptake of RE, examines which policies have been most effective and efficient to date and why, and it looks at both RE specific policies and policies that create an "enabling environment" for RE. Issues concerning individual RE resources and/or technologies are examined in the appropriate technology chapter.

The key findings of this chapter are the following (for more details, see Box 11.1):

- Targeted RE policies accelerate RE development and deployment;
- Multiple success stories exist and it's important to learn from them;
- Economic, social, and environmental benefits are motivating Governments and individuals to adopt RE;
- Multiple barriers exist and impede the development of RE policies to support development and deployment;
- 'Technology push' coupled with 'market pull' creates virtuous cycles of technology development and market deployment;
- Successful policies are well-designed and -implemented, conveying clear and consistent signals;
- Policies that are well-designed and predictable can minimize key risks, encouraging greater levels of private investment and reducing costs;
- Well-designed policies are more likely to emerge and to function most-effectively in an enabling environment;
- The global dimension of climate change and the need for sustainable development call for new international public and private partnerships and cooperative arrangements to deploy RE;

- Structural shifts characterize the transition to economies in which low CO_2 emitting renewable technologies meets the energy service needs of people in both developed and developing countries;
- Better coordinated and deliberate actions accelerate the necessary energy transition for effectively mitigating climate change.

As previous chapters have described, RE capacity and production of electricity, heat and fuels have increased rapidly in recent years, although most technologies are growing from a small base. Large-scale hydropower, which accounts for a significant portion of global electricity generation and represents a major share of total energy production in several countries, is clearly an exception. The number of countries with RE policies in place has also risen significantly, particularly since the early to mid-2000s, as discussed in Section 11.2.

This trend toward more RE policies in a growing number of countries has played an important role in advancing RE and increasing investment in the RE sector; this has been particularly true for non-hydro renewables. RE policies have a critical role to play in the transition to an energy future based on low-CO_2 RE. Although there are limited examples of countries that have come to rely primarily on RE without supportive policies (such as Iceland with geothermal and hydropower; as well as Brazil, which generates more than 80 percent of its electricity with hydropower (IEA, 2009c)), in most cases targeted policies are required to advance RE technology development and use.

11.1.1 The Importance of Tailored Policies and an Enabling Environment

To date, in almost every country that has experienced significant installation of RE capacity, production, and investment in manufacturing and capacity, there have been policies to promote RE. There is now clear evidence of success, on the local, regional and national levels, demonstrating that the right policies have a substantial impact on the uptake of RE and enhanced access to clean energy. A limited number of communities and regions have made quite rapid transitions to or toward 100 percent RE; some countries are also experiencing rapid growth in RE, with some seeing a rapid increase in the share of total energy demand met by RE.

At the same time, the IEA (IEA, 2008b) has found that only a limited number of countries have implemented policies that have effectively accelerated the diffusion of RE technologies in recent years (Lipp, 2007). Simply enacting support mechanisms for RE is not enough.

Tailored policies are required to overcome the numerous barriers to RE that currently limit uptake in investment, in private R&D funding, and in infrastructure investments. Accelerating the take-up of RE requires a combination of policies but also a long-term commitment to renewable advancement, policy design suited to a country’s characteristics and needs, and other enabling factors.

The issue of finance can be examined in ways, including (i) an assessment of the current trends in renewable energy finance, (ii) an analysis of the linkage between policy effectiveness and finance mobilisation, and (iii) a review of public finance instruments as a policy option available to governments.

Policies are most effective if targeted to reflect the state of the technology and available RE resources, and to respond to local political, economic, social and cultural needs and conditions.

Moreover, policies that are clear, long-term, stable and well-designed, and that provide consistent signals generally result in high rates of innovation, policy compliance, and the evolution of efficient solutions. When these factors are brought together, a policy can be said to be well-designed and -tailored.

Well-designed policies are more likely to emerge, and to lead to successful implementation, in an enabling environment. An "enabling environment" is defined as:

"A network of institutions, social norms, infrastructure, education, technical capacities, financial and market conditions, laws, regulations and development practices that in concert provide the necessary conditions to create a rapid and sustainable increase in the role of renewables in local, national and global systems" (i.e., that enable targeted RE policies to be effective and efficient).

An enabling environment combines legal, economic, technological, social and cultural, institutional and financial dimensions, including both the public and private sectors and well as civil society. It is not a critical prerequisite for RE policies. Countries can start small, with simple incentives, and build up. However, the importance is to avoid situations in which lack of attention to the enable environment produces bottlenecks in the sectors—such as lack of a skilled workforce, or inability to obtain affordable financing or permitting. Coordination with policies related to other key and inter-linked sectors—including agriculture, transportation, construction, technological development, and infrastructure—is also important.

Policy and regulation, and their design, play a crucial role in improving the economics of RE, and as such can be central to attracting private capital to RE technologies and projects, and influencing longer-term investment flows.

Finally, achieving a sustainable energy system, one in which low-CO_2 RE meets the energy service needs of people around the world, will require a structural shift to a more integrated energy service approach that takes advantage of synergies between RE and energy efficiency. The RE growth seen to date must be accelerated on a global scale for RE to play a major role in mitigating climate change. This is true not only for those RE technologies which have already seen successes related to manufacture and implementation, but also for other RE resources such as renewable heat, which thus far has experienced limited growth and limited policy support despite its enormous potential (IEA, 2007a; Seyboth, Beurskens *et al.*, 2008).

To enable this shift, a combination of well-designed policies, financing mechanisms, and stakeholder involvement is required which address the broad spectrum of issues barriers ranging from technological through to social concerns. It implies important changes in societal activities, practices, institutions and social norms.

The encouragement of 'innovation' is a central component for realization of successful RE policies and an enabling environment. Although innovation is often understood as the development and implementation of new technologies, it can also be viewed as the development of new practices such as new business models, institutional and social activities. The concept of innovation and its relationship to policies is discussed further in section 11.6.

11.1.2 Roadmap for Chapter

This chapter begins in Section 11.2 by highlighting recent trends in RE policies to promote deployment, as well as trends in financing and research and development funding. Section 11.3 examines the various drivers of RE policies, and 11.4 briefly reviews the many market failures and barriers that impede the development of RE policies. Section 11.5 presents the various policy options available to advance RE development and deployment, and discusses which have been most effective and efficient to date, and why. In Section 11.6, an enabling environment is defined and explained. The chapter concludes with Section 11.7, which focuses on broader considerations and requirements for a structural shift to a sustainable, low-carbon energy economy.

Throughout the chapter, a number of case studies in boxes highlight key messages of the chapter and provide insights into policy experiences that offer lessons for other regions or countries. See, for example, Box 11.2 which examines how Germany has achieved a rapid increase in deployment of many RE technologies across end-use sectors through a combination of well-designed and well-implemented RE support measures that have been predictable and long-term, and that have been adjusted as situations change over time, and that have been enacted alongside policies to create an enabling environment.

Given the tremendous range of conditions, needs, technologies, capacities and other circumstances around the world, the focus of this chapter is very broad. This chapter endeavours to examine policies relevant to RE in many different ways—scale of projects, penetration levels, application, technological maturity, economic state of the country or community where RE technologies are deployed, level of access to modern energy services, and so forth. Figure 11.1 shows just a few of the factors that play a role in decisions and policy making. Clearly, it is not possible to cover everything in a single chapter. For aspects that go beyond what is included here—for example, related to energy access or integration—refer to the relevant chapters elsewhere in this report.

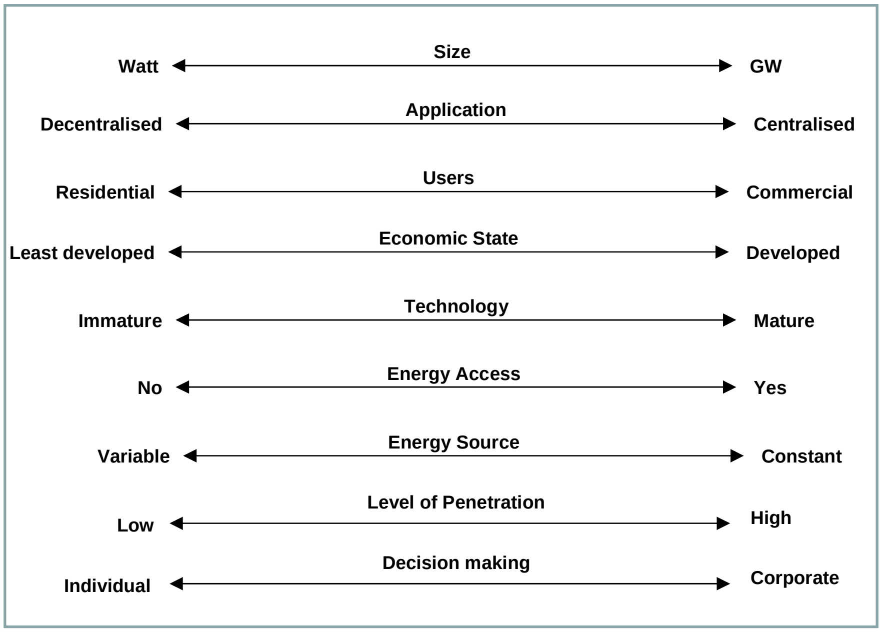

Figure 11.1 Breadth of policy making discussed in Chapter 11

Finance is also covered throughout the chapter as it is a critical and interrelated to every aspect of policies and policy making. The issue of finance can be examined in several ways, including (i) an assessment of the current trends in renewable energy finance, (ii) an analysis of the linkage between policy effectiveness and finance mobilisation, and (iii) a review of public finance instruments as a policy option available to governments. As mentioned above, financing and investment trends are covered in Section 11.2, followed by a box discussing how financiers think and elements necessary to minimize risk and encourage investments. Section 11.4 includes the barriers to financing; 11.5 explains the links between policies and financing, and how best to maximize public funds and encourage private investment.

Box 11.1 Key Messages Related to Policy, Financing and Implementation

1**. <u>Targeted RE policies accelerate RE development and deployment</u>**. Targeted policies should address barriers to RE, including market failures, and appropriate market signals are crucial to trigger significant RE growth, but are not sufficient.

2. **<u>Multiple RE success stories exist around the world and it is important to learn from them</u>**. They demonstrate that the right policies have an impact on emissions reductions and the enhanced access to clean energy. They also demonstrate the importance of learning by doing, including learning from mistakes, to achieving success.

3. **<u>Economic, social, and environmental benefits are motivating Governments and individuals to adopt RE.</u>** In addition to mitigation of climate change, benefits include economic development and job creation, increased security of energy supply, greater stability and predictability of energy prices, access to energy, and reduced indoor air pollution. In general, climate change mitigation is a primary driver for developed countries whereas developing countries focus more on energy access and energy security through RE. In low-lying developing

countries, RE's potential for climate change mitigation becomes an issue of economic and physical survival.

4. **Multiple barriers exist and impede the development of RE policies to support development and deployment.** These primarily relate to the degree of awareness, and acceptance, of climate change policies; a lack of knowledge of how RE can mitigate the problem and a lack of sufficient public governance capacity to elaborate and make RE policies operational; the momentum of the existing energy system, including policies that were enacted to advance or support the existing fossil-based system and that now undermine RE policy; and a lack of understanding on the part of policy-makers of the needs of financiers and investors.

5. **'Technology push' coupled with 'market pull' creates virtuous cycles of technology development and market deployment**. Public RD&D combined with promotion policies have been shown to drive down the cost of technology and sustain its deployment. Steadily increasing deployment allows for learning, drives down costs through economies of scale, and attracts further private investment in R&D.

6. **Successful policies are well-designed and -implemented, conveying clear and consistent signals.** Successful policies take into account available RE resources, the state and changes of the technology, as well as financing needs and availability. They respond to local, political, economic, social, financial, ecological and cultural needs and conditions. RE deployment policies can immediately start in every country with simple incentives, evolving toward stable and predictable frameworks and combinations of policies to address the long-term nature of developing and integrating RE into existing energy systems.

7. **Policies that are well-designed and predictable help to minimize key risks, encouraging greater levels of private investment**. Reducing risk helps to lower the cost of capital, improving access to financing of RE technologies and projects, and reducing their costs as well as the end cost of delivered energy. As a result, they can reduce the amount of public funds required to achieve the same levels of RE development and deployment.

8. **Well-designed policies are more likely to emerge and to function most-effectively in an enabling environment**. An enabling environment integrates technological, social, cultural, institutional, legal, economic and financial dimensions, and recognizes that technological change and deployment come through systemic and evolutionary (rather than linear) processes. Also important is coordination across policies, the dimensions of the enabling environment and, where relevant, different sectors of the economy including broader energy policy, transportation and agriculture.

9. **The global dimension of climate change and the need for sustainable development call for new international public and private partnerships and cooperative arrangements to deploy RE**. RE deployment is a part, and a driver, of sustainable development. New suitable finance mechanisms on national and international levels, involving cooperation between the public and private sectors, work to stimulate technology transfer and worldwide RE investment as well as advancing the necessary infrastructure for RE integration. New partnerships would recognize the diversity of countries, regions and business models.

10. **Structural shifts characterize the transition to economies in which low CO_2 emitting renewable technologies meet the energy service needs of people in both developed and developing countries.** When RE is treated as the norm, as fossil fuels are today, a structural shift

will have occurred. Political will and effective policies to promote RE deployment, in concert with decreasing energy intensity, are an integral part of the needed energy transition. Further, transitions require important changes in societal activities and practices, business conditions and institutions.

11. **Better coordinated and deliberate actions can accelerate the necessary energy transition for effectively mitigating climate change.** The now required transition differs from previous ones in two primary ways. First, the available time span is restricted to a few decades. Second, RE has to develop within the existing energy system (including policies, regulations and infrastructure) that generally were built to suit fossil fuels and nuclear power. Thus it is important to align attitudes and political actions with the known requirements for effectively mitigating climate change. Critical are combinations of strategic and directed policies established to meet interim and long-term RE targets and advance the required infrastructure. Long-standing commitment is essential alongside the flexibility to adapt policies as situations change.

Box 11.2 Case Study Germany: From a single instrument to a comprehensive approach

Since the oil crises in the 1970s, Germany has devoted significant resources to RE technology development and market deployment. As a result of German R&D efforts, by the mid-1980s many different technologies were ready for market deployment even though not yet cost competitive (IEA, 2004a) But in the 1980s and beyond, RE in Germany faced a political–economic structure that was largely hostile. Declining oil prices and surplus electric capacity in the late 1980s made it difficult for RE to compete economically. Further, the electricity supply system was dominated by large utilities that relied on coal and nuclear generation and opposed all small and decentralised forms of generation, which they deemed uneconomic and foreign to the system (Jacobsson and Lauber, 2006).

In 1989, the government established a subsidy (€ 0.031/kWh, USD_{2005} 0.053/kWh) for the first 100 MW of wind power installed in Germany. Beneficiaries were obliged to report on performance so that a common knowledge base was established. In 1990, Germany’s first feed-in law (FIT) was enacted, obliging utilities to connect RE power plants to the grid, to purchase the generated power, and to buy the electricity at a specified percentage of the retail rate: for wind and solar energy, this amounted to 90 percent of the average tariff for final customers. (Lauber and Mez, 2004).

The FIT was revamped in 2000, and broadened into the Renewable Energy Sources Act (Erneuerbare Energien Gesetz - EEG). Geothermal and large biomass power plants were added under the scheme, and cost-based tariffs were introduced. The level of the remuneration is calculated on the basis of a technology’s generation costs, and specified tariffs are guaranteed to all RE generators for at least 20 years (Lipp, 2007).

Reflecting the new structure of electricity markets, the EEG obligated grid operators and electricity suppliers to purchase RE electricity. Under the EEG, the generator delivers RE electricity to the grid operator, who then passes it to electricity suppliers (Langniß, Diekmann *et al.*, 2009). The Act has been amended twice, reflecting progress in technology development and stringent requirements on the integration of RE (Büsgen and Dürrschmidt, 2009). Lately, the extra burden from financing the EEG has been discussed more widely (Frondel, Ritter *et al.*, 2010).The additional costs amounted to 4.3 billion € in 2007 (5.12 billion USD_{2005}) (Büsgen and Dürrschmidt, 2009).

Several other policies have been used to promote deployment of RE electricity, to support further R&D, and to level the playing field (Laird and Stefes, 2009). Federal banks have awarded soft loans with low interest rates and favourable payment conditions, easing access to capital. Changes to German building codes granted RE the same legal status as other power generation technologies. Moreover, municipalities were obliged to allocate potential sites for wind power facilities in their land development plans. The requirements on such sites were legally defined (IEA, 2004b)

Due to a combination of support measures, Germany has seen rapid growth of electricity generation from RE. Germany's share of electricity from RE rose from 3.1 percent in 1991to 7.8 percent in 2002, and more than doubled by the end of 2009 to 16.9 percent (Wüstenhagen and Bilharz, 2006; German Federal Ministry for the Environment, 2009). Wind energy has experienced the greatest increase, but bioenergy and solar PV have grown substantially under this policy as well. (See Figure 11.2). The EEG sets a target for 30 percent of Germany's power to come from RE by 2020 (Büsgen and Dürrschmidt, 2009).

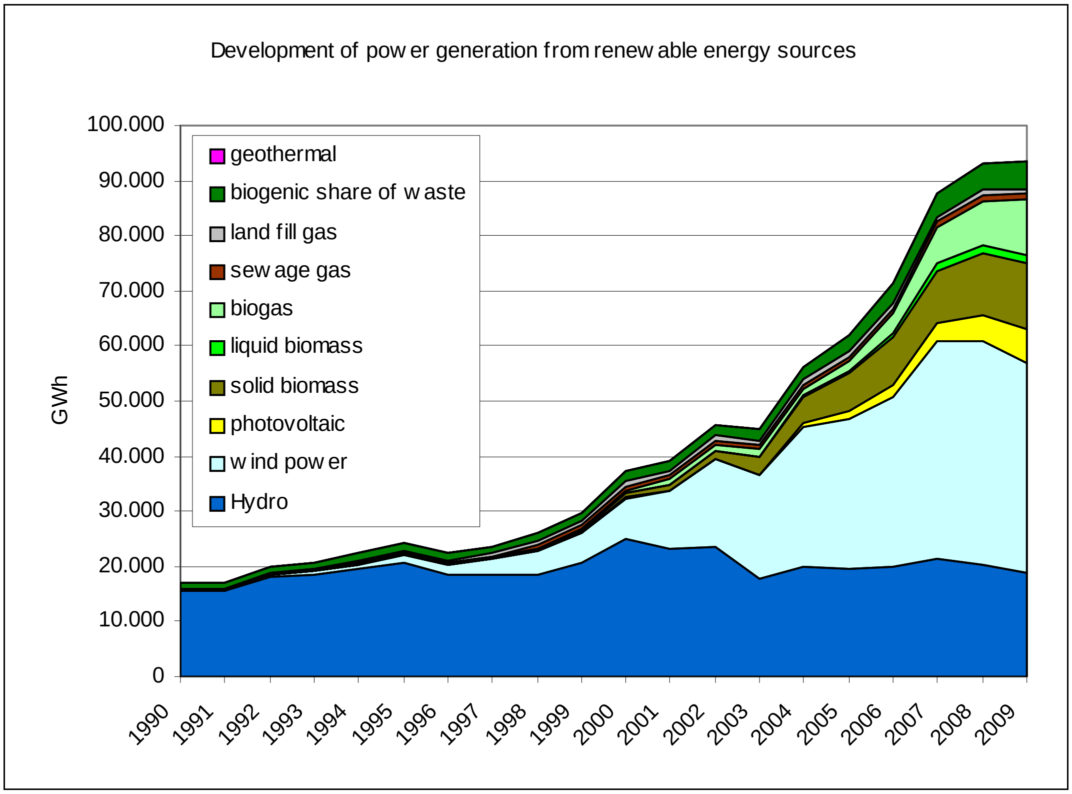

Figure 11.2 Development of Electricity Generation from RE in Germany, 1990-2008 (German Federal Ministry for the Environment, 2009).

Since 2000, the focus of Germany's RE promotion policies has broadened to include heat and transport fuel markets. A comprehensive "market acceleration programme" was introduced to award investment grants and soft loans for RE heat systems. In 2009, this was supplemented with a mandate requiring a minimum share of RE for heating and cooling in new buildings.

Initially promoted by tax exemptions (Bomb, McCormick *et al.*, 2007), RE transport fuels are now mandated through a blending quota on fuel suppliers.

The government's overarching frame for RE development has been creation of ambitious targets for the use of RE in individual sectors and for the economy as a whole. The share of RE in total primary energy supply increased steadily from 1.3 percent in 1990 to 8.9 percent in 2009 (BMU, 2010).

The German example shows how rapidly RE can advance when policies are well-designed and -implemented, conveying clear and consistent signals, and adapting to changes with technologies and in the marketplace. RE deployment policies can start with simple incentives, evolving toward stable and predictable policies and frameworks to address the long-term nature of developing and integrating RE into existing energy systems.

11.2 Current trends: Policies, financing and investment

Policy mechanisms to promote RE are varied and include regulations such as mandated quotas for RE electric capacity, feed-in tariffs, biofuels blending mandates, and building codes requiring passive or active use of solar and other RE resources for heat, light or power; fiscal policies include tax incentives and rebates; and financing mechanisms. Table 11.1 lists and defines a range of mechanisms currently used specifically to promote RE, and notes which types of policies have been applied to RE in each of the three end-use sectors of electricity, heating and cooling, and transportation. Each of these options for promoting RE deployment is discussed further in Section 11.5. Policies that create additional enabling conditions to advance RE are not included here, but are discussed in detail in Section 11.6.

The number of RE policies—specific RE policy mechanisms enacted and implemented by governments—and the number of countries with RE policies, is increasing rapidly around the globe. The focus of RE policies is shifting from a concentration almost entirely on electricity to include the heating/cooling and transportation sectors as well. These trends are matched by increasing success in the development of a range of RE technologies and their manufacture and implementation (See Chapters 2-7), as well as by a rapid increase in annual investment in RE and a diversification of financing institutions. This section describes recent and current trends in RE policies and in public and private finance and investment.

11.2.1 Trends in RE Policies

While several factors are driving rapid growth in RE markets, government policies have played a crucial role in accelerating the deployment of RE technologies to date (Sawin, 2001; Meyer, 2003; Sawin, 2004b; Rickerson, Sawin *et al.*, 2007; REN21, 2009b)(IEA, 2010).

Until the early 1990s, few countries had enacted policies to promote RE. Since then, and particularly since the early- to mid-2000s, policies have begun to emerge in an increasing number of countries at the national, provincial/state, regional, and municipal levels (REN21, 2005; REN21, 2009b). Initially, most policies adopted were in developed countries, but an increasing number of developing countries have enacted policy frameworks to promote RE since the late 1990s and early 2000s (Wiser and Pickle, 2000; Martinot, Chaurey *et al.*, 2002).

1 **Table 11.1** Existing RE Policy Mechanisms, Definitions and Use by Sector

Policy	Definition	Electricity	Heating/ Cooling	Transport
			End-use Sector	
REGULATORY				
Access Related				
Net metering	Allows a two-way flow of electricity between the electricity distribution grid and customers with their own generation. The meter flows backwards when power is fed into the grid.	X		
Priority Access to network	Provides RE supplies with unhindered access to established energy networks.	X	X	
Priority Dispatch	Ensures that RE supplies are integrated into energy systems before supplies from other sources.	X	X	
Quota Driven				
Renewable Portfolio Standard/ Renewable Obligations or Mandates	Obligates designated parties (generators, suppliers, consumers) to meet minimum RE targets, generally expressed as percentages of total supplies or as an amount of RE capacity. Includes mandates for blending biofuels into total transportation fuel in percent or specific quantity. Also RE heating purchase mandates and/or building codes requiring installation of RE heat or power technologies.	X	X	X
Tendering/ Bidding	Public authorities organize tenders for given quota of RE supplies or supply capacities, and remunerate winning bids at prices mostly above standard market levels.	X		

Tradable Certificates	Provide a tool for trading and meeting RE obligations among consumers and/or producers. Mandated RE supplies quota are expressed in numbers of tradable certificates which allow parties to meet RE obligations in a flexible way (buying shortfalls or selling surplus).	X	X	
Price Driven				
Feed-in tariff (FIT)	Guarantees RE supplies with priority access and dispatch, and sets a fixed price per unit delivered during a specified number of years.	X	X	X
Premium payment	Guarantees RE supplies an additional payment on top of their energy market price or end-use value.	X	X	
Quality Driven				
Green energy purchasing	Regulates the option of voluntary RE purchases by consumers, beyond existing RE obligations.	X	X	
Green labeling	Government-sponsored labeling (there are also some private sector labels) that guarantees that energy products meet certain sustainability criteria to facilitate voluntary green energy purchasing. Some governments require labeling on consumer bills, with full disclosure of the energy mix (or share of RE).	X	X	X
Guarantee of origin (GO)	A (electronic) document providing proof that a given quantity of energy was produced from renewable sources. Important for RE trade across jurisdictions and for green labeling of energy sold to end-users.	X	X	
FISCAL				
Accelerated depreciation	Allows for reduction in income tax burden in first years of operation of renewable energy equipment. Generally applies to commercial entities.	X	X	X

Investment grants, subsidies or rebates	One-time direct payments from the government to a private party to cover a percentage of the capital cost of an investment in exchange for implementing a practice the government wishes to encourage.	X	X	X
Energy production payments	Direct payment from the government per unit of renewable energy produced.	X	X	
Production/ investment tax credits	Provides the investor or owner of qualifying property with an annual income tax credit based on the amount of money invested in that facility or the amount of electricity that it generates during the relevant year. Allows investments in RE to be fully or partially deducted from tax obligations or income.	X	X	X
Reductions in sales, VAT, energy or other taxes	Reduction in taxes applicable to the purchase (or production) of renewable energy or technologies.	X	X	X
PUBLIC FINANCE				
Grants	Grants and rebates that help reduce system capital costs associated with preparation, purchase or construction of renewable energy equipment or related infrastructure. In some cases grants are used to create concessional financing instruments (e.g., allowing banks to offer low interest loans for RE systems).	X	X	X
Equity investments	Financing provided in return for an ownership interest in an RE company or project. Usually delivered as a government managed fund that directly invests equity in projects and companies, or as a funder of privately managed funds (*fund of funds*).	X	X	X
Loans	Financing provided to an RE company or project in return for a debt (i.e., repayment) obligation. Provided by development banks or investment authorities usually on concessional terms (eg lower interest rates or with lower security requirements).	X	X	X

Guarantees	Risk sharing mechanism aimed at mobilizing domestic lending from commercial banks for RE companies and projects that have high perceived credit (i.e., repayment) risk. Typically guarantees are partial, that is they cover a portion of the outstanding loan principal with 50%-80% being common.	X	X	X
OTHER				
Public Procurement	Public entities preferentially purchase renewable energy and RE equipment.	X	X	X

According to the Renewable Energy Network for the 21st Century (REN21)[1], the only source that currently tracks RE policies annually on a global basis, the number of countries with some kind of national RE target and/or RE deployment policy in place almost doubled from an estimated [55] in early 2005 to more than [100] in early 2010 (REN21, 2010). At least [80] countries had adopted policy targets for RE by early 2010, up from 45 (43 at the national level and two additional countries with state/provincial level policies) in mid-2005 (REN21, 2006). (See Figure 11.3) Many of these countries aimed to generate a specific share of their electricity from RE sources by a specific date (with most target years between 2010 and 2020), while many (with some overlap) had targets for share of primary or final energy from RE. There were also a large number of countries with specific RE capacity targets by early 2010 (REN21, 2010). In addition, many existing policies and targets have been strengthened over time and several countries have more than one RE-specific policy in place (REN21, 2010).

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[1] REN21 is a global policy network that is open to a range of stakeholders and connects governments, international institutions, non-governmental organisations, industry associations, and other partnerships and initiatives. Its goal is to advance policy development for the rapid expansion of RE in developed and developing and economies.

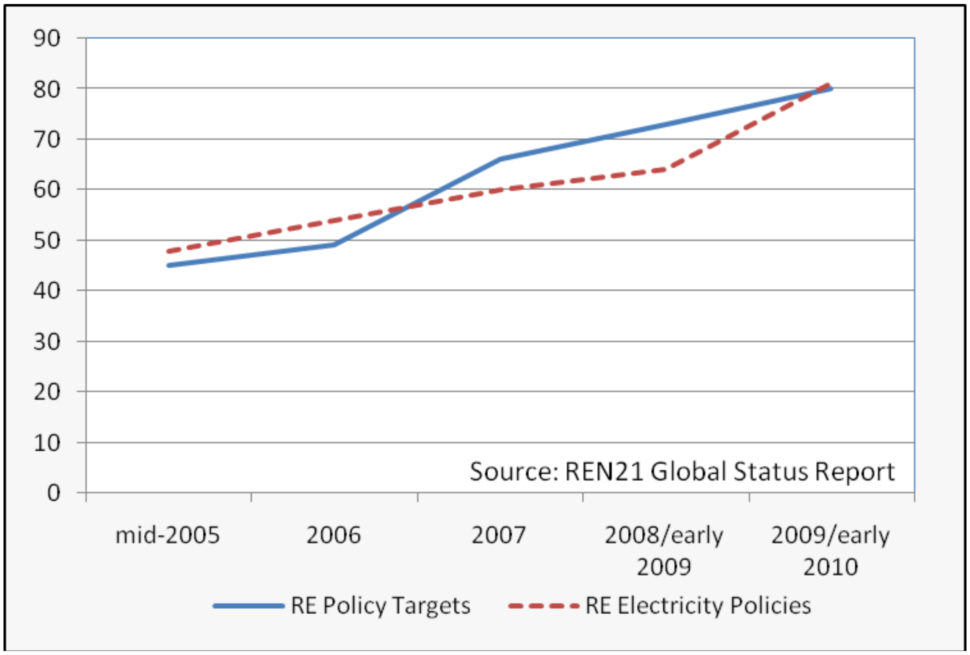

Figure 11.3 Number of Countries with RE Targets or Electricity Policies, 2005-early 2010
Sources: (REN21, 2005; REN21, 2006; REN21, 2007; REN21, 2009b; REN21, 2010). [Authors: To be updated][2]

RE policies are directed to all end-use sectors – electricity, heating and cooling, transportation. However, most RE deployment policies enacted by date of publication had focused on the electricity sector. At least 81 countries had adopted some sort of policy to promote RE power generation by early 2010 (IEA, 2010; REN21, 2010), up from an estimated 64 in early 2009 (REN21, 2009b), and at least 48 in mid-2005 (REN21, 2006). (See Figure 11.3) These included regulations such as feed-in tariffs (FITs), quotas, net metering, and building standards; fiscal policies including investment subsidies and tax credits; and government financing such as low-interest loans. Of those countries with RE electricity policies, approximately half were developing countries from every region of the world (REN21, 2010).

By early 2010, feed-in tariffs had been enacted in at least 50 countries at the national level (including much of Europe), and in 23 states, provinces or territories (Mendonça, 2007; Rickerson, Sawin *et al.*, 2007; Rickerson, Bennhold *et al.*, 2008; REN21, 2009b). Renewable Portfolio Standards (RPS) or quotas are also widely used and, by early 2009, had been enacted by an estimated 10 countries at the national level, and by at least 52 states or provinces (REN21, 2009b).

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[2] Data derived from REN21 Renewable Energy Policy Network (2005): Renewables 2005 Global Status Report, Worldwatch Institute, Washington, D.C., pp. 19-26; GSR 2006 Update, pp. 8-11; GSR 2007, pp. 21-28; GSR 2009 Update, pp. 17-20; and GSR 2010 draft. Note that all numbers are minimum estimates. Not all national renewable energy targets are legally binding. Overall RE targets and electricity promotion policies are national policies or targets, with the exception of the United States and Canada, which cover state and provincial targets but not national. 2006 statistic for number of countries with RE promotion policies is not available, so figure shows the average of 2005 and 2007 data from REN21.

Many additional forms of policy support are used to promote renewable electricity, including direct investment subsidies or rebates, tax incentives and credits, net metering, production payments or tax credits, or sales tax and VAT exemptions. By mid-2005, some type of direct capital investment subsidy, rebate or grant was offered in at least 30 countries (REN21, 2005); this number had risen to at least 45 countries by early 2010 (REN21, 2010).

In addition, an increasing number of governments are adopting incentives and mandates to advance renewable transport fuels and renewable heating technologies (International Energy Agency (IEA), 2007; REN21, 2009b; Rickerson, Halfpenny *et al.*, 2009). For example, in the 12 countries analysed for the International Energy Agency (IEA), the number of policies introduced to support renewable heating either directly or indirectly increased from five in 1990 to more than 55 by May 2007 (IEA, 2007b).

By early 2010, at least 28 countries at the national level and at least 36 provinces or states had adopted mandates for blending biofuels with gasoline or diesel fuel, while others had set production or use targets (REN21, 2009b). Most mandates require blending relatively small (e.g., up to 10) percentages of bio-ethanol or biodiesel with petroleum-based fuels for transportation; Brazil has been an exception, with blending shares in the 20-25 percent range (Goldemberg, 2009). Production subsidies and tax exemptions have also increased in use, in developed and developing countries (REN21, 2010). Another policy trend seen particularly with bioenergy, and biofuels especially, is the adoption of environmental and other sustainability standards, including regulations on associated lifecycle CO_2 emissions, such as the U.S. Renewable Fuel Standard and mandatory sustainability standards under the EU Renewable Energy Directive (European Commission (EC Roadmap), 2009; USEPA, 2010).

Beyond national policies, the number of regional policies and partnerships is increasing. The EU Renewables Directive entered into force in June 2009, setting a binding target to source 20 percent of EU final energy consumption from RE by 2020; all member states have been assigned targets for 2020 which are driving RE policies at the national level (REN21, 2009c)(EC, Directive 2009/28/EC, 2009). Another example is the Mediterranean Solar Plan, an agreement among countries in the region for research and deployment of 20 GW of RE by 2020 (Resources and Logistics (RAL), 2010).

Several hundred city and local governments around the world have also established goals or enacted renewable promotion policies and other mechanisms to spur local RE development (Droege, 2009; REN21, 2009b). Innovative policies such as Property-Assessed Clean Energy (PACE) have begun to emerge on this level. Under PACE programs, local governments issue bonds to raise money and offer low-interest loans for RE investments that are paid back over time through property taxes (Fuller et al, 2009). Indeed, some of the most rapid transformations from fossil fuels to RE based systems have taken place at the local level, with entire communities and cities—such as Samsø in Denmark, Güssing in Austria, and Rizhao in China—devising innovative means to finance RE and transitioning to 100% sustainable energy systems (Droege, 2009; Sawin and Moomaw, 2009).

Despite the increasing number of countries, states and municipalities with RE policies, the vast majority of capacity or generation for most non-hydropower RE technologies is still in a relatively small number of countries. By early 2010, five countries—the United States, Germany, Spain, China and India—accounted for more than 85% of global wind energy capacity. Three countries—Germany, Spain and Japan—represented approximately 82% of the world's solar photovoltaic (PV) capacity, while a handful of countries led in the production and use of biofuels (REN21, 2009b).

11.2.2 Trends in RE Finance

11.2.2.1 Trends Along the Financing Continuum

In response to the increasingly supportive policy environment, the overall RE sector globally has seen a significant rise in the level of investment since 2004-2005. These global figures are aggregated for all types of finance, with the possible exception of public R&D. Figure 11.4 shows that $117 billion [TSU: will need to be converted to USD$_{2005}$] of new financial investment went into the RE sector in 2008, up from 15.5 billion USD$_{2005}$ in 2004[3].

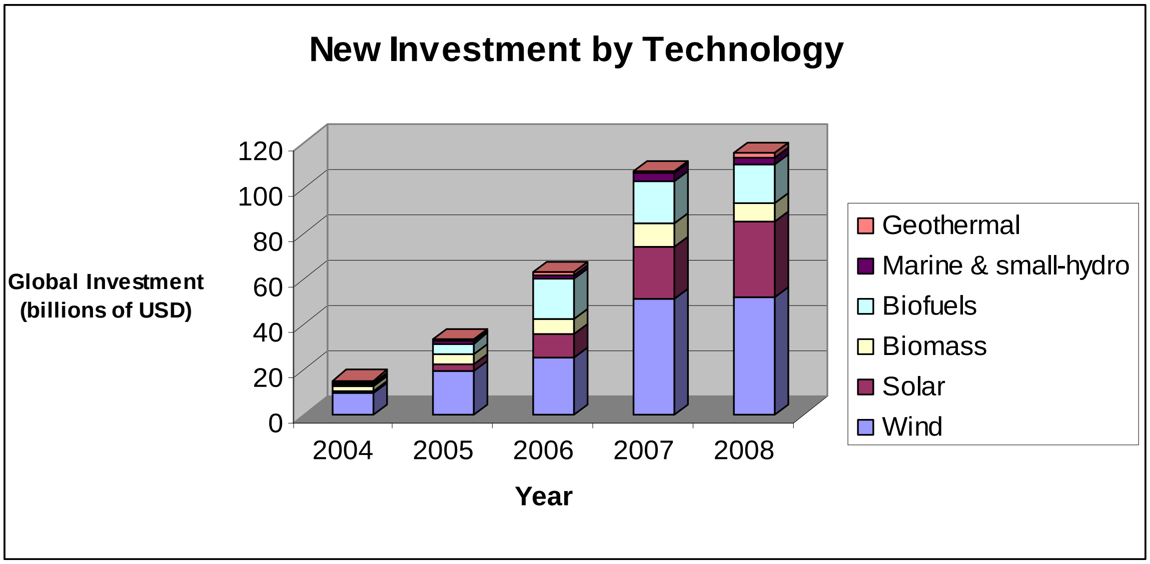

Figure 11.4 Global Investment in RE, 2004 – 2008 (UNEP and NEF, 2009). [TSU: figure will need to be converted to USD$_{2005}$]

Financing has been increasing along the continuum into the five areas of i) R&D; ii) technology development and commercialization; iii) equipment manufacture and sales; iv) project construction; and v) the refinancing and sale of companies, largely through mergers and acquisitions. The trends in financing along the continuum represent successive steps in the innovation process and provide indicators of the RE sector's current and expected growth, as follows:

- Trends in R&D funding and technology investment (i, ii) are indicators of the long to mid-term expectations for the sector – investments are being made that will only begin to pay off several years down the road.

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[3] Derived by stripping out the energy efficiency investment figures from United Nations Environment Programme and New Energy Finance (2009): Global Trends in Sustainable Energy Investment 2009: Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency, Paris. (Will update with 2009 data.)

- Trends in manufacturing investment (iii) are an indicator of near term expectations for the sector – essentially, that the growth in market demand will continue.
- Trends in new generating capacity investment (iv) are an indicator of current sector activity.
- Trends in industry mergers and acquisitions (v) are an indicator of the overall maturity of the sector, and increasing refinancing activity over time indicates that larger more conventional investors are entering the sector, buying up successful early investments from first movers.

Each of these trends is discussed in the following sub-sections. Table 11.2 provides information about the variety of financing types, arranged by phase of technology development. Although the concept of a continuum infers a smooth transition between the different types of financing involved, the reality is that financiers each have their own risk and return expectations and have different external drivers that make the different segments less or more attractive for commercial investment.

11.2.2.2 Financing Technology R&D

Figures collected by the International Energy Agency (IEA, 2008b) are a good guide to public RE R&D spending in OECD countries up till the middle of this decade. (IEA, 2008b) provides supplementary information on spending by large non-OECD economies, while data for spending on some forms of RE technology in non-IEA European countries is provided in (Wiesenthal, Leduc et al., 2009). The IEA data suggest the heyday of public funding in RE R&D occurred three decades ago. Spending on renewables peaked at 2.03 billion USD_{2005} in 1981. As oil prices dropped, spending fell by over two thirds, hitting a low in 1989. It has crept up since then, to about 727 M USD_{2005} a year in 2006.

The relationship between spending on RE R&D and movements in the oil price illustrate the significant role that the ‘security of supply’ consideration has on government decisions to fund research into alternative sources of energy. By this logic, governments would choose to focus their attention on technologies that have greatest potential to harness natural resources that are present on their territories. Indeed, this is argued by (International Energy Agency (IEA), 2008), noting that New Zealand and Turkey have spent 55 percent and 38 percent, respectively, of their RE R&D budgets on developing geothermal energy. Non-IEA countries also justify focusing on a particular energy resource by pointing to its relative local abundance, like solar energy in India (JNNSM, 2009) and Singapore (SERIS, 2009). But there are important exceptions to the rule. Germany, for instance, spends more on photovoltaic R&D than any other country in Europe (European Commission, 2009) but does so with a view to growing a competitive export industry (IEA, 2008b).

Photovoltaics and bioenergy are each now the beneficiaries of a third of all government R&D on RE. The proportion spent on wind has remained stable since 1974 and declined for geothermal, concentrating solar and solar for heating and cooling applications. Ocean energy and other RE technologies have also received support but at a much lower level. An overview of the kind of research being funded around the world in these areas can be found in (European Commission, 2006).

It is perhaps most instructive to look at R&D spending patterns in recent years when policy support for renewables has been growing quickly. Spending on wind, bioenergy, PV and concentrating solar thermal power averaged 536 M USD annually in the EU Member States over the 2002-2006 period, compared to 226 M USD_{2005} in the United States and 95.7 M USD_{2005} in Japan during the same years (European Commission, 2009). The International Energy Agency (IEA, 2008b) notes that averaging figures over this period hides some steep increases in spending, which have occurred in UK, France, Hungary and China. By 2006 Chinese spending on solar and wind R&D was up in the 37 and 42 M USD_{2005} range, roughly equivalent to that of Spain.

The European Commission (European Commission, 2009) provides a snapshot of how nuclear energy, fossil energy and RE spending compared against each other in 2007 (35%, 8% and 22% of total spending, respectively, with the balance going chiefly to energy efficiency). Time-series data for the shifts in spending among different categories of energy technology for OECD countries are available in (IEA, 2008b). The dominance of nuclear energy spending is still apparent, although much lower than in the 1980s.

With regard to private sector support for R&D, data is often collected by public bodies on the share of company turnover that the private sector ploughs back into R&D on its products. A company re-investing a high share of its earnings is taken to recognize that its future profitability depends on its ability to acquire new knowledge. Encouraging companies to behave in this way has long been a strategic priority of EU countries (Lisbon European Council, 2000).

There are marked differences between the R&D re-investment rates of companies headquartered in Europe and active in the energy business. The European Commission (Wiesenthal, Leduc et al., 2009) identifies the wind, PV and biofuel sectors as having rates in the region of 2.2-4.5 percent, consistent with the rates found in the sectors producing electrical components and equipment (3.4 percent) and industrial machinery. Electricity supply companies or oil majors have total (i.e., not just RE) rates of 0.6 percent and 0.3 percent, respectively, which the Commission rationalizes by saying these industries are “supplier dominated”.

11.2.2.3 Financing technology development and commercialization

While governments fund most of the basic R&D and large corporations fund applied or ‘lab-bench’ R&D, venture capitalists begin to play a role once technologies are ready to move from the lab-bench to the early market deployment phase. According to Moore and Wüstenhagen, venture capitalists have initially been slow to pick up on the emerging opportunities in the energy technology sector (Moore and Wustenhagen, 2004), with Renewable Energies accounting for only 1-3 percent of venture capital investment in most countries in the early 2000s. However since 2002 venture capital investment in RE technology firms has increased markedly. Venture capital into RE companies grew from $188 million USD_{2005} to $3.81 billion USD_{2005}[4], representing a compound annual growth rate of 60 percent . This growth trend in technology investment now appears to be a leading indicator that the finance community expects continued

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[4] Derived by stripping out energy efficiency investment from venture capital figures in United Nations Environment Programme and New Energy Finance (2009): Global Trends in Sustainable Energy Investment 2009: Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency, Paris.

significant growth in the RE sector. Downturns such as that experienced in 2008/2009 may slow or reverse the trend in the short term, but in the longer term an increasing engagement of financial investors is foreseen in RE technology development (UNEP and NEF, 2009).

Table 11.2 Table of Financing Types Arranged by Phase of Technology Development

Table of Financing Types arranged by Phase of Technology Development	
R&D	Public and corporate support for technology R&D is provided through a range of funding instruments.
Technology Commercialisation	**Venture Capital** is a type of private equity capital typically provided for early-stage, high-potential, technology companies in the interest of generating a return on investment through a trade sale of the company or an eventual listing on a public stock exchange.
Manufacturing and Sales	**Private Equity** investment is capital provided by investors and funds directly into private companies often for setting up a manufacturing operation or other business activity. (can also apply to Project Construction) Public Equity investment is capital provided by investors into publicly listed companies most commonly for expanding manufacturing operations or other business activities, or to construct projects. (can also apply to Project Construction, below)
Project Construction	Asset Finance is a consolidated term that describes all money invested in generation projects, whether from internal company balance sheets, from debt finance or from equity finance. Project Finance, debt obligations (i.e., loans) provided by banks to distinct, single-purpose companies, whose energy sales are usually guaranteed by power off-take agreements. Often known as off-balance sheet or non-recourse finance, since the financiers rely mostly on the certainty of project cash flows to pay back the loan. Corporate Finance, debt obligations provided by banks to companies using 'on-balance sheet' assets as collateral. Most mature companies have access to corporate finance, but have constraints on their debt ratio and, therefore, must rationalise each additional loan with other capital needs. Bonds are debt obligations issued by corporations directly to the capital markets to raise financing for expanding a business or to finance one or several projects.
Small Scale Technology Deployment	Consumer loans, micro-finance and leasing are some of the instruments that banks offer to households and other end-users to finance the purchase of small scale technologies. Different forms of SME finance is also generally needed to help companies set up the required sales and service infrastructure.

Carbon	Carbon finance in the form of loans or investment can now be accessed from some banks or investors in return for future carbon (e.g. CDM) revenue streams.
Sale of Companies	Mergers & Acquisitions involve the sale and refinancing of existing companies and projects by new corporate buyers.

11.2.2.4 Financing manufacturing facilities

Once a technology has passed the demonstration phase, the capital needed to set up manufacturing facilities will usually come initially from private equity investors (i.e., investors in un-listed companies) and subsequently from public equity investors buying shares of companies listed on the public stock markets. These forms of capital are also used to finance some of the working capital requirements of companies, with the rest coming from bank loans. Private and public equity investment in RE has grown from $0.168 billion in 2002 ($0.155 billion USD_{2005}) to $18.07 billion ($19.92 billion USD_{2005}) in 2008, representing a compound annual growth rate of 118 percent (UNEP and NEF, 2009). Even with this very fast growth in manufacturing investments several technologies had supply bottlenecks through early 2008 that delayed sector growth and pushed up prices. For example the solar sector suffered from global silicon feedstock material shortages while the wind sector experienced an undersupply of key components such as gearboxes and shaft bearings. This pressure eased in late 2008, when the economic downturn slowed order books and led to a major supply glut in the RE industry.

In 2008 stock markets in general dropped sharply, but RE shares fared worse due to the energy price collapse, and the fact that investors shunned stocks with any sort of technology or execution risk, and particularly those with high capital requirements (UNEP and NEF, 2009).

11.2.2.5 Financing Large-Scale RE Projects

Financing RE generating facilities involves a mix of equity investment from the owners and loans from the banks (‘private debt’) or capital markets (‘public debt’ raised through bond offerings). The share of equity and debt in a project typically ranges from 20/80 to 50/50, depending on the project context and the overall market conditions. Both types of finance are combined into the term ‘asset finance’, which represents all forms of financing secured for RE projects.

Asset financing to the RE sector has grown from $6 billion in 2002 ($5.52 billion USD_{2005}) to $97 billion ($106.9 billion USD_{2005}) in 2008, representing a compound annual growth rate of 59 percent (UNEP and NEF, 2009). This rate of growth outstrips actual growth in generating capacity since external investment was not the dominant financing approach early in the millennium when the sector was still being developed and financed in-house by various first mover industry actors.

In recent years capital flows available to RE projects have become more mainstream and have broadened, meaning that the industry has access to a far wider range of financial sources and products than it did around 2004/2005 (UNEP and NEF, 2008). For instance the largest component of total renewable energy capital flows today is through project finance investment (DBCCA, “Investing in Climate Change 2010: A Strategic Asset Allocation Perspective”), an approach that mobilises large flows of private sector investment in infrastructure.

11.2.2.6 Financing Small Scale Technologies

Consumer loans, micro-finance and leasing are some of the instruments that banks offer to households and other end-users to finance the purchase of small scale technologies. However most investment in such systems comes from the end-user themselves, usually through purchases made on a cash basis. Global investment in small and residential RE projects was $20 billion in 2008 (UNEP and NEF, 2008) [TSU: will need to be converted to USD_{2005}], about 17% of total investment in RE projects.

11.2.2.7 Financing Carbon

The mechanisms created through the UNFCCC include a range of instruments used to monetise the GHG offset value of climate mitigation projects. Here they are described as financing carbon, although other GHGs are also involved in this generalisation. Carbon markets include a range of instruments used to monetize the CO_2 offset value of climate mitigation projects. According to the World Bank (World Bank, 2009b), the primary carbon markets associated with actual emission reductions (i.e. the CDM, JI and voluntary transactions) decreased to US$7.2 billion in 2008, down from US$8.2 billion a year earlier. Meanwhile the overall carbon market continued to grow, reaching a total value transacted in 2008 of about US$126 billion, double the 2007 value [TSU: will need to be converted to USD_{2005}].

According to the Risø CDM Pipeline analysis, RE projects now account for the majority of CDM projects, with 60% of all validated and registered CDM projects, 35% of expected Certified Emissions Reductions (CER) by 2012 and 13% of CERs issued to date. The low share of CERs issued is mostly due to the very large industrial gases projects that have been small in number but quick to build, accounting for 75% of CERs issued to date.

The Risoe CDM Pipeline Analysis has also calculated the total underlying investment associated with building the proposed 4,968 carbon mitigation projects that have reached at least the CDM validation stage. Of the $60 billion of total projected investment, $39 billion or 65% is for renewable energy projects [TSU: will need to be converted to USD_{2005}].

11.2.2.8 Refinancing and the Sale of Companies

In 2008, $64 billion ($70.55 billion USD_{2005}) worth of mergers and acquisitions (M&A) took place involving the refinancing and sale of RE companies and projects, up from $6 billion ($5.53 billion USD_{2005}) in 2002 or 48% compound annual growth (UNEP and NEF, 2009). M&A transactions usually involve the sale of generating assets or project pipelines, or of companies that develop or manufacture technologies and services. Increasing M&A activity in the short term is a sign of industry consolidation, as larger companies buy-out smaller less well capitalised competitors. In the longer term, increasing M&A activity provides an indication of the increasing mainstreaming of the sector, as larger entrants prefer to buy their way in rather than developing RE businesses from the ground up.

11.3 Key drivers, opportunities and benefits

There are multiple factors that shape the development of energy policy, including renewable energy. This section sets out some of those other factors, as well as the mitigation potential of RE. Deployment of RE has been driven in great part by government policies, and policies for the deployment of RE are, in turn, driven by several environmental, economic, social and security goals. Drivers are factors that are pushing for the deployment of RE (for example climate change and the need to reduce fossil fuel emissions from the energy sector). Drivers can also take the form of opportunities which, for example, lead a country to invest in RE with the explicit goal of developing a new domestic or export industry. Certain benefits of RE, like for instance reduced emissions, improved health and more jobs may also drive promotion policies. The distinctions among these factors are necessarily close and overlapping. In this section we use the term "driver" to describe drivers in its narrower sense as well as opportunities and benefits. Examples from selected countries are included hear for illustrative reasons.[5]

The relative importance of the drivers, opportunities or benefits varies from country to country and may vary over time, as changing circumstances affect economies, attitudes and public perceptions. RE technologies offer governments the potential to realize multiple policy goals, sometimes simultaneously, that cannot be obtained to the same extent or quality through the development and use of conventional energies (Goldemberg, 2004b).

Key drivers for policies to advance RE are:

- Mitigating climate change
- Enhancing access to energy
- Improving security of energy supply and use
- Decreasing environmental impacts of energy supply
- Decreasing health impacts associated with energy production and use and, a key issue which is both a driver and an opportunity: fostering economic development and job creation.

In general, economic opportunities drive policies in most developing countries, where RE are often the only affordable means for providing energy access. So in terms of share on global population concerned, this driver has been most important. In most developed countries, a driver for the promotion of RE is to reduce environmental impacts of energy supplies and to decrease dependence on energy imports. In terms of RE capacity added globally in the last twenty years, the driver has been most important. In addition, the possibility of developing a new industry with related jobs is seen as an opportunity in some countries. Such motivations are of increasing importance in many emerging and developing economies as well.

11.3.1 Climate change mitigation

RE is a major component for climate change mitigation, its potential being the focus of this report. The degree to which RE mitigates climate change depends on many factors. Policy

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[5] For a comprehensive review of features of RE compared to other energy carriers refer to Chapter 9.

makers have also acknowledged that the use of RE may also increase greenhouse gas emissions in particular cases (see Chapter 10).

As a result, RE is an integral aspect of government strategies for reducing carbon dioxide (and other) emissions in many countries (Burton and Hubacek, 2007; Lipp, 2007), including all member states of the European Union (e.g. (BMU, 2006; European Parliament and of the Council, 2009). Several U.S. states, including California (California Energy Commission and California Public Utilities Commission, 2008) and Washington (CTED, 2009), and numerous U.S. cities, from Chicago (Parzen, 2009) to Miami (City of Miami, 2008), have adopted RE targets and policies to advance their strategies for addressing climate change. Over 1,300 European municipalities have joined the Covenant of Mayors by March 2010 committing them to reduce carbon dioxide emissions beyond the EU objective of 20 % by 2020 with the help of among others the deployment of RE (European Commission, 2010).

Developing countries are also enacting RE policies in order to address climate change, among other goals. The 2009 meeting of Leaders of Pacific Island Countries observed that in addition to RE offering the promise of cost-effective, reliable energy services to rural households it will also provide a contribution to global greenhouse gas mitigation efforts (Pacific Islands Forum, 2009).

11.3.2 Access to energy

This section explores the goal of universal access to energy as a driver of RE technologies. Broader ‘access’ issues for RE technologies, such as access to networks or resources is discussed in Sections 11.4 and 11.6.

Renewable energies have the ability to effectively and quickly provide access to affordable modern energy services, including lighting, communication, and refrigeration, and therefore RE plays an important role in achieving the millennium development goals (Flavin and Aeck, 2005). Distributed RE can avoid the need for costly transport and distribution networks, which can make energy more costly for people in poor, remote communities than it is for urban populations (Flavin and Aeck, 2005). Access to modern, cleaner energy may also reduce indoor air pollution, improving infant and maternal health; it advances education, agriculture and communications; it improves income generation; and it supports hunger eradication (Asian Development Bank, 2007; Asian Development Bank, 2009).

One of the benefits of RE technologies is that the size of the plant can be adapted in response to the energy resource or demand at hand. Moreover the capacity addition of some RE technologies, such as wind energy or photovoltaics, can be in modular form, making it adaptable to increasing demand. Also because of their modularity and flexible size, RE technologies have received increased attention from governments looking to electrify rural and remote areas [Authors: Reference missing]. Another significant benefit of RE is that it often provides the lowest-cost option for remote and off-grid areas (Mahapatra et al. 2009; Pereira et al. 2006)

Programmes to increase the rate of access to energy and based on RE have occurred in many countries. For example, in 1996, the Government of Nepal established the Alternative Energy Promotion Centre for RE technologies in non-electrified areas to improve the well-being of the country’s impoverished rural population [Authors: Reference missing]. Likewise in Nigeria, where two-thirds of the population lives in rural areas, the government’s Renewable Energy Master Plan calls for RE deployment to improve energy services to the poor and thereby advance rural economic development (Energy Commission of Nigeria and United Nations Development Programme, 2005). Other developing countries—including Bolivia (REN21, 2009b), Bangladesh (Urmee, Harries *et al.*, 2009), Brazil (Pereira 2009) China (The Peoples Republic of China, 2005) India (Hiremath, Kumar *et al.*, 2009), Mozambique (Fundo de Energia 2007); Nepal (MEST, 2006), Pakistan (Government of Pakistan, 2006), Tonga, South Africa (Department of Minerals and Energy, 2003), and Zambia (Haanyika, 2008)—have adopted RE policies for providing energy access to rural areas.

Energy access is not just a developing country issue (European Commission, 2006). Low income households in developed countries generally spend substantially higher shares of their income on energy than do higher income households. Policy makers have identified RE as one potential means to ensure affordable energy services to low income households;(Walker, 2008a). Examples of these programmes include the Weatherization Assistance Program in the United States [Authors: Reference missing] and the linking of Carbon Emission Reduction Target to fuel poverty in the UK (DECC, 2009).

Policy makers have also regarded RE, many of which can be used for decentralized systems, as a means to provide independence from central energy supply structures, thus allowing customers more freedom, control and governance on how energy is sourced and systems are managed Examples can be drawn from more than few hundreds micro hydro power plants that are managed, operated by local communities (Chhetri, Pokharel et al., 2009). In this respect, renewable energy technologies empower communities and allow more democratic decisions as opposed to centralised decisions of companies not controlled by public will.

11.3.3 Energy security

The addition of RE technologies to the broad energy mix alters concerns of energy security in different ways. The addition of RE to networks, gas or electricity, introduce new issues to its operation, and this is dealt with in Chapter 8. However, RE power plants may make a power grid more robust against grid failures and break-downs (Sawin and Hughes, 2007) thereby increasing the energy security of that system. Decentralizing energy systems, via RE or other options, can also reduce vulnerability to energy disruptions that might result from damage to infrastructure resulting from natural disaster or attack (Sawin, 2006). Some U.S. states rely on solar power, wind and other distributed generators for public safety and emergency preparedness purposes (Sawin, 2006).

RE can diversify energy supply portfolios. Thereby RE represents a portfolio in itself with different sources tapped. Diversity has a number of energy system benefits (Stirling, 1994) but the use of RE may also displace the need for other fuels. This is particularly valuable for countries that import large amounts of energy, or are particularly dependent on one fuel source or supplier (Lipp, 2007; Chien and Hu, 2008; Katinas, Markevicius *et al.*, 2008; Lee, Mogi *et al.*, 2009) (Hedanus, Azar et al, 2010). For example, China established its 2005 Renewable Energy Law, among others, to diversify energy supplies and safeguard energy security (Standing Committee of the National People's Congress, 2005). Brazil has promoted ethanol from sugarcane as an alternative to fossil transport fuels for thirty years to decrease dependency on imported fuels (Pousa, Santos *et al.*, 2007). The Jamaican Government aims to diversify its energy portfolio by incorporating RE into the mix, reducing reliance on oil (Government of Jamaica, 2006). RE sources are not necessarily domestic as for instance international trade with solid biomass (Ericsson and Nilsson, 2003), with ethanol (Walter, Rosillo-Calle *et al.*, 2008), and prospectively with power from solar energy (Battaglini, Lilliestam *et al.*, 2009) indicates. Thus REs do not necessarily decrease dependency on energy imports in general but they are a means to diversify energy supply in any case.

Even countries that are rich in fossil fuel reserves are recognizing that their fuel production could peak and begin to decline in coming years (Reiche, 2010). As a result, meeting demand for domestic use and/or for export could become increasingly challenging. One of the drivers for Nigeria's Renewable Energy Master Plan is the recognition that its petroleum age will likely end in a few decades. While increased exploitation of gas provides a bridge to a low carbon energy future, renewables loom large in the long-term energy vision for the country (Energy Commission of Nigeria and United Nations Development Programme, 2005).

Fossil fuel imports, which result in large budget and trade deficits for many developing country nations, have undermined their ability to meet the needs for basic services such as education, health care, and clean water (Flavin and Aeck, 2005). In contrast, many governments have regarded RE (particularly biofuels) as a means to enhance national balance of trade by substituting domestic renewable fuels for imported fuels (The National Greenhouse Strategy, 1998; Department of Minerals and Energy, 2003; DTI, 2007; Smitherman, 2009).

Finally, a 2005 study by the U.S. Department of Defense found that RE can provide reliable, flexible and secure electricity supplies for many installations and for perimeter security devices at remote installations, thereby enhancing the military's mission (U.S. Department of Defense, 2005).

11.3.4 Fostering Economic Development and Job Creation

A report by Goldemberg (2004) that compiled the results of several studies found that RE technologies have far greater job creation potential than do fossil fuel or nuclear-based energy systems.[6] The European Union underlines the potential of job creation - especially in rural and isolated areas - in the reasoning for the Directive on the promotion of the use of energy from renewable sources (European Parliament and of the Council, 2009). Manufacturing and operation of RE have led to a total of 157,000 jobs in Germany in 2004, and this number has grown to 280,000 in 2008 (Lehr, Nitsch *et al.*, 2008). Spain has more than 1,000 enterprises in the RE industry, employing 89,000 workers directly and an estimated 99,000 indirectly (Sainz, 2008). An EU modeling exercise found that, conservatively and under existing policies, the RE industries would have about 950,000 direct and indirect full-time jobs by 2010 and 1.4 million by 2020 in the EU-15. These are net numbers that account for projected losses elsewhere in the economy (UNEP, 2008). Developing domestic markets for RE are also seen as a means to attract new industries which may supply international markets in a second step thereby gaining competitive advantages. (Lewis, 2007; Lund, 2008). Policies to promote energy crops have been established to create new income streams for farmers allowing the adaptation of traditional policies to support the agricultural sector.

Similarly, RE development activities are providing significant employment in developing countries, e.g. the Nepalese biogas programme that has installed more than 200,000 individual

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[6] Chapter 9 discusses employment effects in more detail

household biogas plants employs more than11,000 people [Authors: Reference missing]. The South African government recognizes that, since the White Paper on Energy Policy was published in 1998, great strides have been made in empowering historically disadvantaged South Africans by redressing historical racial and gender imbalances in employment through RE [Authors: Reference missing]. And the Energy Research Institute and Chinese Renewable Energy Industries Association estimate that China's RE sector employed nearly one million people in 2007, with most of these in the solar thermal industry (UNEP, 2008).

Deployment and development of RE industries offer significant potential for economic development and job creation. However, the weight of such an assertion is weakened by the absence of an agreed method for calculation of economic development from RE, including the number of jobs created and the number of jobs omitted in other sectors (e.g. (Sastresa, Usón *et al.*, 2009).

Rural development is often tied with the deployment of RE in developing countries. The biogas program, operated by the Nepalese Alternative Energy Promotion Center together with the Dutch development organisation SNV, links the deployment of RE with its socio-economic development program. Digestate, a co-product in the generation of biogas, is widely promoted to boost cash crops and agriculture production. Micro-hydro technology is being used to run transport systems . In much of the world, the development and availability of information and communication devices have prompted companies and communities to develop electricity supply, and the easiest way is often through RE [Authors: Reference is missing]. Biogas systems in Shanxi Province, China, financed by local government subsidies and a local environmental association, have saved households money on fuel wood or coal, electricity, and fertilizer costs. The residue fertilizer has also increased food production, enabling household incomes to rise by as much as 293 USD annually ($302.45 USD$_{2005}$) (Ashden Awards for Sustainable Energy, 2006) referenced in (Droege, 2009)

In the developed and developing world, RE is seen as a means for increasing eco-development or tourism, and for driving economic (re)vitalisation. For example, the Austrian town of Güssing saw up to 400 tourists weekly by the late 2000s, coming to learn from the town's shift to RE. A new hotel, heated and powered by RE, was built to accommodate the influx of tourists (Droege, 2009). The Navarre region in north-eastern Spain has witnessed creation of thousands of jobs and revitalization of many old villages since it began installing wind turbines in the early 1990s. Populations of Iratxeta and Leoz, for example, doubled after the installation of local wind farms (Droege, 2009).

11.3.5 Non-Climate Change Environmental Benefits

The benefits of sustainable RE may include improvements in air and water quality, and reduced impacts of fuel extraction, and energy production and use on biodiversity. For example, recognition of the risks to health, particularly to women and children (Syed, 2008), brought about by poor air quality indoors and out, has led governments to establish a range of initiatives, including policies to advance RE. For example, avoiding negative environmental impacts is a major driver to promote clean energy technologies in China (Standing Committee of the National People's Congress, 2005; Gan and Yu, 2008) ; the government of Pakistan intends to develop RE in order to avoid local environmental and health impacts of unsustainable and inefficient traditional biomass fuels and fossil fuel-powered electricity generation (Government of Pakistan, 2006). The South African government, recognizes that inadequate living conditions and the lack of infrastructure in much of the country means that millions of people are routinely exposed to noxious gases and particulates from fossil fuel burning; thus, the need to improve air quality is a motivating factor in plans to deploy renewable energy technologies(Department of Minerals and Energy, 2003).

There is a growing recognition among scientists and policy makers that the exploitation of energy resources, if not properly controlled and managed, will have harmful impacts on biodiversity of plant and animal species (IPCC, 2002). Growing awareness of this potential of RE technologies has led governments to establish targets, or adopt other policies, to increase RE deployment. For example, the Commonwealth of the Bahamas pays special attention to RE technology as a means to sustain vulnerable ecosystem services (National Energy Policy Committee, 2008). In Nepalese villages, RE systems have been deployed to mitigate negative impacts on biodiversity resulting from the unsustainable use of biomass (Zahnd and Kimber, 2009).

However, policy makers have also recognized that not all RE are necessarily environmental sound and may even have negative impacts on the climate. For this reason, the German government has issued an ordinance on requirements pertaining to sustainable production of bioliquids for electricity production (German Federal Ministry for the Environment, 2009).

11.4 Barriers to RE policy-making and financing

This section focuses on the barriers to putting RE policies in place and barriers to RE financing to enable those policies being implemented. Chapter 1 offers an overview of barriers to RE development and implementation It categorises the barriers as: information and awareness; socio-cultural; technical and structural; economic and institutional and this section follows the same categories. The technical Chapters (2 to 7) cover the technology specific barriers, with Chapter 8 addressing energy system lock-in and RE integration. Barriers to the deployment of sustainable development potentials are discussed in Chapter 9. This final Chapter provides no overview or synthesis of the barriers covered in the preceding chapters.

This section 11.4 describes the barriers to policy-making; Section 11.5 sets out the policies which in large part are designed to overcome various barriers to RE as set out in Chapter 1, not only those related to policy-making. Section11.6 is also written in such a way that the key barriers to RE are matched by a dimension of the enabling environment to further overcome.

11.4.1 Barriers to RE Policy

As highlighted in Chapter 1, the categories of barriers to RE are not entirely unambiguous, and some can be argued to be in more than one category. Bearing this in mind, the central barriers to implementing RE policy are:

11.4.1.1 A Lack of Information and Awareness

- There is limited consensus on how the transitions of the various energy systems in the world would best proceed. Low-carbon energy portfolios may be composed of varying degrees of improved energy efficiency, increased RE supplies, fast-track development of carbon capture and storage at large fossil fuel conversion installations, or a new boost for nuclear power. Assessments of the different portfolios on transparent sets of sustainability criteria are generally lacking (IEA, 2006; IEA, 2008a).

- Many policy-makers lack the required knowledge to, and experience of, pro-actively integrating RE supplies with other low-carbon options (like energy efficiency), with other policy goals (such as poverty alleviation; spatial planning), and across different sectors such as agriculture, housing, education, health, telecommunication, tourism, transportation and industry [Authors: Reference is missing].
- RE technological development is uncertain, dynamic, systemic, and cumulative (Grubler, 1998; Fri, 2003; Foxon and Pearson, 2008). RE sources are local and circumstantial; their inventory and development requires multi-disciplinary expertise (Twiddell and Weir, 2006). Staying informed about the best technical options for local conditions requires time and links to the practitioner and scientific communities.
- Experience of how to enable a comprehensive transition to a sustainable energy system is not available, although there is some understanding of how energy transitions have occurred over the past centuries (Fouquet, 2008). While it is argued by some that a transformation to a low carbon energy system can only emerge from interactions between multiple interest groups covering specific stakeholders, such as individuals and businesses, and also wider institutional and social constituencies (Smith, Stirling *et al.*, 2005; Verbong and Geels, 2007), this is still an absence of evidence of how to do it.

11.4.1.2 Socio-Cultural

Changing energy behaviour is not a simple, nor a mechanical process. While prices, information, education and technological availabilities contribute to changing people's ways of producing and consuming energy, energy behaviours are not dictated by context variables in a mechanical way. This is especially the case for what is called "active" behaviour – the fact of actually changing "ways of doing" with energy, such as adopting a distributed RE technology or switching to a RE electricity supply – as opposed to "passive" behaviours – the fact of subscribing to a campaigning NGO, or supporting a policy to increase the share of RE in the supply mix. This translates into a slow build-up of support for RE, followed by pressure to have RE policies; and then a complex active-passive interaction with the outcomes of those policies.

- Behaviour relates in a complex way to individual values (Stern, Dietz, Abel, Guagnano & Kalof 1999), attitudes (Ajzen 1991), personal norms (Oskamp 2000), social norms (Cialdini 1990) and current ways of living (Sovacool 2009 ; Shove, 2003, 2004). This makes it sometimes difficult to find ways of sustaining a shift from "passive" to "active" behaviours.
- There often remains a gulf between the high levels of "passive" support for RE found in opinion polls [reviewed in Devine-Wright 2005] and the lesser extent of active support for distributed generation and renewable energy (Sauter & Watson 2007; McGowan & Sauter 2005; Bell et al 2005).

11.4.1.3 Technical and Structural

Energy use and supply is a complex, global technical-socio-economic activity (Williamson, 1985; IEA, 2009c). Most energy systems worldwide are still fossil fuel based (IEA, 2009c). Economic regulation of markets and networks with their rules, standards and licenses which maintain the character of those fossil fuel based energy systems occupy a central place. The existing energy system exerts a strong momentum for its own continuation (Hughes, 1987), which Locks-in and locks-out new technologies and ways of doing things (Unruh, 2000) and this leads to the following barriers to policy making:

- the encumbants of a system includes specialised and skilled staff, organizational strength, influential networks, and lobbying power (Hughes, 1986; Hall, 2003).
- Technical, administrative and political codes, procedures and laws constrain the scope, applicable instruments, and time horizon of change via public regulation (Mitchell, 200).
- Regulatory and administrative frameworks set up for non-renewable energy sources do not need to address market failures for RE. For example, split – incentives relate to the lack of incentive for a tenant to improve their rented home or land; or between owners of water rights to install a hydro plant that might benefit a riverside village, despite benefits which the latter may accrue; or between a lack of understanding on the part of policy-makers or officials living in urban areas of the benefits RE may bring rural populations (Beck and Martinot, 2004).
- The current educational and skill base unduly supports incumbent technologies and firms as distinct from potential ones, thereby failing to react quickly enough to the emergence of new generic technologies. This then leads to inadequate workforce skills due to an absence of, or insufficient capacity, for training. This constrains the rate at which RE installations can be constructed, repaired and maintained. It constrains the knowledge on emerging options; it aggravates a low awareness and acceptance by authorities, companies and the public.
- The socio-political aspect of momentum also ensures change is constrained. Apart from an asymmetry of information, regulators, policy-makers and politicians may lack commitment, have their own hidden agendas, or be captured by interest groups and as a result may not optimize ‘social welfare’ (Laffont and Tirole, 1998)

11.4.1.4 Economic

- Discourse and action in the energy world is still based on the concept of “cheap fossil fuels” and “affordable nuclear risks” (IEA, 2006; IEA, 2008b). The external costs and risks of non-sustainable options continue to be insufficiently recognized, identified , quantified and incorporated (Beck and Martinot, 2004, Renewable Energy Technology Development (RETD), 2006). This means that energy markets continue to favour fossil fuels and nuclear power more than they should. While it is widely accepted that the social costs of energy use should be incorporated into the price of energy (Stern, 2006), it is difficult to measure those social costs (Stirling, 1994). Even accounting for the difficulties of appropriate measurement, public energy policies are only modestly moving in the direction of full social cost pricing (Stewart, Kingsbury et al., 2009).
- Well-intended regulations can turn perverse when not carefully designed and operated. Willis et al. (2009) document several barriers for RE under the CDM, for example. RE projects are at a comparative disadvantage in the CDM compared to projects which reduce other types of greenhouse gases (e.g. landfill methane flaring, HFC23 destruction)

because of insufficient regulatory certainty, difficulty in attracting project finance and high transaction costs (Stewart et al, 2009).

11.4.1.5 Institutional

- The building blocks, or enabling environment, of a successful RE policy may not be in place, and it may not be clear to policy-makers of all levels, whether international through to local, what institutions are required to get a policy going; and support to understand their best practice possibilities may be absent (Renewable Energy Technology Development (RETD), 2006) Clear goal setting implies boosting sustainable innovation regimes and operational dialogues with stakeholders (van den Bergh and Bruinsma, 2008); but a planning framework or inter-agency coordination may not exist or be rudimentary (ECLAC, 2009)
- RE project developers face a number of administrative barriers. There can be many authorities involved in deploying RE and a lack of co-ordination between them. A different acceptance of RE benefits between national and local authorities or disagreements on spatial planning rules for accommodating RE installations may lead to a long process for obtaining the necessary permits (OPTRES, 2007).

11.4.2 RE Financing barriers

As we have seen, there are many barriers to RE deployment and policy and market failures to overcoming them. This section focuses on their effect on the availability of financing.

Renewable energies represent a major step-change innovation as compared with existing energy-supply options. In terms of scale, capacity, energy resource characteristics, points of sale for output, status of technology, and a number of other factors, RE technologies are usually markedly different from conventional energy systems. The differences are not lost on financiers, as financing a RE plant is different from financing conventional fossil-fuelled power plants and requires new thinking, new risk-management approaches, and new forms of capital.

To become more effective at placing capital in RE markets, financiers must travel up a learning or experience curve. Market failures impede this learning process and create barriers to entry into the market. To operate effectively, markets rely on timely, appropriate, and truthful information. In perfect markets this information is assumed to be available, but the reality is that energy markets are far from perfect, particularly those like the RE market in technological and structural transition. As a result of insufficient information, underlying project risk tends to be overrated and transaction costs can increase (Sonntag-O'Brien and Usher, 2004).

Compounding this lack of information are the issues of financial structure and scale. RE projects typically have higher capital costs and lower operational costs than conventional fossil-fuel technologies. The external financing requirement is therefore high and must be amortised over the life of the project. This makes exposure to risk a long-term challenge. Support mechanisms like the CDM fail to directly address this barrier “until recently CER purchasers, even where those purchasers are financial institutions, have largely tended to limit their involvement in the project to being an off-taker of CERs, with payment to be made upon delivery, rather than providing project finance or becoming equity participants in the project” (Willis, Wilder *et al.*, 2009).

Since RE projects are typically smaller, the transaction costs are disproportionately high compared with those of conventional infrastructure projects. Any investment requires initial feasibility and due-diligence work and the costs for this work do not vary significantly with project size. As a result, pre-investment costs, including legal and engineering fees, consultants, and permitting costs have a proportionately higher impact on the transaction costs of RE projects. These costs apply as well to the CDM where, according to Willis and Wilder, the transaction costs of developing smaller scale RE projects as CDM projects may be prohibitively high compared to the volume of CERs expected to be generated (Willis, Wilder *et al.*, 2009). Furthermore, the generally smaller nature of RE projects results in lower gross returns, even though the rate of return may be well within market standards of what is considered an attractive investment.

Developers of RE projects are often under-financed and have limited track records. Financiers therefore perceive them as being high risk and are reluctant to provide non- recourse project finance. Lenders wish to see experienced construction contractors, suppliers with proven equipment, and experienced operators. Additional development costs imposed by financiers on under-capitalised developers during due diligence can significantly jeopardise a project.

11.5 Experience with and Assessment of Policy Options

Key Messages of Section 5

Most knowledge about policy mechanisms is to do with Feed-in-Tariffs and Quotas for renewable electricity. Because of this, there is a good understanding of their benefits and difficulties, their costs and their success. Although there are many other options for supporting RE, as set out in Table 11.1, often these options have only been tried in a few places and for a short period of time so there is less clarity about their value, difficulties, success, cost and so forth.

To date only a handful of countries have implemented effective support policies that have accelerated the diffusion of renewable technologies. (IEA, 2008a).

There are many ways to judge the success of renewable energy policy mechanisms. The most usual is via efficiency and effectiveness. Fairly clear and accepted methodologies of how to do this have been developed. There are other ways to assess renewable energy mechanisms, for example increased access to energy; improved health and so on, but there is not necessarily good evidence or information to do this very well.

The diversity of contexts for RE requires a policy designed for a particular place and use, and where possible having learnt from experiences in other contexts. It is therefore not possible to make a general statement such as: a FIT is better than a Quota mechanism, or vice versa. However, it is possible to make more specific statements, for example, that a FIT is better than a Quota mechanism if an energy policy goal is new renewable energy entrants; or a Quota mechanism is better than a FIT if a goal of the policy designers is to know the maximum annual cost of it.

The cost of moving to a sustainable energy system has been quantified in the hundreds of billion of dollars (Chapter 8), including maintenance and upgrades. This is so large that both public and private investment and involvement is required. Well designed policies reduce the risk of investment. These help both the flow of private finance, but also reduce the cost of capital, thereby initiating a virtuous cycle for investment.

Carbon and RE interact in different ways. Carbon policy is not enough on its own to encourage sufficient deployment of RE.

The diversity of contexts requires adapted support policies and mechanisms that however can learn from experiences in other contexts.

RE policies are necessary to effectively and efficiently fulfil the various energy policy and technical integration issues asked of them and discussed in Chapters 1, 8, 9 and 10, including overcoming the large number and variety of economic, technical, social and other barriers as outlined in Chapter 1 and Section 11.4.

The Globe is faced with a different policy challenge with respect to climate change and the need to move to a low carbon energy system. While there have been very many past transitions, none before have been required to occur at a certain rate to meet a scientific outcome (Fouquet and Johansson, 2008). This means well-designed, strategically directed RE policy design is extremely important.

This section explains the available instruments, and their design, that policy makers can select to support RE technologies from their infant stages through to maturity and growth. Early on in a technology's development, R&D support is required. As a technology moves through its development cycle, different types of Government policies (for example, regulatory or fiscal) can be initiated (see Figures 11.5 and 11.6). These policies should, ideally, work together to create a virtuous cycle of support. (see Figure 11.5). Well designed policies should attract more private investment. This should lead to more deployment and cost reduction which in turn should attract more private investment (Hamilton, 2009), which also feeds into the virtuous cycle, whilst also leveraging public money as far as possible.

Section 11.5 provides analysis of policy design and what makes various policies most effective. It covers only those policies specifically targeting RE advancement; a full discussion of other policies required to create an enabling environment is provided in 11.6. Section 11.5.1 introduces the range of policy options available for developing and promoting RE, including government RD&D, and regulatory, fiscal and financial instruments as summarized in Tables 11.1 and 11.2. Section 11.5.2 gives an overview of policies for RE technology development and 11.5.3 discusses issues specific to developing countries. The next three sections examine policies to promote deployment of RE electricity (11.5.4), RE for heating and cooling (11.5.5), and for transportation (11.5.6), respectively. The section is summarised in 11.5.7. All of this occurs within an enabling environment, to a greater or lesser degree. This section has incorporated the policy issues related to financing through the relevant sub-sections of 11.5. 11.5.1 describes general policies for financing – specific policies for electricity, H&C, developing countries are in those sections.

11.5.1 Laying out the Policy Options

This section describes policy options in place around the world. It is possible to categorise and divide these policy in a number of ways (for example, those directly effecting RE price or those effecting RE demand). Our division is set out in Table 11.1 as regulatory, fiscal, public finance (including R&D) and other mechanisms, such as Government (or any other) procurement or green pricing.

Those policies can also be differentiated between those which provide technology push support, which tend to occur at the start of their development, and demand pull policies, which are implemented as the technology becomes nearer competitiveness. An appropriate balance between technology push and demand pull policies for any given technology can lead to a virtuous cycle of reducing costs, increasing investment and increasing demand and deployment (See Figure 11.5). Technology push policies can improve technologies and reduce their costs, attracting investment which can, along with demand pull policies, help introduce them to the market cycle and lead to greater deployment. The demand pull also helps to reduce their costs which in turns makes them more attractive in the market, which increases deployment which allows technology learning to occur, thereby improving the technology. In this virtuous cycle, investors have confidence in the technology, as a result of the earlier R&D, and capital becomes easier to access, leading new companies to enter the market and to increased competition for market shares through additional R&D investment for technological improvement. Designing a series of policies which together enables this virtuous cycle will lead to effective and efficient technology development and deployment. This section shows how this can be done. The general policy options available to policy makers, as set out in Table 11.1, are described. Greater detail about them occurs in the relevant renewable electricity, heating and cooling and transportation sections of 11.5.4, 11.5.5, and 11.5.6.

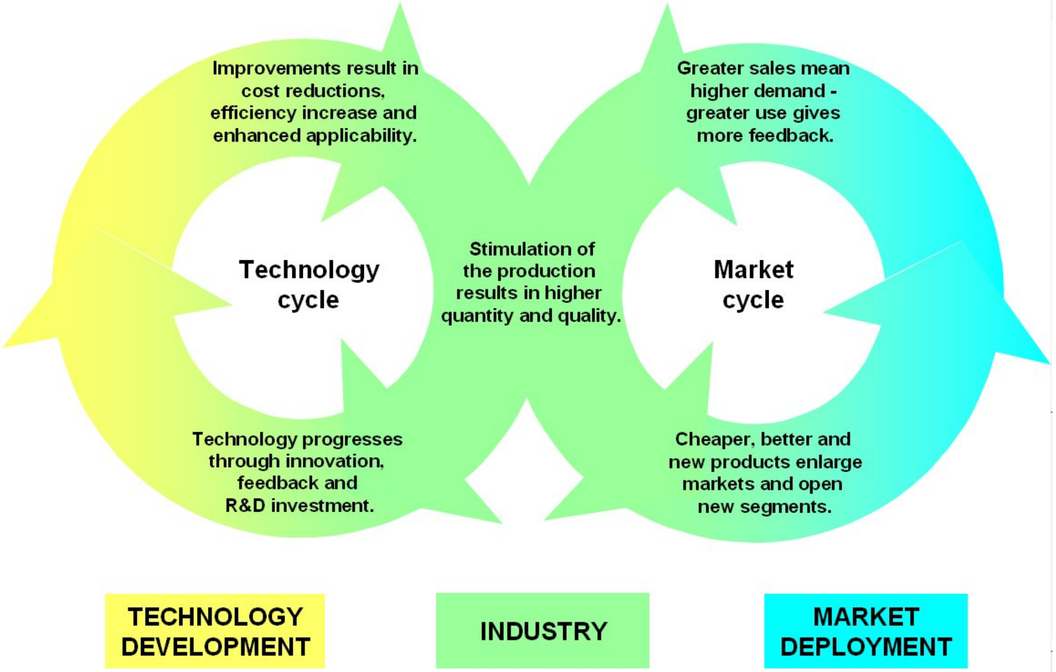

Figure 11.5 The mutually-reinforcing "virtuous cycle" of technology development and market deployment drives technology costs down (IEA, 2003).

11.5.1.1 Policies for Different Targets

RE policies can provide support from the R&D technology area through to payments for installed or available production capacity (heat or power), or generated electricity or produced heat (kWh). Both capacity and generation supplies can be qualified by RE source (type, location, flow or stock character, variability, density), by technology (type, vintage, maturity, scale of the projects), by ownership (households, co-operatives, independent companies, electric utilities), and other attributes that are in some way measurable which allows the amount of support to be made contingent upon it (Jacobsson and Lauber, 2006; Mendonça, 2007; Couture and Gagnon, 2009; Verbruggen and Lauber, 2009)). RE may be weighed by additional qualifiers such as time and reliability of delivery (availability) and other metrics related to RE's integration into networks (Klessmann, Nabe *et al.*, 2008; Langniß, Diekmann *et al.*, 2009).

11.5.1.2 Who enacts Policy?

Several levels of public authorities can be involved in implementing RE policies. International institutes may agree on goals and mechanisms (for example the International Energy Agency); some can enact Directives (for example, the European Commission; others mainly enhance understanding and awareness and distribute information (for example REN21 and IRENA). National Governments can vote laws, assign different policies and adapt, or create, regulations and other enabling environment dimensions (see 11.6). State, provincial or regional, and municipal or local initiatives may provide important support for local policies. In some countries, regulatory agencies and public utilities may be given responsibility for, or on their own initiative, design and implement support mechanisms.

11.5.1.3 Who benefits from Policy?

The direct beneficiaries of the policies are those across the technology development spectrum, although ultimately it is society. Beneficiaries range from scientists through to financing companies (banks, venture capitalists); incumbent energy supply companies owning, for example, grid assets, through to independent power producers such as local companies or public institutions; and industrial and commercial companies through to farmers, households, community-based co-operatives and other social innovations (Kok, Vermeulen *et al.*, 2002; Fouquet and Johansson, 2008).

11.5.1.4 Who pays for Policy?

Payment for technology push type-support tends to come from public budgets (multinational, national, local). Demand-pull mechanisms tend to place the cost on the end-users. For example, the cost of a renewable electricity policy is added to the electricity, although with exemptions or re-allocations for industrial or vulnerable customers where necessary or for equity or other reasons (Jacobsson, Bergek *et al.*, 2009) note that, if the goal is to transform the energy sector over the next several decades, then it is important to minimise costs over this entire period. However it is important to include all costs and benefits to society in that calculation. With this in mind, there is evidence that it may be cheaper to provide significant national investment over a period of perhaps 15 to 20 years – in order to bring renewables rapidly down their learning curves and reduce costs rapidly– rather than to introduce RE relatively slowly, with an associated slower reduction in costs (Fischedick, Nitsch *et al.*, 2002).

11.5.1.5 Description of Policy Options for Deployment and Infrastructure

Policy options available to policy makers can be divided primarily between regulatory, fiscal, public finance and other, as set out in Table 11.1.

- The regulatory policies are described as access based (meaning they are either related to payment for RE once it has accessed the distribution grid, beyond self-generation; or related to rules of connection access to a grid or rules for taking RE generation before other sorts of generation); Quota driven (such as obligations or mandates; Tendering/Bidding, Mandating, Tradable Green Certificates (TGC)); Price driven (Feed-in tariffs, premium or bonus payments); and Quality driven (such as green energy purchasing, green labeling and guarantees of origin).
- The Fiscal policies related to accelerated depreciation, investment grants, subsidies and rebates, energy production payments, production or investment tax credits; reductions in taxes (for example sales tax, VAT and so on)
- Public finance policies relate to grants; equity investments, loans and guarantees; and
- Other policies include public procurement.

The details of these are set out in the end-use sections.

11.5.1.6 The link between policy and finance

Policies, and their design, play an important role in improving the economics of renewable energy systems, and as such can be central to attracting private finance and influencing longer-term investment flows. Stern et al (2009) have proposed that governments have a role to play in reducing the cost of capital and improving access to capital by mitigating the key risks involved, particularly non-commercial risks that cannot be directly controlled by the private sector (Stern, 2009).

Private sector investment decisions are underpinned by an assessment of risk and return. Financiers want to make a return proportional to the risk they undertake, the more risk means a greater return will be expected [Finance Guide, 2009]. Expectations about the level of risk that will be taken, and the returns required varies with different financial institutions across the spectrum (see Figure 11.6). A policy framework to induce investment will need to be designed to reduce risks and enable attractive returns, and be stable over a timeframe relevant to the investment. To be fully effective, or ‘investment grade’, policy needs to cover all of the factors (see Box 11.3) relevant to a particular investment or project (Hamilton, 2009).

Box 11. 3 Investment Grade Policies

General features of investment grade policies include:

- Clearly set objectives: financiers may want to anticipate a policy review or change should progress not be on track. Policy design to achieve the objective may also differ: for example achieving a simple volume increase of renewable energy and seeking a diversity of renewable technologies within the energy mix are likely to require different incentive design.
- Stability across project-relevant time horizon: project finance may cover a 15 year period or greater. The legal or mandatory nature of goals and support mechanisms can foster greater confidence in policy and regulatory stability, together with a clear enforcement or penalty regime.

- Simplicity: complex market systems can increase risk and uncertainty, compared to more straightforward ones.

For a specific project, relevant policy areas include:

- Planning or licensing approval: clarity over average timeframe to move through the planning process and costs involved are directly relevant. Financiers will want to know if experience indicates a long planning period with a track record of objections, or multiple approvals from different agencies, that could delay project start-up (and revenue generation), this could prove unattractive
- Support mechanisms/incentives : a crucial part of making returns attractive; the design of mechanisms including feed-in tariffs will be important, with one international bank describing the design features as ‘transparency, longevity and certainty’ (Deutsche Bank, 2009) review provisions will also be closely scrutinised.
- Policy coherence across any relevant national or international supply chain, e.g. policies that might impact access to biomass feedstock; sustainability, water etc.
- Grid or infrastructure availability, access and costs: projects are unlikely to get financed if there is uncertainty over the availability of underlying infrastructure e.g. for offshore grid for offshore wind projects. The ability to sign a long-term power purchase agreement from a creditworthy off-taker may also be a key part of the financing equation. Infrastructure has implications for sequencing of planning and policy, as well as anticipating new regulatory needs.

A regional policy perspective, beyond national boundaries, may be increasingly relevant for larger scale penetration of renewable energy, with respect to anticipating medium-term rising levels of interconnection, particularly electricity, which could have implications for energy trading, energy pricing and so on. Source (Hamilton, 2009)

11.5.1.7 When public finance is needed

In addition to regulatory and fiscal policies, the provision of public finance can also be needed in some areas. For many renewable energy projects the availability of commercial financing is still severely limited, particularly in developing countries, where the elevated risks and weaker institutional capacities frequently inhibit private sector engagement. The gaps can often only be filled with financial products created through the help of public finance mechanisms (PFM). In addition, public financing can be required also for helping the commercial investment community gain experience with the new types of revenue streams that renewable energy projects provide, such as carbon and green certificate revenues delivered through new regulatory instruments. Without an understanding of these revenue streams, few investors will be willing to provide the up-front finance for these capital intensive projects. Having a public entity co-invest up-front capital in a project can provide the sort of comfort factor that private investors need to enter this space.

The fiscal policies include accelerated depreciation, reduction in sales VAT, energy production payments, production tax credits, capital and investment grants/subsidies and rebates. All of these are intended to make RE more competitive relative to other sources of energy.

Tax credits amount to tax-deductible sums that are calculated as pre-defined fixed amounts or a percentage of total investment in an installation. Investment tax credits focus on initial capital costs, whereas production tax credits address operating production costs. Credits can then be applied against other investments. Tax reductions and exemptions generally cover property, sales and value added tax and act directly on the total payable tax, thereby reducing its magnitude and thus the total cost associated with development (Connor, Bürger *et al.*, 2009b).

11.5.1.8 Other Options

Public procurement of RE and energy efficiency technologies is a frequently cited but not often utilized mechanism to reduce the long-term costs of purchased fossil fuel while stimulating the market for RE systems. The potential of this mechanism is significant: in many nations state and federal energy purchases are the largest components of public expenditures, and in many nations the state is the largest consumer of energy (IEA, 2009b).

11.5.2 Policies for Tech. Development

Key Section Messages

The costs of the transition to a low carbon economy are so large, that Governments are aiming to leverage their funding as far as possible with private collaboration and investment across the technology development spectrum

Policy measures in the RD&D sphere are becoming more collaborative and innovative as they seek new means of tapping into potential financiers, investors and innovators.

The amount of funding is not the only important factor – achieving an appropriate balance between R&D and deployment funding can accelerate 'learning' as can supporting efforts for 'bricolage' (or the steady progression of small scale learning which sum up to large scale innovation) rather than 'breakthrough' (i.e. focusing on large scale innovation)

Specific policies in support of renewable energy are required from the early stages of technology development through to when they become commercially mature. An important Government role is to fill in the 'gaps' in this continuum where support for technology development is lacking, while at the same time encouraging input (i.e. financial /in-kind support) from other sectors where possible. (Smith, Stirling *et al.*, 2005, IEA, 2008) (Stirling, 2009). A technology in the early and mid-stages of commercialization can enter a virtuous cycle of development, discussed above, as a result of the interaction of appropriate technology push and demand pull policies and enabling inputs, as set out in Figure 11.6 below.

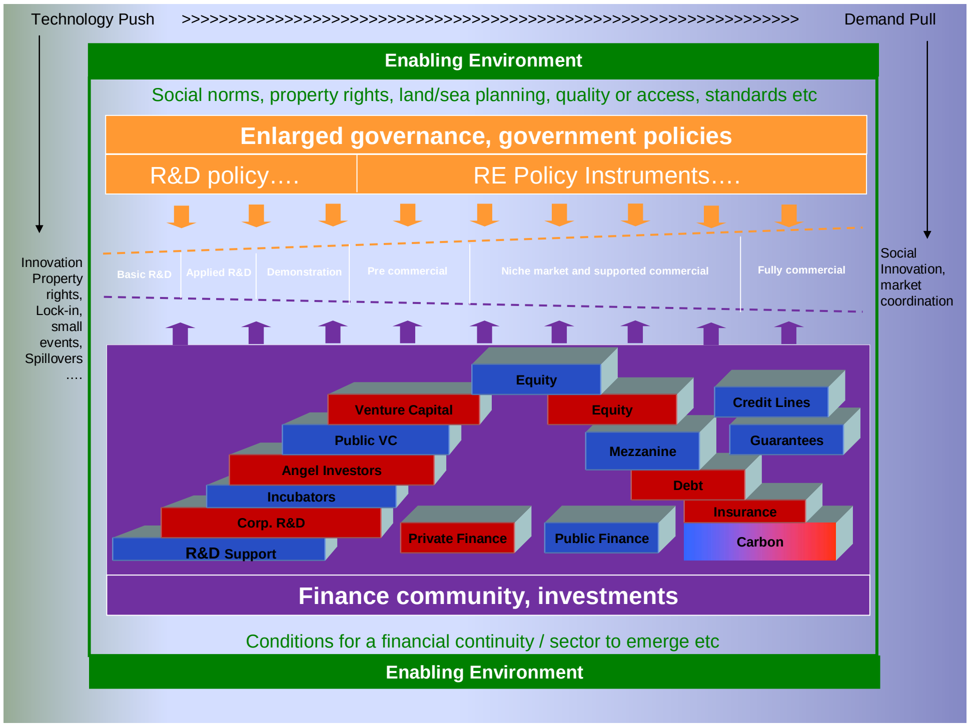

Figure 11.6 Enabling Inputs for Technology Development

Successful outcomes from R&D programmes are not necessarily related to the total amount of funding. Karnoe, 1990, compared the U.S. and Danish wind energy R&D programmes and found that, while the United States had invested 10 times as much in funding, they were less successful in turbine development because the United States had focused on scale and other factors rather than reliability (Sawin, 2001, Karnoe, 1990). In another paper, Garud and Karnoe 2003 (Garud and Karnøe, 2003) argue that 'bricolage not breakthrough' is the more successful approach to R&D policy. If a Government focuses on 'big' breakthroughs it tends to miss the small innovative additions to learning, which together gradually builds up to large scale innovation. Garud and Karnoe use the term bricolage 'to connote resourcefulness and improvisation on the part of the involved actors. Bricolage was characterised by co-shaping of the emerging technological paths as actors in Denmark sought modest yet steady gains. In contrast, actors in the US pursued a path Garud and Karnoe label as 'breakthrough' a term they use to evoke an image of actors attempting to generate dramatic outcomes. Successful technology development occuring via the bricolage, rather than the breakthrough, approach, is supported by detailed studies of RE technology development in Europe (Jacobsson and Johnson, 2000) but also the Japanese and Thai Case Studies (see boxes 11.4 and 11.8).

As Figure 11.6 above shows, technology development and deployment covers a broad range of policies, inputs and financing investments – both public and private. This spectrum of inputs should be available for RE technologies during their development. The timing of R&D policies, and their balance with other deployment policies, is also important (Langniß and Neij, 2004; Neij, 2008). R&D is best in the early phases of maturity, with deployment policies in the later phases. However, relatively early deployment policies in a technologies development accelerates learning, whether learning through R&D or learning through utilization (as a result of manufacture) and cost reduction. (Neij, 2008). Disentangling the contribution of public R&D

spending and economies of scale from cost reduction is difficult, especially since the commercialization of the technology stimulates private sector investment in R&D (Schaeffer, Alsema *et al.*, 2004).

Figure 11.6 above shows where investment – whether public or private – tends to be available in the technology development process. As with any new technology, RE technologies at some point area likely to traverse what has become known as the 'Valley of Death'. In this phase, development costs increase but the risk associated with the technology are not reduced enough to entice private investors to take on the financing burden (Murphy and Edwards, 2003). Continued support from governments is necessary in this phase (House of Commons - Innovation, 2008). In the United States and Europe, public-private partnerships for demonstration (where industry-led projects demonstrate new technologies with government co-funding) are increasingly viewed as one appropriate vehicle to vault this valley (Strategic Energy Technology Plan, 2007; House of Commons - Innovation, 2008; U.S. Department of Energy, 2009).

Governments should focus on 'smart subsidy' style policies that do not create dependence, i.e. a tendency to remain in a research slump that keeps technologies at the R&D and first demonstration stages rather than moving them on to deployment, Smart subsidies attempt to grow a new technology area, while minimizing long-term market distortions. They are meant to lead technology innovators toward commercialization and help attract early and later risk capital investment that otherwise would not be available because investors see high risk and protracted investment horizons. Grant-support models that are linked to performance can allow developers to build a track record, which developers who receive only traditional up-front grants cannot. It is also crucial that grant support remain as consistent as possible to avoid increased risk aversion in the event of public-funding cuts. At the same time, R&D subsidies remain "smart" when they have an 'exit-strategy' as the technology reaches pre-commercialization that will leave a functioning and sustainable sector in place upon their removal (ICCEPT, 2003).

Policy measures in the RD&D sphere are becoming more collaborative and innovative as they seek new means of tapping into potential financiers, investors and innovators. This encourages 'buy-in' from partners as early as possible in the technology development spectrum, and uses public money as efficiently and effectively as possible. This collaboration may be:

- **all public collaborations** (i.e. international centres of excellence);
- **or it may involve public private partnerships in research**, for example:
    - co-funded research has the benefit of creating direct research networking among different sectors (academy, industry), disciplines or locations. Research networks have the opportunity to draft joint action plans in order to meet short-, medium- and long-term goals for the performance and cost of their technology (IEA, 2008a). Governments can then scrutinize and adopt these plans. Road mapping is one example of collaborative R&D which has been outlined in Japan for photovoltaic technology, and in the European region (Strategic Energy Technology Plan, 2007; NEDO, 2009).
    - 'Open innovation' is a way for companies to acquire intellectual property by jointly contracting with one or more public R&D centres, while endorsing both the costs and benefits associated with the innovation. It is currently developed for silicon PV cells

in Belgium and the Indian government wants to explore a similar scheme (IMEC, 2009a; IMEC, 2009b; JNNSM, 2009).

- **or by Government or non-Government stimulation.** Prizes are sometimes used to foster technology development. For example, by late 2009, ten prizes of more than $1m ($1.1m USD$_{2005}$ [deflated using the 2008 factor] existed in the United States (Next Prize, 2009); In December 2008, the Scottish Government launched the 10 million Pound ($20.38 millionUSD$_{2005}$) ‘Saltire’ Prize for advances in wave and tidal energy (Scottish Government, 2008). Competing for a prize places the R&D risk on the shoulders of the competitors, but it gives them freedom in the way they approach innovation and is sometimes an easier process than applying for public grants (contracting, reporting, control) (Peretz and Acs, 2010).

Besides R&D support, public funding is also needed to help move technology innovations through the product development stages towards commercialization. This phase is often characterized by high-cost activities such as initial and secondary prototype development and testing, site development, supply chain formulation, construction, and grid interconnection. To convince investors, developers must prove that their technology will be able to perform in real-market conditions and be commercially viable (UNEP, 2005).

To lead technology innovation towards the market and to engage commercial investment in the RE sector, governments are starting to implement a range of new financing mechanisms capitalized by public sources. These include technology and business incubators, contingent grants, convertible loans and public-backed venture capital.

Technology incubators can assist developers in covering operating costs, provide advice on business development and raising capital, help to create and mentor management teams, and provide energy-related market research. An example is the UK Carbon Trust Incubator Programme, which furnishes an important stepping-stone to commercialization for new sustainable energy and “low carbon” technologies (UNEP, 2005).

Contingent grants are grants that are ’loaned’ without interest or repayment requirements until technologies and intellectual property have been successfully exploited. They can serve to cover some of the costs during the highest-risk development stages and in some cases increase investor confidence and, in so doing, leverage highly needed risk capital.

Commercial bank loans are rarely accessible at the pre-commercial stage however some public agencies have been providing soft and convertible loans at this early phase of development. The Massachusetts Sustainable Energy Economic Development (SEED) Initiative, for example, provides loans from $50,000 to $500,000 for clean energy companies undergoing new product development [TSU: will need to be converted to USD$_{2005}$]. The state of Connecticut offers a range of financing instruments to promote and commercialize RE technologies through the Connecticut Clean Energy Fund (CCEF). One of their financing schemes combines grant support for demonstration projects with a soft loan that is repayable if the technology reaches commercialization.

Various government agencies have been experimenting with venture capital mechanisms as part of their overall industrial and economic development policy aimed at turning promising research into new products and services (SEF Alliance, 2008). Publicly driven venture capital funds have emerged in the United States, Australia and the UK. In most cases public sector VC is either invested independently or requires a matching commitment from commercial VC investors.

Box 11.4 Japan and PV: Coupling Technology Push with Market Pull

Japan first turned to RE in the 1970s, in search of energy security and stable supply after the first oil shock seriously weakened the nation's economy [ref: (Sugiyama, 2008)]. Starting in 1974, MITI (Japan's Ministry of International Trade and Industry) launched the "Sunshine Project", which aimed to achieve technological breakthrough with new energy technologies, and significant funds were directed to PV R&D (MEXT, 1978).

MITI worked to link this project to Japan's industrial development. Although the primary goal was development of solar energy technologies, especially PV, MITI expected that technological advances could have far reaching benefits beyond the energy field. In addition to providing electric power on a large scale, it was hoped that PV technologies would lead to new international markets for solar calculators and other appliances, taking the value created from the national investment in R&D beyond the objective to improve energy security through realization of a domestic supply of energy. [Authors: Reference is missing]

The investment paid off with the global increase in demand for electronic appliances and the expansion of a semiconductor market for computer "chips". By 1990, when MITI established an R&D consortium for PV development (Photovoltaic Power Generation Technology Research Association), electronic machinery companies like Sanyo and Sharp were the major players [ref: (Watanabe, 2000)].

By 1992, the "Sunshine Project" had demonstrated that PV could provide an alternative energy supply. In 1993, the purpose of RE advancement expanded to encompass sustainable development and environmental objectives including CO_2 reductions, and Japan transitioned to the "New Sunshine Project." Parallel to its R&D efforts, Japan established targets for PV deployment and initiated a gradually-declining subsidy for residential rooftop PV systems, in exchange for operational data, with the goal of driving down PV costs through economies of scale and commercial competition among manufacturers. To create market awareness, the government began promoting PV through a variety of avenues, including television and newspapers (IEA, 2003).

The result was a dramatic increase in installed capacity and accompanying reduction in PV costs. Japan rose from a minor player to become the world's largest PV producer in less than a decade. Over the 1994-2004 period, system costs declined by one third, from 2000 yen/kW ($18.0 USD$_{2005}$) in 1994 to 660yen/kW (6.0 USD$_{2005}$) in 2004 [Authors: Reference is missing]. (See Figure 11.7). Although market growth slowed when the subsidy program ended in 2005, the momentum of PV as viable power source had been proven.

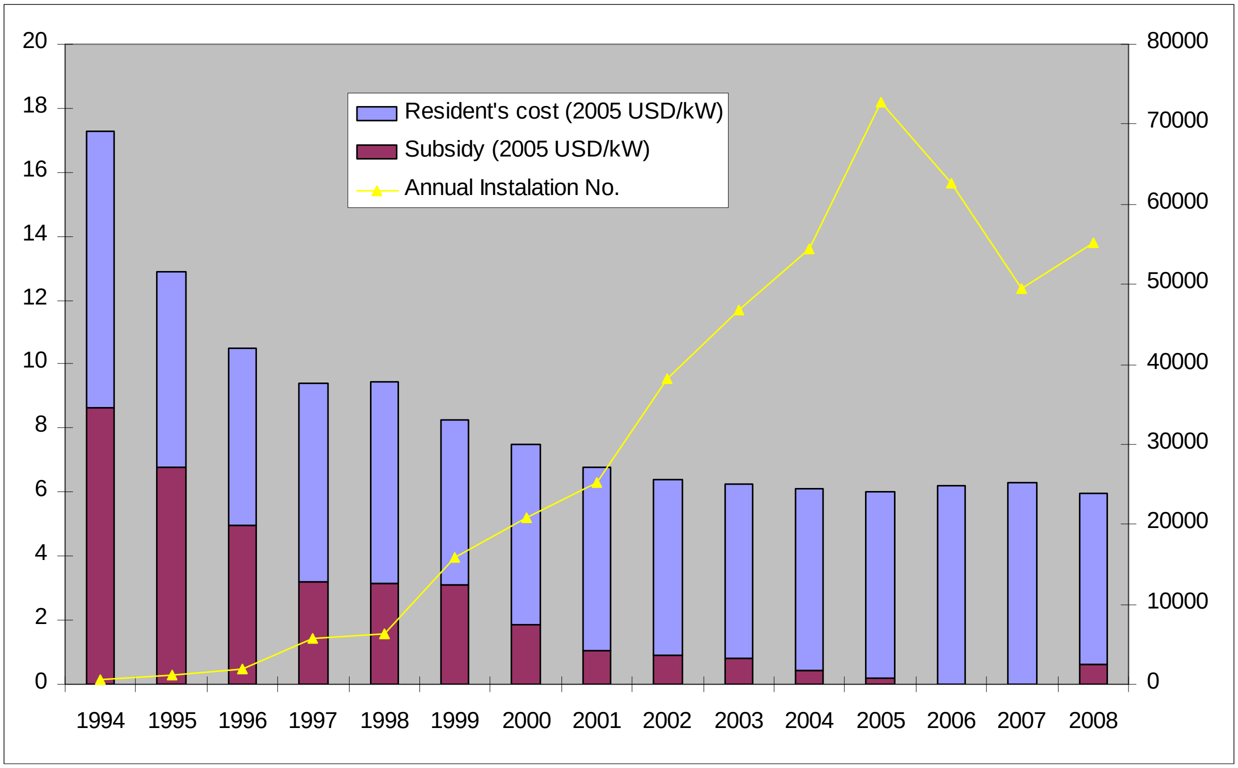

Figure 11.7 Annual costs, subsidies and numbers of rooftop PV in Japan (Ito, 2003; Kobayashi, 2003; NEPC, 2009)

In 2009, in the midst of a global recession, Japan's PV industry found further cause to support PV deployment—for the purpose of job creation and increased competitiveness in the international marketplace. The government introduced a buy back system for residential rooftop PV (residential producers can sell excess power to the utility company at the retail rate). The purpose is to further accelerate the introduction of PV and provide an incentive for customers to minimize their own use in order to sell as much as possible to their utility (METI, 2009).

For most of the past three decades, Japan enacted effective and consistent policies to promote PV and retained them even through major budget crises. It's experience demonstrates the importance of long-term targets and planning, the potential to link RE development to other applications and industries, as well as the virtuous cycle of declining costs, technology advances and increasing deployment that result from coupling technology push (R&D) with policies to create a market.

11.5.3 Developing Country Off-grid and Rural Issues

Many of the issues related to RE development are the same for developed and developing countries. There are several challenges for investors in RE in developing countries – just as there are in developed countries – and these are discussed in more detail in 11.5.4, 11.5.5 and 11.5.6. There have been several reviews of the importance of RE policies for developing countries, for example from the World Bank (World Bank, 2009a); their successes and difficulties (Parthan, Osterkorn *et al.*, 2010). These reviews reinforce the central role that national policy plays. There is no 'one size fits all' (Hamilton, 2009). The overall policy environment needs to provide enough confidence for investors.

There are a number of case studies relevant to developing countries: a case study on China, which is an example of a developing country which combines high tech manufacturing of RE; the largest deployer of RE in the globe of both large scale and small scale. It also provides an example of Kenya, and the very particular situation there which enabled RE success without policy support. Section 11.5.4 provides a case study of the FIT policies in Thailand; 11.5.6 provides a case study of Brazil; and biofuels section 11.6 provides a case study of capacity building in Box 11.15 Nepal. All these case studies illuminate the very diverse situation.

However, the rest of the section focuses on off-grid and rural issues – given the specific differences of requirements from developed countries.

11.5.3.1 Off-grid and rural RE policies in developing countries

About 1.5 billion people in developing countries lack access to electricity and about 3 billion people rely on solid fuels for cooking (UNDP and WHO, 2009). Indoor air pollution from biomass burning affects more than 2.4 billion people; 99 percent of the two million deaths annually due to in-door air pollution (primarily due to cooking with biomass) occur in developing countries (UNDP & WHO, 2009). Access to energy is of paramount importance as it increases living standards of rural populations, providing essential goods and services (Thiam, 2010). RE enhances access to reliable, affordable clean energy to meet basic needs, especially through small scale decentralized systems renewable, and it allows for industries, production and transport to leapfrog and avoid dependence on fossil fuels (Deutsche Bank, 2009).

This large population of people awaiting modern energy services cannot be served “unless new approaches are developed and put into action” (Zahnd and Kimber, 2009); New approaches include policies and implementation modalities to promote RE. Barriers include geographical disparity, which causes variation in transportation especially in remote hills and mountains; and lack of infrastructure which causes price variation in energy supply systems.

11.5.3.2 Successful examples

Smart subsidies such as those in Nepal (Renewable Energy Subsidy Policy 2009, Govt of Nepal) and in India have helped to overcome barriers to RE deployment. In Nepal, by 2009, more than 200,000 rural families were using domestic biogas technology for cooking (Pokharel, Mitchell *et al.*, 2010). By early 2009, in India, a cumulative total of 4250 villages and 1160 hamlets had been electrified using RE (REN21, 2009b). Contrary to that Nepal has managed to install more than 150, 000 domestic biogas plants from *ad-hoc* support mechanisms before a national rural (renewable) energy policy promulgated in 2006(Pokharel, Mitchell *et al.*, 2010). In Bangladesh to more than 100,000 solar home systems were promoted before a national level renewable energy policy was promulgated in 2008 (Pokharel, Munankami *et al.*, 2007).

Table 11.3 Financing of Small Scale RE sources in Various Developing Companies.

Country	**Investment Cost in US$ for 6 m3 biogas digester**	**Subsidy in US$**	**% of upfront investment contribution by users**	**% of GDP in 2009**
Bangladesh	346.17	142.21	58.9%	
Cambodia	551.23	165.37	70.0%	
Indonesia	661.48	220.49	66.7%	
Nepal	657.07	195.13	70.3%	
Pakistan	471.85	98.11	79.2%	
Vietnam	347.27	69.45	80.0%	

Source: compiled from SNV (2009) [figures deflated using 2008 factor]

As of 2000, Argentina's government offered concessions through which the winning company gained a monopoly in a given region, and the government provided grants to cover lifecycle costs, subsidizing rural household electricity consumption up to only a minimum level in order to keep costs down and target only those truly in need of assistance (Reiche, Covarrubias *et al.*, 2000). Benefits of this system included creation of a large market which provided a critical mass for commercially sustainable businesses and to reduce unit costs through economies of scale (for equipment, transactions, operation and maintenance). In addition, it has appealed to large companies that have their own sources of funding. This system has been duplicated in a number of other developing countries, including Benin, Cape Verde, South Africa and Togo (Reiche, Covarrubias *et al.*, 2000; Osafo and Martinot, 2003).

In both the Philippines and Bangladesh, there are networks of consumer-owned and -managed cooperatives that receive financial incentives in exchange for meeting annual performance targets and providing electricity to members and the local community. As of 2003, results in both countries were mixed (Osafo and Martinot, 2003).

11.5.3.3 Enabling Policies for Rural and Off-grid Electrification

For many low income developing countries, simply channelling a subsidy to rural areas is not enough. This is due to immature markets and a lack of capacity, and a weak and fragmented supply chain (see Box 11.15). Even demand for RE needs to be generated with awareness and sensitivity because illiterate people cannot realize the advantages of RE, lack information on technology and its accessibility as well as availability (see Box 11.15). It is also important for policies to encourage private sector investment. To account for this, the Rural Energy Policy 2006 of Nepal emphasises the need for public-private partnerships to promote RE in rural areas. Bangladesh, too, has adopted an RE policy that aims to mobilize internal as well as external resources for investment to achieve its RE. The *Bhutanese* Government has a comprehensive policy that promotes public-private partnerships in addition to long-term direction that aims to ensure energy security through diversification of supply mix and demand-side management.

While developing policy to enhance access to energy some issues like pro-poor orientation, regional balanced, and social inclusion are given due consideration (e.g. Sunsidy policy of Nepalese and Indian government). Increased emphasis for linkages with micro credit and other rural development activities are also focused policy in Bangladesh and Nepal. Although energy access through REs are subsidy driven, policies are formulated envisaging the assurance of enhanced commercialisation and sustainability of the sector.

Developing countries have multiple tasks of development, so more integrated renewable policies emphasising on energy access, rural and regional development, betterment of health and education sector and promoting better environment, employment and industrial sector development should be promulgated.

Box 11.5 Building the Solar Energy Market in Kenya through Product Quality

Kenya is home to one of the largest and most dynamic per capita solar PV markets among developing countries. Cumulative sales since the mid-1980s are estimated to be in excess of 300,000 systems, and annual sales growth has regularly topped 15% since 2000 (Acker and Kammen, 1996; Jacobson and Kammen, 2007). Household systems account for an estimated 75 percent of solar equipment sales in Kenya. This unsubsidized market arose to meet demand for reliable power in rural areas through relatively low-cost and dependable solar home systems. Solar is the largest source of new electrical connections in rural Kenya and, starting in about 2000 also began spreading to neighbouring countries (Jacobson and Kammen, 2007).

Despite this commercial success, product quality threatened to derail the market in the 1990s, when reports began to emerge about problems with low-quality amorphous silicon (a-Si) modules, which were indistinguishable from high-quality modules (Duke, Graham *et al.*, 2000; Hankins, 2000; Duke, Jacobson *et al.*, 2002). It was not clear initially if this performance gap related to inherent properties of the solar technology (Staebler and Wronski, 1977) or to issues in the manufacturing and/or field performance (Duke, Graham *et al.*, 2000; Hankins, 2000; Duke, Jacobson *et al.*, 2002; Faiman, Bukobza *et al.*, 2003). Advertisements in local newspapers sparked a heated debate about quality, consumer rights, and the ethics of negative advertising.

In 1999, a set of private studies on the performance of the solar modules for sale in Kenya indicated clearly which brands were performing well, and which were not (Jacobson, Duke *et al.*, 2000). This information – disseminated widely and publicly– had a major impact on the industry, inducing manufacturers to improve product quality. As a result, the market resumed rapid growth (Jacobson and Kammen, 2007).

Several years after the 1999 study, a new line of low performing a-Si modules began to enter the market in significant quantities. The approach to weeding out these panels was a close repeat of the earlier episode (Duke, Jacobson *et al.*, 2002). Re-emergence of quality problems in the Kenya market confirmed that the issue could not be solved decisively by one time testing efforts, or by focusing on the improvement of individual low performing brands. Rather, institutional solutions that persistently require high performance for all brands are needed to ensure quality.

As a result of these events, the Kenya Bureau of Standards (Kenya Bureau of Standards, 2003) collaborated with the Kenya Renewable Energy Association to draft performance standards for a range of solar products, including a-Si modules. The government drafted and adopted new standards, drawing heavily from codes established by the International Electrotechnical Commission (IEC, 2001).

However, because the KBS lacked access to the necessary equipment and technical capacity to carry out all specified tests, continued involvement of local solar groups and international academic teams was critical to communication, and at times enforcement, of the Kenyan national solar standards. Thus, while the move to adopt national performance standards represented a positive step towards an institutionalized approach to quality assurance, the adoption of un-enforced standards requires continued vigilance and partnerships among research and testing groups, the solar industry, and the government.

This Kenya solar story makes clear that an ‘enabling environment’ for a clean energy technology can evolve during or even after the market begins to expand. Further, there is often a need for continued assessment and analysis to build what initially can be fragile RE markets, and science and engineering inputs can be critical at many stages of the evolution of a RE system and market. At present the Kenyan solar market has, with some ups and downs, continued to expand; as of 2007 over 35,000 new systems were sold annually in Kenya (Jacobson and Kammen, 2007).

11.5.3.4 Financing for Off Grid and Rural RE in Developing Countries

Various policies exist to mobilize the different forms of financing required for RE deployment, and there are covered earlier in 11.5. In addition to policy mechanisms, the provision of public finance can also be required because financing for RE continues to be a challenge in most regions of the world. For many projects, the availability of commercial financing is limited, particularly in developing countries, where elevated risks (geopolitical, economic and regulatory) and weaker institutional capacities inhibit private sector engagement. Risk is a critical obstacle to the flow of future revenue streams for financing the deployment of new technologies (UKERC, 2007). In developed countries, governments can play a role in reducing the cost of capital and improving access to capital by mitigating the key risks, particularly non-commercial risks that cannot be directly controlled by the private sector (Stern, 2009). In the developing world, stronger intervention may be necessary to unlock private-sector investment in new technologies (UNEP Finance Initiative, 2009). As in the developed world, a stable national regulatory regime can reduce the risk of investments in new technologies. But given the budgetary constraints facing most developing country governments, additional funding—including direct public financing of projects—may be necessary to underwrite the costs of low-carbon policy frameworks.

This lack of appropriate financing mechanisms available to end-users in developing countries is a barrier for financing (Derrick, 1998). Although several micro financing institutions are working in rural areas of developing countries (i.e. Bangladesh, Cambodia, Nepal), interest rates are high. Where such end-users financing is not available people are more likely go toward low quality cheaper RE products. Financing mechanism which enhance consumers’ ability to pay for renewable-generated services have been instrumental in many institutions in increasing the up-take of RE (Renewable 2004). There are some end users financing mechanisms in place in developing countries, for example: a revolving fund, credit cooperatives, renting schemes, utility schemes/leasing and hire purchase (Derrick, 1998)

According to Policy recommendation of Bonn Conference (Goldemberg, 2004a), financing strategies for renewable should address the financing needs of both suppliers/vendors and different categories of end-user consumers in a balanced manner. Any financing policies or mechanism targeting mainly rural areas of developing countries need to create renewable energy markets where individual households, small businesses and local communities can play a greater role in financing. Small scale and decentralized renewable energy systems in developing countries are normally financed with subsidies from the government, end-users contribution either in cash or kind (Pokharel, Mitchell *et al.*, 2010). Community or local villagers will invest their labor, time, and other social capitals in the renewable energy systems (Pokharel, Chhetri *et al.*, 2008). Micro-credits are also helping to mobilize the upfront investment from the users and based on technology users some time can also contribute own labour and local materials.

Box 11.6 Rural Electrification and Large-Scale RE in China

China has relied increasingly on RE to help meet rising energy demand, improve its energy structure, reduce environmental pollution, stimulate economic growth and create jobs (Zhang, Ruoshui *et al.*, 2009). During 2009, China installed more wind power capacity than any other country and, by the end of the year, ranked first globally for RE capacity and third for non-hydro RE (REN21, 2010). A strong domestic manufacturing industry for wind power, photovoltaics and solar thermal collectors has emerged, triggered in part by special promotion policies (Han, Mol *et al.*, 2010; Liu, Wanga *et al.*, 2010; Wang, 2010).

The Chinese government has devoted significant attention to RE development in recent decades. China began developing wind power in the early 1970s for the primary purpose of supplying power to remote areas (Changliang and Zhanfeng, 2009). Grid-connected wind power started in the 1980s with small-scale demonstration projects and evolved to a main source of power supply by 2003, when the Wind Farm Concession Program was established (Wang, 2010). Solar water heaters have been promoted since the 1970s (Han, Mol *et al.*, 2010), and biogas digesters since the 1980s (Peidong, Yanli *et al.*, 2009). Under the Township Electrification Programme, more than 1,000 townships in nine western provinces were electrified in just 20 months, bringing power to almost one million rural Chinese (National Renewable Energy Laboratory (NREL), 2004). Important to the success of China's rural electrification efforts have been education of local and national decision-makers, training and capacity building, technical and implementation standards, and community access to revolving credit (Wallace, Jingming *et al.*, 1998; National Renewable Energy Laboratory (NREL), 2004; Ku, Baring-Gould *et al.*, 2005).

In 2005, China issued the Renewable Energy Law, which institutionalized a number of support policies including mandatory grid connection standards, renewable energy planning, and promotion funding (Zhang, Ruoshui *et al.*, 2009). It was followed in 2006 and 2007 by specific regulations and measures supporting development of wind, solar, and biomass sources. The Medium and Long-term Renewable Energy Development Plan, released in 2007, set a national target for RE to meet 10 percent of total energy consumption by 2010 and 15 percent by 2020 (Wang, 2010). The 30 GW wind power target for 2020, as specified by The 11th Five Year Plan for Renewable Energy in 2008, was achieved a decade ahead of schedule (Wang 2010).

China continues to address challenges as they arise by developing and revising RE policies and measures, including: enhancing technical skills; establishing institutions to support R&D development and a national RE research institute; extending electricity transmission to ensure that new RE capacity can be effectively brought online; creating a domestic market to stimulate demand and avoid over-reliance on overseas markets; and establishing a national RE industry association to coordinate development and formally bridge the industry and policymaking processes (Martinot and Junfeng, 2007; REN21, 2009a).

11.5.4 Policies for Deployment - Electricity

To date, far more policies have been enacted to promote RE for electricity generation than for heating and cooling or transportation, and this is reflected in the vast literature available regarding RE electricity policy mechanisms. By the beginning of 2009, at least 64 countries had some sort of mechanism in place to promote renewable power generation (REN21, 2009b). As described in 11.5.1 above, we have divided RE policies into regulatory, fiscal, public finance and other. The two main regulatory mechanisms are the ‘Feed-in tariffs’ - which guarantee a price - and ‘quotas’ or RPS (Renewable Portfolio Standards) which ensure a quantity or market share through government-mandated targets, quotas or mandates. This section analyses and compares these 2 mechanisms before moving on to ‘net metering, another less widely used regulatory policy, and then public financing mechanisms

11.5.4.1 Regulatory Policies

Feed-in Tariff (FIT)

The most prevalent national policy for promoting renewable electricity is the FIT (REN21, 2009b), also known as Feed Laws, Standard Offer Contracts, Minimum Price Payments, Renewable Energy Payments, and Advanced Renewable Tariffs (Couture and Gagnon, 2009), and is an over-arching term for price driven support. FITs can be divided between those where the Government sets a fixed price which is independent of electricity market prices and those that are linked to electricity market prices but paid a fixed premium price, also set by the Government. All FITs have different impacts on investor certainty and payment, ratepayer payments, the speed of deployment, and transparency and complexity of the system (Couture, 2009).

FITs have driven dramatic renewable electric capacity growth in several countries—most notably Germany and Spain—over the past 15 years (see Boxes 11.2 and 11.7) and have spread rapidly across Europe and around the world (see Box11.8) (REN21, 2006; Mendonça, 2007; Rickerson, Sawin et al., 2007; Girardet and Mendonca, 2009; REN21, 2009b). Although they have not succeeded in every country that has enacted them, those countries with the most significant market growth and the strongest domestic industries have had FIT policies in place (Sawin, 2004a; Mendonça, 2007). The IEA argues that the key for countries like Germany, Spain and Denmark has been high investment security coupled with low administrative and regulatory barriers (IEA, 2008b).

Box 11.7 Case study: Photovoltaics in Spain

Spain’s experience with solar PV promotion is a clear case of learning by doing. To provide a predictable and transparent framework to attract private investments, the Spanish government enacted a feed-in tariff in 1998 and published indicative 2010 targets for installed capacity in the Plan to Promote Renewable Energies 2000-2010 (MIyE (Ministerio de industria y Energía), 1998; IDAE, 2009).

Due to the immaturity of the market, initially the FIT was not enough to develop the PV sector and, in 2001, a combination of investment subsidies and low-interest loans were established. They remained in place until 2005, and total direct subsidies to PVs during the period amounted to 64.6 USD_{2005} (IDAE, 2009).

The FIT was revised in April 2004 (ME (Ministerio de Economía), 2004) and again in May 2007 (MITyC (Ministerio de Industria Turismo y Comercio), 2007). In addition to raising the tariff for PV, both acts increased the maximum capacity of projects that could receive the high tariff (to 10 MW from May 2007). Combined with the economies of scale of these larger projects, the 2007 policy changes encouraged development of several new ground-mounted projects of 10 megawatts (MW). Newly installed capacity increased from 21 MW in 2005, to 107 MW in 2006, and 555 MW in 2007 (IDAE, 2008).

In September 2007, 85 percent of Spain's RE target had been achieved, setting off a one-year deadline for the government to publish new targets and tariffs, and for developers to complete projects under the existing scheme. This period was fine for most RE projects already under development, with relatively long lead times; but PV projects can be developed quite quickly. The one-year notice set off a mad rush to install PV systems before the existing system expired. As a result, 2,480 MW of PV were added in 2008, breaking all past records and making Spain the world leader for PV installations that year (IDAE, 2009).

Because the country's 2010 targets had been exceeded, in September 2008 the government established a new economic regime for future installations (MITyC (Ministerio de Industria Turismo y Comercio), 2008). For the first time, a differentiated tariff was established for building-integrated PV (BIPV) to encourage installations that don't require additional land and contribute to the social dissemination of RE. In addition, annual caps were set for new capacity, with separate caps set for ground-mounted (up to 10 MW) and rooftop (under 20 kW; and 20 kW to 2 MW) PV projects. If the caps are achieved in a given year, they can be increased by 10 percent the following year. At the same time, if the caps are reached, the succeeding year's tariffs for new installations decrease by a maximum of 10 percent.

The purpose of this new scheme was to: provide long-term predictability; better control the cost of the FIT; guarantee profits more-appropriate for a regulated market; encourage declining installation costs; increase competitiveness; and encourage distributed generation through BIPV.

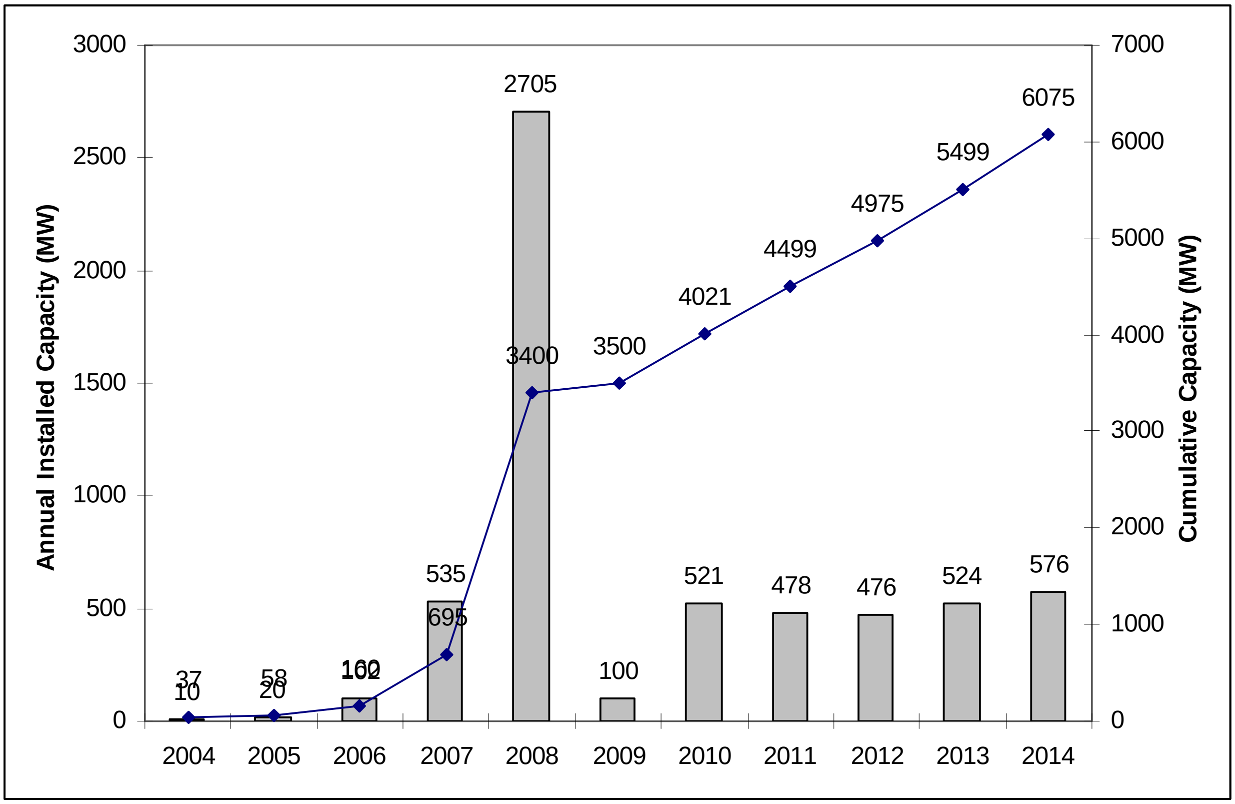

Figure 11.8 PV Installations in Spain, actual and projected (2004-2014).
Data are actual through to 2008; 2009 is an estimate and 2010-2014 data are projections. (IDAE, 2010)

The policy change resulted in a significant increase in distributed rooftop projects (IDAE, 2010). The tariff for ground-mounted projects continues to decrease over time. At the same time, uncertainty about the design of the new framework, to be adopted in late 2009, and the reduction in market size due to the cap on ground-mounted systems, led to job losses and company closures in 2008 (ASIF (Asociación de la industria Fotovoltaica), 2009). In 2009, the market collapsed and only [100] MW were added. (IDAE, 2010) Now that a firm policy is in place, the market is expected to pick up again and to remain constant. (MITyC (Ministerio de Industria Turismo y Comercio), 2008) (See Figure 11.8).

Overall, lessons from Spain's experience include: a combination of support schemes can be important for advancing RE technologies, particularly when the market is immature; ambitious long-term targets are critical as are predictable policies; and transitional incentives that decrease over time can foster technological innovation and control the total costs.

Box 11.8 Renewable energy in Thailand: policies and results

Decentralized, grid-connected RE has made a substantial and rapidly increasing contribution to Thailand's electricity supply. As of March 2010, 1364 MW of private sector RE was online with an additional 4104 MW in the pipeline (EPPO, 2010b; EPPO, 2010d). Strong market growth has been due to plentiful agricultural residues and a comprehensive set of policies including streamlined grid interconnection access, feed-in tariffs (FITs), tax breaks, and low-cost financing (Amranand, 2009; Fox, 2010).

Policies to accommodate grid interconnection of customer-owned RE started in 1992 with the Small Power Producer (SPP) program, which included standardized interconnection and power purchase agreements for generators up to 90 MW (Greacen and Greacen, 2004). By 2007 the program had saturated at 53 RE generators (mostly bagasse cogeneration) with combined nameplate capacity of 967 MW (EPPO, 2007b).

In 2002, Thailand adopted Very Small Power Producer (VSPP) regulations, modelled on U.S. net metering legislation, further streamlining utility interconnection requirements (Greacen, Greacen *et al.*, 2003). Initially attractive primarily to biogas projects in agricultural industries with substantial waste streams (Plevin and Donnelley, 2004), by February 2007 they brought on line 98 VSPP generators totaling 25 MW of capacity (EPPO, 2007b).

In 2006, the Thai government enacted a FIT that provides an adder paid on top of utility avoided costs, differentiated by technology type and generator size, and guaranteed for 7-10 years. Additional per-kWh subsidies are provided for projects that offset diesel use in remote areas, and utilities are provided further incentives to accommodate VSPPs. Incremental costs are passed through to consumers. (Amranand, 2008)

The government's decision was driven by concerns about increasing reliance on imported fossil fuels; difficulty siting new coal and natural gas plants; interest in reducing greenhouse gas emissions; encouragement from the Thai RE industry; and a national target of 8 percent RE by the 2011 (Prommin Lertsuriyadej, 2003; Thai Ministry of Energy, 2003; Amranand, 2008).

In response to the FIT, VSPP RE online capacity increased sharply, from 25 MW in February 2007 to 792 MW by March 2010; biomass and biogas account for most of this capacity"(EPPO, 2007a; EPPO, 2010c) .

Other important incentives for RE include an 8-year corporate tax holiday; reduction or exemption of import duties; technical assistance; and low-interest loans and government equity financing (Yoohoon, 2009).

Further, the government has worked to address challenges as they arise. For example, in response to companies that applied for power purchase agreements only to sell them to developers, the government began requiring a reimbursable bid bond for projects over 100 kW, and projects must produce power within one year of the scheduled date of commissioning to receive subsidies (Tongsopit, 2010). The variability of RE and small size of individual generators has been difficult to accommodate using traditional planning methods (Greacen, 2007). This has been acknowledged and partially addressed in the most recent 2010 revision of the Power Development Plan (EPPO, 2010a).

Thailand's experience demonstrates that well-designed and effectively implemented policies can lead to substantial deployment of RE in developing countries. The FIT adder has been instrumental in the increase, and in encouraging a diversity of RE sources. Explicit financial incentives for Thai utilities to purchase VSPP power helps overcome their reluctance to accommodate interconnection, grid operations, and billing challenges that can accompany distributed generation. The sequence of regulation, starting with interconnection policies and later adoption of FITs has allowed utilities to 'learn by doing' as they ramp up programs to accommodate distributed RE.

Counter-intuitively most FIT systems do not support the quantity of electricity *fed to* the grid, but the quantity of renewable power *generated*. FIT policies offer guaranteed, mostly nominal (without inflation correction) fixed prices for fixed periods of time, which are sufficient to cover the full costs of the project including a sufficient return on investment for every kWh RE produced by an identified and technically qualified plant. The FIT rates are fixed in a particular year depending on the state of development of RE technologies and then decrease over the years with technological progress.

FITs can be very simple – for example, available for one technology only, such as wind power. However, they are suited to incremental adjustments and can become more complex so that new technologies are added and prices are differentiated according to different attributes of the RE supplies, such as resource, location or time of day generated (Mendonça, 2007; Couture and Gagnon, 2009; BMU, 2010). The costs of the FITs or premium payments are covered by energy taxes or, more frequently, by an additional per-kilowatt hour charge spread across electricity consumers, sometimes with exemptions, for example the major users in Germany (BMU, 2010).

Like all mechanisms, their success comes down to details but the most successful FIT designs have included most or all of the following elements (Sawin, 2004b; Mendonça, 2007; Klein, Held *et al.*, 2008; Couture, 2009):

- Priority dispatch and access
- Establish tariffs based on cost of generation and differentiated by technology type and project size;
- Ensure regular adjustment of tariffs, with incremental adjustments built into law, to reflect changes in technologies and the marketplace
- Provide tariffs for all potential generators, including utilities
- Guarantee tariffs for long enough time period to ensure adequate rate of return
- Ensure that costs are integrated into the rate base and shared equally across country or region
- Provide clear connection standards and procedures to allocate costs for transmission and distribution
- Streamline administrative and application processes.

Quota Obligations

After FITs, the most common policy mechanism in use is a quota obligation, also known as Renewable Portfolio or Electricity Standards (RPS or RES) in the United States and India, Renewables Obligations (RO) in the United Kingdom, Mandatory Renewable Energy Target in Australia (Lewis and Wiser, 2005). By the end of 2008, quotas were in place in at least 9 countries at the national level and by at least 40 states or provinces, including more than half of U.S. states (REN21, 2009c).

Under quota systems, governments typically mandate a minimum share of capacity or generation to come from renewable sources. Any additional costs of RE are generally bourne by electricity consumers. With the most common form of quota system, generators comply with the quota by installing capacity which an actor purchases. In the case, of the UK this is the electricity supplier who is responsible for all contractual arrangments. Elsewhere, for example Texas, renewable electricity may by bought through a bidding process.

Quota's and FITs can be linked to tradable systems, although it is only quotas where this has happened in practice , for example "tradable green certificates" (TGCs) in Europe, or "renewable energy credits/certificates" (RECs) in the United States (Sawin, 2004b; Mitchell, Bauknecht et al., 2006; Ford, Vogstad et al., 2007; Fouquet and Johansson, 2008). Generally, certificates are awarded to producers for the renewable electricity they generate, and add flexibility by enabling those actors which have a quota laid on them, for example, utilities, and generators to trade, sell, or buy credits to meet obligations—provided there is sufficient liquidity in the marketplace (Sawin, 2004b). The electricity suppliers, or other agents in the power sector, are also able to 'prove' they have met their obligation by showing the regulator (or other executive body) the number of certificates equal to their obligation.

Most quotas have in-built costs for those actors which don't comply with the quota – either a direct penalty payment or a more indirect 'buying-out' of their obligation. The penalty on certificate shortfalls must sufficiently exceed the expected market price of TGC. The expenses incurred by the actors in fulfilling their quota's – whether as penalties or buy-outs - are passed on in the standard electricity prices paid by customers (Mitchell, 2008).

In the early stages of quota systems, countries experimenting with TGC systems strictly applied 1 TGC/1 MWh. Since then "banding" has occurred meaning that I MWh of RE is given a different number of TGCs per MWh depending on their technology or attributes. For example, 1 MWh of wave power in the UK receives 2 ROCs. This doubles the value of the RE to the generator.

As with FITs, there are significant variations from one scheme to the next, even among various U.S. state policies (Wiser, Namovicz et al., 2007). Research by the Lawrence Berkeley National Laboratory suggests that more than 50 percent of total U.S. wind power capacity additions between 2001 and 2006 were driven at least in part by State RPS laws (Wiser, Namovicz et al., 2007). Experience in the United States demonstrates that the effectiveness of quota schemes can be high and compliance levels achieved if RE certificates are delivered under well-designed policies with long-term contracts which mute (if not eliminate) price volatility and reduce risk (Lauber, 2004; van der Linden, Uyterlinde *et al.*, 2005; Agnolucci, 2007; Rickerson, Sawin *et al.*, 2007; Toke, 2007; Wiser, Namovicz *et al.*, 2007)

Nevertheless, in some U.S. States (Wiser, Namovicz et al., 2007), as well as the United Kingdom, Sweden and elsewhere (Jacobsson, Bergek et al., 2009), targets have not been achieved. For example, under the UK Renewables Obligation in 2005, 2006, 2007 and 2008, eligible sources rose from 4.0 to 5.4 percent of electricity generation rather than the obligated 5.5 to 9.1 percent . From 2005 and 2008, between 59 to 73 percent of each annual obligation was met, with an annual average of 65% (DUKES, 2009).

As with FITs, the success or failure of quota mechanisms comes down to the details. The most successful mechanisms have included most if not all of the following elements, particularly those that minimize risk (Sawin, 2004b):

- System should apply to large segment of the market
- Include specific purchase obligations and end-dates; and not allow time gaps between one quota and the next
- Establish adequate penalties for non-compliance, and provide adequate enforcement
- Provide long-term targets, of at least 10 years (van der Linden, Uyterlinde et al., 2005)
- Establish minimum certificate prices
- Liquid market to ensure that certificates are tradable
- Are accompanied by technology-specific investment subsidies (van der Linden, Uyterlinde *et al.*, 2005)

Comparison of Feed-in and Quota Systems

For several years, particularly in Europe and to a lesser extent in the United States, there has been debate regarding the efficiency and effectiveness of FITs versus quota systems (Rickerson, Sawin et al., 2007; Commission of the European Communities, 2008; Cory, Couture et al., 2009). Some 112 countries, states, provinces around the world have had experience with one or both of these mechanisms (REN21, 2009c). There are FITs that have been very successful and FITs that have not; quotas that have been effective, and some that have not (Sawin, 2004b). Because there are so many mechanisms in place and so many years of experience, it is possible to see from evidence the impacts of different design features.

An increasing number of studies, including those carried out by the International Energy Agency and the European Commission, have determined that well-designed and –implemented FITs are the most efficient (defined as the comparison of total support received and generation cost) and effective (defined as the ability to deliver increase of the share of renewable electricity consumed) support policies for promoting renewable electricity (Sawin, 2004b; European Commission, 2005; Stern, 2006; Mendonça, 2007; Ernst & Young, 2008; International Energy Agency (IEA), 2008; Klein, Pfluger *et al.*, 2008; Couture and Gagnon, 2009).

FITs have consistently delivered new supply, from a variety of technologies, more effectively and at lower cost than alternative mechanisms, including quotas, although they have not succeeded in every country that has enacted them, (Ragwitz, Held *et al.*, 2005; Stern, 2006; de Jager and Rathmann, 2008). The IPCC Fourth Assessment Report (2007) concluded that FITs have been more effective than quotas at deploying renewables and increasing production efficiency (IPCC, 2007a). According to Jacobsson et al (2009), tradable green certificate (TGC) systems in Sweden, the UK and Flanders are not meeting the criteria of effectiveness, efficiency and equity well (Jacobsson, Bergek et al., 2009). Although some U.S. states have successfully achieved their targets with RPS, others have not (Wiser, Namovicz et al., 2007).

However, quota systems have a number of characteristics, which may make them more attractive to policy-makers than FITs. Quota systems, particularly those with tradable certificate markets and without banding, do not regulate technology choice or price. Because of this some policy makers and analysts have considered them to be more market-oriented than FITs (Lipp, 2007). Moreover, quotas enable an annual maximum cost calculation, useful for those policy-makers which wish to know the total annual cost of the mechanism (Mitchell and Connor, 2004) , which is not the case for FITs, unless it is a ‘capped’ FIT. It is also relatively easy for a certain quota, of a certain technology, to be ‘obligated’ on an actor by a certain time – thereby providing short-term flexibility for the policy-maker.

Risk

An important key message of the chapter is that a policy’s efficiency and effectiveness is very linked to its ability to reduce risk. The Stern Review on the Economics of Climate Change (Stern, 2006) concluded that “feed-in mechanisms achieve larger [RE] deployment at lower cost. Central to this is the assurance of long-term price guarantees [that come with FITs]…. Uncertainty discourages investment and increases the cost of capital as the risks associated with the uncertain rewards require greater rewards.” (Stern, 2006) The IPCC (2007) notes that, in theory, if bidding prices and FIT payments are at the same level, the same capacity should be installed under either mechanism. However, “the discrepancy can be explained by the higher certainty of current feed-in tariff schemes and the stronger incentive effect of guaranteed prices.” (IPCC, 2007b).

The degree of risk related to quotas will depend on the details of the mechanism. Risk may arise in a number of forms, including price risk (fluctuating power and certificate prices), volume risk (no purchase guarantee), and market risk; and all three risks increase the cost of capital (Mitchell, Bauknecht et al., 2006). While these risks exist within the British RO, they may not be experienced in other quota systems which set minimum prices, contract lengths and provide offtake contracts. However, while quota and tendering systems theoretically make optimum use of market forces, they may have a stop-and-go nature not conducive to stable conditions. Moreover, low-bid projects may not be implemented.

Technological and Geographic Diversity

Quota systems have been found to benefit the most mature, least-cost technologies (Espey, 2001; Sawin, 2004b; Jacobsson, Bergek et al., 2009). In the United Kingdom, Sweden and Flanders, TGC systems have advanced primarily biomass generation and some wind power, but have done little to advance other renewables (Jacobsson, Bergek et al., 2009). In the United States, between 1998 and 2007, 93 percent of non-hydropower additions under state RPS laws came from wind power, 4 percent from biomass, with only 2 percent from solar and 1 percent from geothermal (Wiser and Barbose, 2008b). It is of course possible for quotas to support specific technologies by giving them more tradable green certificates per MWh – as has recently happened in the UK in a direct attempt to increase diversity; or by mandating a technology quota under which utilities must purchase a certain number of RECs from a technology to meet their mandated quotas. For example, solar RPSs are becoming more common in the United States. FITs have encouraged both technological(Huber, Faber et al., 2004) and geographic diversity (Sawin, 2004b), and have been found to be more suitable for promoting projects of varying sizes (van Alphen, Kunz et al., 2008); Mitchell and Connor, 2004).

Participation and Social Equity

Jacobsson et al (2009) have noted that “equity is a crucial factor in creating social legitimacy for policies supporting an industrial revolution.”(Jacobsson, Bergek et al., 2009) Verbruggen and Lauber (2009) argue that the transition to sustainable power systems requires that independent power production is fully integrated in power systems (Verbruggen and Lauber, 2009). FITs tend to favour ease of entry and local ownership and control of RE systems (Sawin, 2004b; Lipp, 2007; Farrell, 2009), and thus can result in wider public support for renewables (Damborg and Krohn, 1998; Sawin, 2001; Sawin, 2004b; Hvelplund, 2006; Mendonça, Lacey et al., 2009).Mendonça et al (2009) have found that steady, sustainable growth of RE will require policies that ensure diverse ownership structures and broad support for renewables, and propose that local acceptance will become increasingly important as renewable technologies continue to grow in both size and number (Mendonça, Lacey et al., 2009). This is supported by studies in New Zealand and elsewhere (Barry and Chapman, 2009).

Many analysts argue that quota systems primarily benefit incumbent actors, which enables them to introduce RE at their own preferred pace (Girardet and Mendonca, 2009; Jacobsson, Bergek *et al.*, 2009; Verbruggen and Lauber, 2009). The transaction and administrative cost of a TGC system are higher than with FIT, making participation of small scale new entrants cumbersome, and therefore limited (Mitchell, Bauknecht *et al.*, 2006).

Support mechanisms shift economic wealth from some groups in society to others. Such shifts may simultaneously meet efficacy, efficiency, and equity concerns, or cause conflicts among them. Bringing RE electricity to deprived rural and urban populations increases equity. This is less clear if the cost of RE policy is spread across electricity consumers, but acquisition of the subsidy for domestic renewable energy technologies is by the wealthier (Jacobbson, 2010). The absence of excess profits makes it easier to balance the cost of support for the beneficiaries with payments made by non-beneficiaries (taxpayers or grid electricity customers). The few TGC systems that have functioned for a number of years and have been analyzed, show high or higher profits for the suppliers (Commission of the European Communities, 2008; Cory, Couture *et al.*, 2009; Jacobsson, Bergek *et al.*, 2009{Rickerson, 2007 #313)}.

Other regulatory RE policies

Other regulatory polices are related to access. Priority access and priority dispatch are generally important constituents of FITs. However, net metering, or net billing, enables small producers to “sell” into the grid, at the retail rate, any renewable electricity that they generate in excess of their total electricity demand over a specific billing period. Customers have either two unidirectional meters spinning in opposite directions, or one bi-directional meter that is effectively rolls forward and backwards, so that net metering customers pay only for their net electricity draw from the grid (Klein, Held *et al.*, 2008). Although net metering is most common in the United States, where it has been enacted in most states (Database of State Incentives for Renewables & Efficiency (DSIRE), 2009), the mechanism is also used in some countries in Europe and elsewhere around the world (Klein, Held *et al.*, 2008). The number of programs and participants has been increasing steadily (Energy Information Administration (EIA), 2008).

However, while the customer may see it as ‘fair’ that they are paid the same per kWh they inject into the electricity system as they pay for all incoming kWhs, electricity companies do not necessarily see it the same way arguing that they have to make, payments for distribution , transmission and network services and paying customers their retail price effectively costs them money (EGWG, 2001). Klein et al (2008) found that the remuneration is generally insufficient to stimulate significant growth of less competitive technologies like photovoltaics, since generation costs are significantly higher than retail prices (Klein, Held *et al.*, 2008). Based on impacts seen on small wind systems in the United States, Forsyth et al (2002) concluded that net metering alone provides only minimal incentives for consumers to invest in RE systems, particularly where people must deal with cumbersome zoning and interconnection issues. However, when combined with public education and/or other financial incentives, net metering might encourage greater participation (Forsyth, Pedden *et al.*, 2002). It is certainly easy to implement, in the sense that it requires only a meter which turns backwards.

11.5.4.2 Public Finance Mechanisms for Deployment

RE projects generally operate with the same financing structures applied to conventional fossil-fuelled energy projects. The main forms of capital involved include equity investment from the owners of the project, loans from banks, insurance to cover some of the risks, and possibly other forms of financing, depending on the specific project needs.

For many projects the availability of these needed forms of commercial financing is limited, particularly in developing countries, where the elevated risks and weaker institutional capacities inhibit private sector engagement. The gaps can often only be filled with financial products created through the help of public finance mechanisms.

There is a growing body of experience with the use of these instruments for promoting investments in RE deployment, mostly in the electricity sector. Their role is to help commercial financiers act within a national policy framework, filling gaps and sharing risks where the private sector is initially unwilling or unable to act on its own (UNEP, 2009).

Public finance mechanisms have a twofold objective: first, to directly mobilise or leverage commercial investment into RE projects and, secondly, to indirectly create scaled up and commercially sustainable markets for these technologies. To make the best use of public funding, it is essential that both these direct and indirect outcomes are sought when designing and implementing such mechanisms. Direct short-term benefits should not create market distortions that indirectly hinder the growth of sustainable long-term markets (UNEP, 2010).

The following provides an overview of the main public financing mechanisms being used today for promoting RE deployment and some of the experiences with their use.

In many countries there are significant gaps in the availability of equity financing for RE projects, particularly but not only in the developing world. Banks do not generally provide equity financing and the type of investment community that does so in the developed world is hardly present in developing countries. Equity-focused public financing mechanisms are therefore needed that are structured either as *funds* that take direct investments in companies and projects, or as “*funds of funds*” that invest in a number of commercial managed funds, each of which then invests in projects or companies (London School of Economics, 2009).

The bulk of the financing needed for RE projects is in the form of loans (concessional or otherwise), termed debt financing (London School of Economics, 2009). The challenges to mobilising this debt relate to access and risk. Many countries lack sufficiently developed financial sectors to provide the sort of long-term debt that clean energy and other infrastructure projects require. In these situations public finance mechanisms can be used to provide such financing, either directly to projects or as credit lines that deliver financing through locally-based commercial financial institutions. Credit lines are generally preferable, when possible, since they help build local capacity for RE financing (UNEP, 2009).

Credit lines can be an effective means of providing the needed liquidity for medium to long-term financing of clean energy projects. In markets where high interest rates are seen as a barrier, credit lines can be offered at concessional rates or structured on limited/non-recourse basis, or alternatively offered as subordinated debt to induce borrowing and direct credit to target sectors and projects: by taking on a higher risk position in the financial structure, this approach can leverage higher levels of commercial financing (London School of Economics, 2009). For example, credit lines from the World Bank, KfW and ADB helped the Indian Renewable Energy Development Agency become an important lender to, and key to the success of, the RE sector in India (see Box 11.9).

Box 11.9 Public Finance Case Study: India Renewable Energy Development Agency (IREDA)

IREDA is a Government-owned company incorporated in 1987 that provides debt financing to RE projects. IREDA invests mainly as a senior lender, lending up to 80 percent of a project's investment cost on terms up to 10 years with up to two year grace periods. Funded projects total over USD1 billion and have included wind, hydro, bio-mass cogeneration, industrial waste heat recovery power plants, industrial process efficiency. It has received international credit lines from the World Bank, ADB and KfW, amongst others, as well as grant support from the GEF. About one third of its capital is now raised domestically, both through bank borrowing and the issuance of tax free bonds. In India, State governments are now authorised to establish energy conservation funds; IREDA, as a national entity, has potential to replicate its capability by supporting development of such State funds (UNEP, 2009).

Mechanisms can also be targeted specifically at reducing the financing cost of credit provision, while the commercial finance institution provides the actual bulk of the financing. The spread between the interest rates collected from borrowers and the competitive returns paid back to the bank is essentially financed by public funds buying down the interest rate. This approach has been applied successfully in India for domestic solar thermal and solar PV systems, in Tunisia for solar thermal and in Germany for a range of RE technologies (UNEP, 2009).

In some countries guarantees can be a more effective instrument for helping local banks who are uncomfortable financing RE projects because of high perceived credit risk (i.e. repayment risk). The role of a guarantee is to mobilise domestic lending for such projects by sharing with recipient banks the credit risk of project loans they make with their own resources. Guarantees are most effective at addressing elevated perceptions of risk in that they help a bank gain experience in managing a portfolio of RE loans, which puts them in a better position to evaluate true project risks.

Fostering improved access to finance is necessary, but is not always sufficient to promote RE project deployment. Successful public finance mechanisms typically combine (i) access to finance with (ii) technical assistance programmes designed to help prepare projects for investment and build the capacity of the various actors involved (UNEP, 2009). Many examples exist of finance facilities that were created, but did not disburse because they failed to find and generate sufficient demand for the financing. Successful mechanisms actively reach back into the project development cycle to find and prepare projects for investment; that is, they work on both the supply and the demand side of the financing equation. Strategies to generate a flow of well-prepared projects for financing can involve partnerships with many market actors such as utilities, equipment suppliers and project developers, end user associations, and governmental authorities.

Box 11.10 Public Finance Case Study: Berkeley Sustainable Energy Financing District

The City of Berkeley, California established a Sustainable Energy Financing District (also called Property Assessed Clean Energy, PACE) in which it issued bonds and used the proceeds to provide loans to commercial and residential property owners for the installation of solar PV systems and energy efficiency improvements. Loans to property owners have 20-year terms, allowing loan payments to be matched with the energy savings. The City bears the credit risk of the loans but, in an important innovation, collects loan payments on the property tax bill. This tax assessment belongs to the property rather than the individual end-user, who effectively sells it with the property if he moves on. PACE investments effectively add to the property value. A number of additional U. S. cities (Boulder, CO, Palm Desert, CA, Babylon, NY, and others) have implemented versions of the PACE districts, and efforts are underway in Germany, Italy, and Portugal (Fuller, Portis *et al.*, 2009). This mechanism has the potential to ‘flip’ the financial equation such that the costs are not front-loaded but are paid for during the period of use. (Fuller, Portis *et al.*, 2009)

Box 11.11 Policy Experience with Wind Power in the United States

In the United States, installed wind energy capacity grew from 2.6 GW in 2000 to more than 35 GW in 2009. Federal tax incentives, state renewable portfolio standards (RPS), the improving economics of wind, and other RE incentives drove this development (Menz and Vachon, 2006; Wiser, Namovicz *et al.*, 2007; Adelaja, Y.Jailu *et al.*, 2010). The U.S. experience highlights the need for stable and consistent policies as well as multiple incentives to create a robust market that promotes steady growth in capacity and manufacturing facilities.

From 2001-2005, failure to consistently renew the federal production tax credit (PTC), which provides approximately 2 cents per kilowatt-hour for the production from wind facilities for the first 10 years of operation, created a boom and bust cycle for wind development (Bird, Bolinger *et al.*, 2005). Figure 11.9 shows the impact of allowing the PTC to expire in 2002 and 2004.

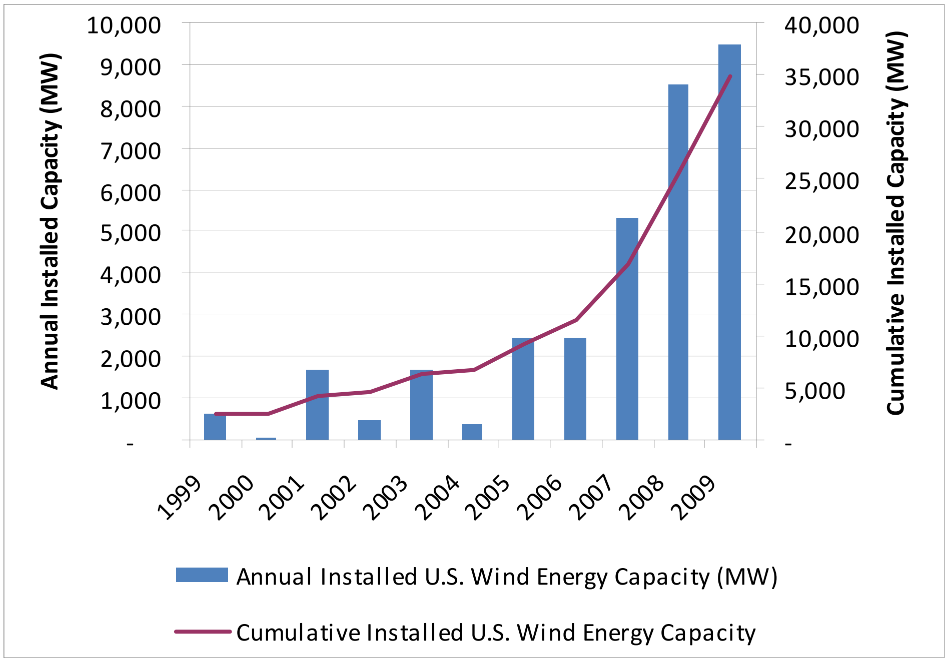

Figure 11.9 U.S. Wind Capacity, 2001-2009 [TSU: Source is missing]

Between 2005 and 2009, the rate of annual installations climbed steadily, as federal tax credits were re-authorized before expiring, more states adopted RPS laws, and many states strengthened preexisting RPS targets. As of May 2010, 29 states had adopted an RPS and another half dozen had established renewable energy goals. Many states require electricity providers to obtain 20 percent or more of the power needed to serve their loads from RE sources by 2020. Collectively, these state RPS policies call for more than 65 GW of new RE by 2020 (Wiser and Barbose, 2008a).

Some states have seen rapid growth through these policies, and Texas achieved its 2025 goal of 10 GW installed wind capacity by April 2010 (ERCOT, 2010). However, the socio-political context and siting barriers have impeded development in other states (Fischlein, Larson *et al.*, 2010), demonstrating the need to address barriers, such as siting and transmission, in addition to establishing targets and financial incentives.

Collectively, the combination of binding, long-term state RE targets and federal and state financial incentives, and efforts to address siting and financing barriers have created greater market certainty and reduced regulatory risk, which in turn have led to investments in manufacturing capacity and steadier industry growth in recent years (Wiser and Bolinger, 2009). Between 2004 and 2009, U.S. domestic manufacturing of wind turbines and their components increased 12-fold and, in 2009, 16 turbine manufacturers opened or announced plans for factories in the United States, up from only one turbine manufacturer in 2004 (AWEA, 2010).

Starting in 2008, the federal government provided RE support as part of its effort to help fuel economic recovery. In response to the inability of investors to utilize tax incentives during the recession, the government provided project developers with the option to receive cash grants in lieu of the federal tax credits and extended the tax credits for wind through 2012. This led to a record number of new wind power installations in 2009, which will likely extend through 2010 (Wiser and Bolinger, 2009).

11.5.5 Policies for Deployment - heating and cooling

Heating and cooling processes account for 40-50 percent of global energy demand (IEA, 2007a; Seyboth, Beurskens *et al.*, 2008) with consequent implications for emissions from fossil fuels. Historically, renewable energy policy has tended to have a greater focus on renewable electricity, with increasing activity in support of biofuels for transportation over the last decade. However, renewable energy sources of heat (RES-H) have gained support in recent years as awareness of their potential has been increasingly recognized. Many nations have some form of district heating. As well as heat delivery infrastructure this tends to imply some pricing and regulatory oversight. Waste heat from fossil fuel and nuclear generation is commonly used in systems across Eastern Europe, former soviet states and Scandinavia. (Ericsson and Svenningsson, 2009). RE for cooling (RES-C) has even fewer mechanisms of support than RE for Heating. As a result, experience of what works and what doesn't is far less than that for RE electricity or fuels>

The supply and servicing infrastructure relevant to RES-H and RES-C technologies in most countries is immature, though there are significant exceptions to this, with some nations being advanced in terms of manufacturing, integration and infrastructure, often in technology specific areas. Examples include solar water heating in a number of nations, most especially China but with significant uptake in some Mediterranean nations, and geothermal energy in Iceland, where it accounts for over 90% of national heat demand.

There is considerable scope for learning from the RES-E policy experience but proper attention is needed in applying them to RES-Heating/Cooling due to significant differences in the generation, delivery, metering, trading and regulatory environment and use of heat and cooling. Policy instruments for both RES/H and RES-C need to specifically address the much more heterogeneous characteristics of resources including their widely varying range in scale, varying ability to deliver different levels of temperature, widely distributed demand, relationship to heat load, variability of use and the absence of a central delivery or trading mechanism (Connor, Bürger et al., 2009a). It should also be noted that RES-H technologies vary in technological maturity and in market maturity, for example some solar water heating systems are closer to being competitive in China or Israel than in Europe (Xiao, Luo et al., 2004), while solar water heating is more technologically and market mature than, for example, biomass based substitute natural gas, (Connor, Bürger et al., 2009a). Policy instruments which acknowledge this as well as other relevant local differences are likely to be more effective (Haas, Eichhammer et al., 2004).

Policy mechanisms currently in place to promote renewable heat include regulatory mechanisms, such as bonus mechanisms and quotas; fiscal instruments such as tax-credits, tax-reductions and tax-exemptions and accelerated depreciation; and educational efforts (as discussed in 11.6). There is significant potential for other instruments to also be applied. (DEFRA/BERR, 2007; Bürger, Klinski et al., 2008; Connor, Bürger et al., 2009a).

This section describes mechanisms which are suitable for both heating and cooling. There is one short section later on which talks about issues relevant to cooling on.

11.5.5.1 Regulatory Mechanisms

Bonus Mechanisms and Quotas

The bonus (or tariff) mechanism and the quota or renewable portfolio standard (RPS) are the two key variations in providing support to RES-H. The bonus mechanism (roughly, the equivalent to the RES-E FIT) has been characterised as a "purchase/remuneration obligation with fixed reimbursement rates" (Bürger, Klinski et al., 2008). It legislates a fixed payment for each unit of heat generated, with potential for setting different levels of payment according to technology. Payments can be capped either for a fixed period, or for a fixed output, and can be designed to vary with technology and building size to complement energy conservation efforts. Digression may be applied to reduce the level of the bonus payment annually to allow the capture of cost reductions for the public purse. Digression has been cited as 'best practice' in the consultation document for the adoption of a renewable heating tariff in the UK, based on experience with RES-E tariffs in Europe (RES, 2009) .

Currently, no RES-H/C centred quota mechanism has been applied in practice nor are any planned. Efforts to legislate a RES-H quota mechanism in the UK in 2005 were unsuccessful and the UK has now adopted legislation for a RES-H bonus mechanism with a projected April 2011 adoption (DECC, 2009) largely on the grounds of the greater projected cost associated in a comparison of quota ad tariff mechanisms . Germany also favoured a bonus mechanism for RES-H, but finally adopted mandatory installation of RES-H in new buildings. The Australian Government's Mandatory Renewable Energy Target (MRET) was established on 1 April 2001 to encourage additional RES-E generation and achieve reductions in greenhouse gas emissions. The MRET includes solar hot water systems as eligible sources for certificates where solar water heating displaces electrical energy use. Owners of solar water heaters can either: assign their RECs to an agent in exchange for a delayed cash payment or upfront discount, or register RECs online to be sold and transferred to a registered agent during the life of the scheme .

Key differences between an electricity FIT and the RES-H bonus/tariff include the many more renewable heat generators expected and that heat generation will generally be used at the same site as the load. This has the potential to add substantial complexity and costs due to metering and administration. Applying the UK's RES-E quota mechanism at the micro scale doubled administrative costs for an increase in renewable energy generation of only 0.05% (Bürger, Klinski et al., 2008), One proposed solution is consolidation, that is, including a third party organisation to aggregate and distribute benefits for output. This is likely to be combined with a policy of only paying out the bonus funds on a limited number of occasions, perhaps 2-3 over the lifetime of an installed technology (Bürger, Klinski et al., 2008), reducing administrative costs but potentially reducing access to funds for the investor.

Subsidy can be given either as a result of metered output or some form of estimation of output. Where metering is not applied it is essential to have a robust procedure for assessing likely useful heat and load to restrict overpayment from the public purse. A system for ensuring quality of installation and of installed systems will also be essential for the same reason. Given the relative costs of energy efficiency improvements against renewable energy subsidy costs good practice should ensure that installation of RES-H systems follows proper investment in energy efficiency.

Mandating Connection Technology

One simple application is to mandate the inclusion of the basic connection technology in new buildings, which would allow for later integration of RES-H/C. However, this option is limited by the potential for meeting the requirements of different forms of technology, by the increases in the costs it would engender. Integration of the technology for later connection to district heating or cooling is one potential application that might have a good fit with later investment (Connor, Bürger *et al.*, 2009b).

‘Use’ Obligation

More significantly in terms of expanding demand and growing support infrastructure for RES-H technology applications of building regulations can be used to compel the adoption of RES-H/C technologies, as in the case of the ‘Use Obligation’ instrument. A use obligation effectively compels spending on renewable systems, either by the initial builder who effectively passes costs to the purchaser or, in more advanced approaches, by compelling retro-fitting of new systems.

Initially adopted in various municipalities in Spain, Germany, Italy, Ireland, Portugal and the UK, this mechanism has been expanded to apply at the national level in Spain and Germany and the process of adoption is underway in the UK, where integration of renewables into new buildings will form a part of the Code for Sustainable Homes, following increasingly tough energy efficiency standards . Basic or first stage applications of this instrument tend to compel developers of new buildings to ensure a specified fraction of energy use is from renewable sources, with variations as to the eligible technologies, the fraction of energy to come from renewable sources and whether the energy has to be on site or can be located elsewhere. One useful element of the use obligation is that it can be applied at different levels of governance and for district heating as well as individual decentralized systems. The goal is the stimulation of an initial market for the technology and of the attendant necessary infrastructure, such as training of personnel. Use obligations may be applied to a single or multiple technologies, with the option to have different minimum fractions attach to adoption of different technologies producing either RES-E, RES-H or RES-C or some combination of these (Bürger, Klinski et al., 2008; Puig, 2008).

Such regulations are justified on the grounds that renewable heating technologies or their enabling technologies are more cost-effective if installed during construction rather than retro-fitted. The impact on the total building cost is therefore relatively low. Such a mechanism offers benefits in terms of growing the scale of public demand, and there is an argument that they might operate most effectively by steadily increasing the level of the obligation over time in order to ensure both that demand is maintained and occurs on a graduated basis allowing for realisation without unjust punishment for obligated parties unable to source material or skills to meet their obligations (ESTIF, 2006).

Standards and Building Regulations

The application of a system of standards to ensure a minimum quality of hardware, installation, and design planning when implementing obligations for renewable heat is likely to be essential to ensuring proper compliance with the mechanism; a monitoring system including periodic examinations of installations and/or minimum quality standards is advisable, though this will increase administrative costs (Connor, Bürger *et al.*, 2009a). Restriction of non-compliance is fundamental to the success of the use obligation (Bürger, Klinski et al., 2008).

Where additions to buildings are compulsory through 'use' obligations, good regulatory practice should offer protection on the grounds of economic, technical and environmental feasibility incorporated (as for example, with the European Building Performance Directive). Compulsory refurbishment should ideally also include protection for the economically vulnerable (Connor, Bürger *et al.*, 2009a).

National planning regulation regimes also have the potential to significantly hamper growth of RES-H/C technologies, as has sometimes been the case for RES-E. Different territories have very different approaches to planning and zoning as regards RE; despite this, there are clear examples to inform good practice (Upreti and Van Der Horst, 2004; Loring, 2007). A District Heating system requires strong oversight if the consumer is to be protected from being locked in to high energy prices. As seen in Box 11.12, Sweden provides an interesting example of a successful DH system using a significant share of biomass. it (Ericsson and Svenningsson, 2009).

Box 11.12 Sweden's Experience with Biomass District Heat

Sweden's experience with district heating illustrates how policy and other factors can shape the development of an enabling infrastructure as well as a shift to RE sources. The biomass share in district heat production has increased from zero in 1980 to 44 percent (90 PJ) in 2007 (see Figure 11.10). An additional 12 PJ of biomass was used to co-generate 3 TWh of electricity in 2007. Underlying drivers since 1980 have included Sweden's ambitions to reduce oil dependence and utilise indigenous RE sources, replace nuclear power, and reduce GHG emissions. (Ericsson and Svenningsson, 2009).

Virtually all Swedish towns have a district heating system, and district heating now accounts for about 50 percent of heating in the residential and service sectors. The main expansion took place in the period 1965-1985 when municipal administrations and companies built, owned and operated the district heating systems. It was facilitated by strong local planning powers and high acceptance for public sector led solutions. Important motivations included opportunities for combined heat and power (CHP) production, fuel flexibility, economic efficiency, and better pollution control compared to individual boilers. High oil prices and taxes on oil products instigated a major shift away from oil in the 1980s to a variety of fuels and energy sources, including coal, municipal solid waste (MSW), industrial waste heat, and electricity. (Ericsson and Svenningsson, 2009)

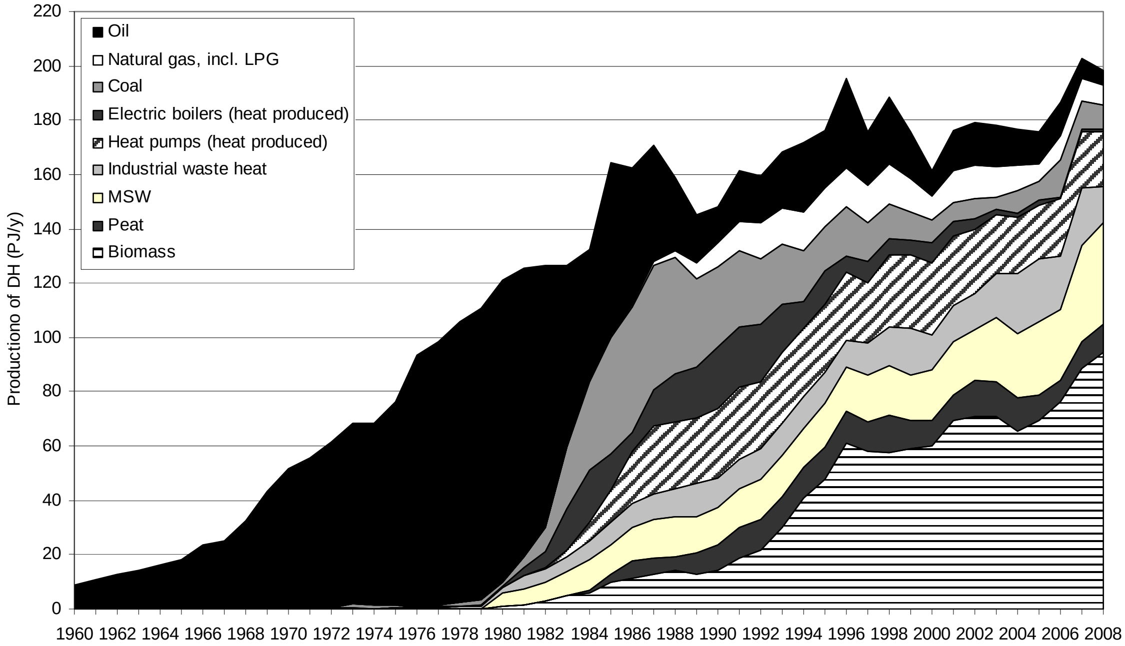

Figure 11.10 District heat production in 1960-2008, broken down into fuels and energy sources. (Ericsson and Svenningsson, 2009)

Curves are not corrected for outdoor temperature variations.

The second major shift took place after 1990, in response to the 1991 energy tax reform, which included a carbon tax at 41 USD_{2005} per tonne of CO_2. This tax has gradually increased and reached 130 USD_{2005} per tonne in 2007. As a result, the use of biomass expanded rapidly, from 14 PJ in 1990 to 60 PJ in 1996. Energy recovery from MSW incineration produced 35 PJ (half or more of this is considered as RE) in 2007, partly in response to bans on landfilling combustible and organic waste (Ericsson and Svenningsson, 2009).

CHP production has not been used to its full potential since the nuclear power expansion 1975-1985 resulted in an electricity "surplus" and large electric utilities were able to mount disincentives to municipal power production. Instead, electric boilers and heat pumps came into use, as seen in the figure. The ambition to replace nuclear power, however, motivated biomass based CHP investment subsidies 1991-2002 and the green certificates scheme introduced in 2003. In response, electricity from CHP increased from about 2 TWh in 1990 to 7.5 TWh in 2007; of this, 41 percent was from biomass and 20 percent from MSW. Electricity from biomass based CHP in the district heating sector and the forest industry accounted for more than two-thirds of the tradable certificates under the Swedish quota based system in 2007 (Bergek and Jacobsson, 2010).

11.5.5.2 Fiscal Instruments

Ireland, Italy, Portugal, Sweden and the Netherlands have all applied some form of tax break to support different RES-H technologies *(Bürger, Klinski et al., 2008)*. Likewise, indirect support, as exemptions from eco-taxes, carbon and energy charges levied on conventional heating fuels, provides a comparative advantage for RES-H. A clear example is Sweden's fuel switch to bio-energy driven by high CO_2 tax (*(Ericsson and Svenningsson, 2009)*.

Additionally, accelerated depreciation against investment in RE can also be a useful instrument in improving the economics of investment. The Netherlands VAMIL programme, Canada's Accelerated Capital Cost Allowance (CCA) and the UK's Enhanced Capital Allowance Scheme are examples (Worrell and Graus, 2005; IEA, 2007a).

11.5.5.3 Public Finance

Capital Grants

Capital grants and rebates assist directly with reducing plant capital investment , with a government typically contributing a specified level of financial support, for example a refund per megawatt of installed capacity or a percentage of total investment, up to a set limit. They can apply from the small-scale, for example a domestic solar thermal system, through to large-scale generating stations such as biomass combined heat and power (CHP). Grants are the most commonly applied instrument for RES-H (and RES-C to a lesser extent), with various applications in multiple countries and regions including Austria, Canada, Greece, Germany, Ireland, the Netherlands, Poland and the UK *(Bürger, Klinski et al., 2008; Connor, Bürger et al., 2009a)*.

Grants generally also require some form of oversight to ensure spending occurs based on set conditions and continued operation post-deployment to be effective and that the quality of new generating capacity achieves at least a minimum standard. They can be vulnerable to fluctuations in budgets to the detriment of stable demand growth, as with the German Market Incentive Program (MAP) and the UK's Low Carbon Building Programme. Conversely, the opposite has been observed from the French experience, where the implementation of the 2005 Finance Law provided a successful ex-post incentive method with no subsidy pre-approval required, and suggesting an easy-to-administer, simple and straightforward promotion system *(IEA, 2007a; Roulleau and Lloyd, 2008; Walker, 2008b; Gillingham, 2009)*.

Soft Loans

Soft loans, provided for example, through a government directed bank or other agency, may come with low or zero interest rates, with delays on repayments or with long-term repayment periods. They can be easy to apply at the administrative level, though there is potential for political difficulties in territories without histories of providing public funds in this manner (IEA, 2007a). Soft loans have long been a feature of German efforts in support of RES technologies and the Environment and Energy Saving Program has included RES-H since 1990, though the bulk of funds has gone to PV and wind. Norway and Spain also have loan programs relating to heat, and Japan and Sweden have both employed soft loans previously (IEA, 2007a).

The adoption of RES-H/C at the domestic level has the potential to be severely hampered by the initial capital barrier to system purchase. The available policy instruments discussed here address this to particular extents. Both the quota and tariff mechanisms provide regular payments over the lifetime of a project, the latter with perhaps greater predictability than the former. Soft loans address both the initial capital problem while also widening the scope of potential consumers who can benefit from any available subsidy, rather than the focus lying with those with access to sufficient capital.

11.5.5.4 Policy for Renewable Energy Sources of Cooling (RES-C)

Policy aiming to drive uptake of RE sources for cooling (RES-C) is considerably less well-developed than that for RES-H, even in nations with a higher cooling load and that tend to have higher potential for location of RES-C technologies. The relative lack of diversity and greater homogeneity of existing RES-C technologies in comparison with RES-H means that development and application of policy instruments is less complex (IEA, 2007b; Desideri and Proietti, 2009).

Many of the mechanisms described above will be able to be applied to RES-C, generally with similar advantages and disadvantages, though with a continuing need to account for the particular characteristics of the technology and its application. Most renewable cooling is based on the use of heat initially produced from RES, though not all RES-H technologies are yet at a stage where they might be useful as RES-C sources. The reduced scope for use should mean a comparatively greater level of homogeneity and thus less potential problems in applying the instruments to RES-C (DG TREN, 2007). The key areas of crossover are likely to be in the application of heat exchangers and in the area of district cooling.

11.5.6 Polices for Deployment - Transportation

This section describes policies designed to encourage the deployment of renewable options in the transport sector. First it analyzes policy instruments that have been enacted to promote the direct use of RE, in the form of biofuels. It then examines policies to promote the indirect use of RE for transportation, via intermediate storage media (batteries and hydrogen). It concludes with a brief look at low-carbon fuel standards.

Table 11.4 Direct Use of RE for Transport - Biofuels

Policy	Target	Example
Renewable fuel standards	Biofuels	RFS1 (USA)
Tax incentives	Mostly biofuels	Excise tax exemption on biodiesel (Germany)
R&D	Biofuels and intermittent technologies	US
ZEV mandates	Intermittent technologies	California
GHG emission standards for mobile sources	To second degree intermittent technologies & biofuels	EC No 443/2009 (EU); EPA regulation (USA)
Low carbon fuel standards	All fuels, incl. biofuels & electricity/ hydrogen from ren. sources	S-01-07 (Califronia); COM-2007-18 (EU)
Emission Trading	All fuels	Proposed for California
Preferential government purchasing & urban policies	Intermittent technologies (electric cars)	London, Malmo

A range of policies have been implemented to support the deployment of biofuels in countries and regions around the world. Robust biofuels industries exist only in countries where government supports have enabled them to compete in markets dominated by fossil fuels. An example of this is Brazil (see Box 11.13). There are many countries where basic regulations for the production, sale, and use of biofuels do not yet exist (FAO/GBEP, 2007; PABO, 2009). Some countries, like Mexico and India, have implemented national biofuels strategies in recent years (Altenburg, Schmitz *et al.*, 2008; Felix-Saul, 2008). The most widely used policies include volumetric targets or blending mandates, tax incentives or penalties, preferential government purchasing, and local business incentives for biofuel companies.

11.5.6.1 Regulatory Policies

Renewable Fuel Mandates and Targets

National targets are key drivers in the development and growth of most modern biofuels industries. Blend mandates have been enacted or are under consideration in at least 27 countries surveyed by this report, and 40 countries have some form of biofuels promotion legislation. (A Blueprint for Green Energy in the Americas Strategic Analysis of Opportunities for Brazil and the Hemisphere Featuring: The Global Biofuels Outlook 2007. Prepared for the Inter-American Development Bank by Garten Rothkopf). Among the G8 +5 Countries, Russia is the only one that has not created a transport biofuel target (FAO/GBEP, 2007). Voluntary blending targets have been common in a number of countries. However blending mandates enforceable via legal mechanisms are becoming increasingly utilized and with greater effect (Canadian Food Grains Bank, 2008).

The distinction between voluntary and mandatory is critical since voluntary targets can be influential, but do not have the impact of legally binding mandates. This was evident in Europe, for example, when all but two of the EU member countries failed to achieve the voluntary biofuels for transport blending target of 2 percent by 2005 (FAO/GBEP, 2007).

The EU currently has a target of 10 percent RE in transport by 2020 (Official Journal of the European Union, 2009). Brazil has had a mandatory ethanol blending requirement for many years and more recently created biodiesel blending mandates (citation and details). India set a five percent national ethanol blending mandate, then increased it to ten percent, and then in 2008 set an additional indicative target of a minimum 20 percent ethanol and biodiesel blending nationally by 2017 (Altenburg, Schmitz *et al.*, 2008; IGovernment, 2008; Ritch, 2008).

Governments do not need to provide direct funding for blending mandates since the costs are paid by the industry and consumers. Mandates have been quite effective in stimulating biofuels production, but they are very blunt instruments and should be used in concert with other policies, such as sustainability requirements, in order to prevent unintended consequences (Sustainability Science Program; Lee, C.Clark *et al.*, 2008).

Sustainability Standards

Although environmental quality is regulated in most countries, comprehensive sustainability laws for biofuels are in place only in Europe where individual government efforts (especially in the Netherlands, the United Kingdom, and Germany) led to an EU-wide mandatory sustainability requirements for biofuels that was put into law in 2009. These include biodiversity, climate, land use and other safeguards (Hunt, 2008; Official Journal of the European Union, 2009).

At the international level, there are no legally binding sustainability regulations for biofuels that address the potential negative social and environmental impacts of biofuels (such as habitat conversion, water and air pollution, and land-use conflicts). However, a number of requirements that aim to ensure the sustainable development of biofuels are being developed.

Some countries have attached certain sustainability requirements to their biofuels support policies. For example, Mexico's Law for the Promotion and Development of Biofuels, passed in 2008, includes an explicit prohibition of changing land from forest to agricultural land for the production of biofuels feedstocks (Felix-Saul, 2008).

In order to avoid competition with food, India's 2008 National Biofuels Strategy mandates that biofuels come from non-edible feedstocks that are grown on waste, degraded or marginal lands (Altenburg, 2008) (Ritch, 2008)}.

There is a requirement in the United States' renewable fuel standard that biofuels (except grandfathered production) reduce GHG emissions relative to conventional fuels, based on full life-cycle accounting, and that feedstocks not be grown on previously forested land (US Congress, 2007).

Brazil developed a Social Fuel Seal as part of its biodiesel program whereby producers can receive the seal and the associated tax benefits and credit only if they enter into a legally binding agreement with them producers to establish specific income levels and guarantee technical assistance and training (Governo Federal, 2006).

Box 11.13 Brazilian ethanol: Lessons learned

Brazil first mandated the blending of ethanol with gasoline in 1931, but ethanol was not used there in significant quantities until the mid-1970s, when Brazil was hit hard by the first world oil crisis. Taking advantage of its position as a leading sugar producer, in 1975 the government established the Brazilian Alcohol Program (PROALCOOL) to promote sugarcane ethanol as a gasoline alternative in order to reduce oil imports. The program, which set production goals and included producer subsidies, has created environmental, economic and social benefits for Brazil (Goldemberg, 2009).

Initially ethanol was available for ethanol-only engines or as an octane enhancer, and the government mandated that it be blended with gasoline in ranges from 20-25 percent. In the mid-1980s, low gasoline prices, high sugar prices and a shortfall in ethanol production led to a serious crisis and the gradual abandonment of ethanol-only cars. Responding to government pressure, auto manufacturers introduced flex-fuel motors in 2003, solving the problem associated with fluctuating supply and prices. Flex-fuel cars, which can run on any blend of gasoline or ethanol, allow drivers to make price-driven fuel choices. Today more than 95 percent of all new cars sold in Brazil are flex-fuel (Goldemberg, 2009). About 60 percent of ethanol distilleries in Brazil are dual-purpose, producing sugar when world sugar prices are high, and converting it to ethanol at other times (Ministry for Agriculture Livestock and Supply, 2008).

Other early challenges included the need for a national network for transport, distribution and refueling with ethanol. Initially the Brazilian government undertook all activities related to purchasing, transporting, storing, distributing, and blending ethanol. But the private sector eventually took over and there is now an extensive network associated with ethanol production and use (Goldemberg, 2009).

Although ethanol production in Brazil was initiated as a highly subsidized program, over time, improvements in technology and economies of scale drove down production costs. By 2004, ethanol in Brazil had become economically competitive with gasoline without subsidies (Goldemberg, 2004a).

As of 2010, Brazil was the world's second largest producer of ethanol, after the United States. Brazil produced 569 million tons of sugarcane during 2008-2009, resulting in 27.5 billion liters of ethanol; in the domestic market, ethanol replaces 50 percent of gasoline for transport (UNICA - Sugarcane Industry Association, 2010).

Bagasse, residue from sugarcane, is used for heat and power generation in the refining process, reducing environmental impacts, lowering associated carbon emissions, and improving the economics of ethanol production (Cerri, Easter *et al.*, 2007). The mills not only meet their own energy needs but sell excess electricity to the grid, which provides another source of income. Early production was stimulated through incentives; today, owners of mills can sell directly into the grid through contracts or auctions. In 2010 the installed bagasse capacity was approximately 4,831 MW (ANEEL (Agência Nacional de Energia Elétrica), 2010).

The growth of ethanol produced from sugarcane in Brazil to supply an expanding market as well as exports to other countries has raised concerns over its sustainability regarding soil quality, water consumption, agrochemical inputs and social impacts. Several measures have been enacted to address such problems including ecological and economical zoning laws that dictate where sugarcane and ethanol production can occur (Goldemberg, Coelho *et al.*, 2008).

11.5.6.2 Fiscal Policies

Taxes

Taxes are one of the most widely used and most powerful policy support instruments for biofuels because they change the cost competitiveness of biofuels compared to fossil fuel substitutes in the marketplace. In theory at least, tax incentives or penalties can be gradually increased or decreased as technologies and supply chains develop and as markets evolve. Governments either forgo some tax revenue – in the case of tax breaks – or gain revenue, from added taxes on competing, non-renewable fuels, or on CO_2 emissions from competing fuels for example example (Deurwaarder, 2007).

There are several disadvantages to using tax policy, including: tax breaks can be quite costly to governments, and tax increases can be quite difficult to implement politically (USDOS, 2008). In addition, tax policy can be difficult to modify over time. A partial solution to this could be tax structures that are linked to fuel prices in the market so that they self-adjust. In recent years, the European countries and several of the other G8 +5 countries have begun gradually abolishing tax breaks for biofuels, and are moving to obligatory blending (FAO/GBEP, 2007).

In some cases, like in Germany, the impacts on industry have been dramatic. Prior to August of 2006, German consumers paid no excise tax on biodiesel and the industry flourished, selling 520,000 tons of biodiesel in 2005 (Hogan, 2007). In 2006 the government began to tax biodiesel at a rate of 9 euro cents per litre (0.109 $USD_{2005/}$litre) with plans to scale up the tax up to 45 euro cents/litre (0.548 USD_{2005}/litre) by 2012, the same rate at which fossil diesel is taxed. As of late 2009, German biodiesel was taxed at a rate of 18 euro cents/litre (0.219 USD_{2005}/litre (tentatively deflated by 2008 deflator)] and sales had dropped to an estimated 200,000 tons (Hogan, 2009). This tax policy is responsible for the reduction in biofuels' share of German total fuel consumption from 7.2 to 5.9 percent between 2007 and 2009 (BMU, 2009).

A more dramatic case is the introduction of flex fuel vehicles in Brazil.. For example, reduced taxes on flex fuels cars, and the capability to run on any blend of ethanaol or gasoline, from 100% ethanol to 100% gasoline, resulted in these vehicles accounting for 73% new cars sales in just 18 months (Rothkopf, 2007).

The above examples represent incentives in the demand side. Tax can also be used as a financing tool from supply side as in the case of production tax credit in the tax-equity market of the USA. However, biomass and biofuels are tradable and the market can be international causing a problem in competitiveness. This means that issues like trade policy around import of feedstock or fuels, or policies/subsidies in other another country which might affect the competitiveness of imported products, are also very important. (Hamilton, 2009).

Other Direct Government Support for Biofuels

Governments issue grants, loan guarantees, and other forms of direct support for biofuel production and use systems. In fact most countries that are encouraging biofuels development are using some form or forms of direct loan or grant supports (FAO/GBEP, 2007). It is common for state/province or local governments to give incentives for the construction of domestic/local biofuel production plants to stimulate job creation and economic activity. Direct supports are being used in a number of countries specifically to help accelerate the commercial development of second-generation biofuels. Direct financial supports have the advantage of easily quantified results, however, their outcomes tend to be limited to individual projects, as opposed to broader reaching support instruments. These supports are generally paid for directly by governments (FAO/GBEP, 2007).

11.5.6.3 Indirect Policy

Policies, other than those that are focused on renewable energy, can also be supportive for renewable transport fuels. This section briefly touches on agricultural policies (discussed further in Chapter 2); on storage (discussed further in Chapter 8) ;and on non-RE specific transport policies (for example, urban transport policies, also discussed in Chapter 8); and low carbon fuel standards.

Because nearly all liquid biofuels for transportation are currently produced from conventional agricultural crops, agricultural policies have significant impacts on biofuels markets. This is discussed in more detail in Chapter 2.

Renewable energies such as wind or solar can power vehicles for transportation indirectly with electricity/batteries or hydrogen. Storage technologies are crucial for large-scale deployment of RE to match the variable nature of some renewable sources with demand such that the system improves in responsiveness, flexibility and reliability while reducing capital and operating costs (Schaber, Mazza *et al.*, 2004; Kintner-Meyer, Schneider *et al.*, 2007). Making these secondary forms of energy carriers cost-effective and efficient is one condition for providing renewable energies for transport. This is discussed in more detail in Chapter 8, the technology integration chapter but has implications for policy.

Urban transport policies can facilitate deployment of RE in transportation. Price signals such as parking fees and congestion charges mostly try to regulate transport demand (Prud'homme and Bocajero, 2005; Creutzig and He, 2009), but can induce rapid shift to alternative fuel vehicles by tax or fee exemptions, e.g. by 10 percent discount on the London congestion charge for alternative fuel and electrically-propelled vehicles (Transport for London (TfL), 2009), or free parking for electric cars (Williams, 2008).

Increasingly policies are put in place to reduce the carbon intensity of fuels. For example, in Europe, there is a framework for reducing emissions of new cars from the average 153.5 gCO2/km to 130 gCO_2/km by 2015; and a commitment to further reduce this to 95gCO2/km by 2020 (Arnold, 2009; EC, 2009; UNFCCC, 2009) Similarly, as of January 2010, California is mandating a low carbon fuel standard (LCFS) for an emission reduction of 10 percent from the entire fuel mix by 2020 (CARB (California Air Resources Board), 2009). A price subsidy so called Feebates of California for low-carbon emission vehicle is also an incentive from the demand side (Bunch and Greene, 2010).

11.5.6.4 Infrastructure Policies

Alternative fuels, including electricity, hydrogen and biofuels all require new infrastructures and capital investment to supply transport users with propellants. The dynamics underlying competition between fuels are crucial. Conventional fuels and power trains represent sunk investments, and with experience and economics of scale they have developed down their respective technological learning curves for 100 years; alternative fuels and technologies are naturally disadvantaged. Hence, policies addressing infrastructure investments are needed to overcome fossile fuel dependence. The degree of these investments, however, varies among alternative fuels.

First Generation Biofuels

Most first generation biofuels require among others investments into low-carbon crops, low-carbon agronomic practices , biorefinery construction, biofuel distribution and fueling infrastructure and flex-fuel vehicles. The last three are most relevant from an infrastructure point of view. A price signal on GHG emissions is insufficient to induce construction of biorefineries, for the lock-in effect described enough. Policies addressing fuel producers directly, such as renewable fuel standards or low carbon fuels standards, however, require fuel producers to invest into biorefineries, and hence, are inadequate for this purpose. Biorefinery and co-product utilization, as well as crop management, are decisive in overall life cycle GHG emissions of biofuels. New biorefineries and practices can make ethanol production effective with respective to climate change mitigation (Liska et al, 2008). Hence, policies need to incentivize specifically those infrastructures that enable biofuel production with low global warming potential (e.g., the Californian low carbon fuel standard).

Flex fuel vehicles allow the utilization of biofuels in the vehicle fleet. An increase in the proportion of flex fuel vehicles increases the attactiveness of biofuel production (ESMAP, 2005). Brazil is the world’s largest market for flex fuel vehicles with all gas stations also offering biofuels. In the US, car producers can earn fuel efficiency credits for selling flex fuel vehicles. Sweden jump-started a flex fuel vehicle market by a combination of measures, including a) an initial order of 2000 flex fuel vehicle by the city of Stockholm in 1998; b) tax exemptions for biofuels until 2009; c) demand side instruments such as cash incentives for buyers of flex fuel vehicles and exemptions from the Stockholm congestion charge. As a result, Sweden also provides more E85 fuel stations then all other EU countries combined.

Drop-in Renewable Fuels

An array of technologies are being developed to produce what are being called “drop-in” fuels because they are completely compatible with existing liquid transport fuel distribution and use infrastructure. These fuels include several types of renewable hydrocarbons that can be substituted for, or blended with, conventional gasoline, diesel and jet fuels. These fuels will require significant investments in research, development, and deployment, but no investment in new distribution or end use infrastructure. (Kagan, Joshua and Travis Bradford. Biofuels 2010: Spotting the Next Wave. The Prometheus Institute. GreenTech Media Inc. 2009.)

Electricity and hydrogen infrastructures

Some new renewable transport energy technologies require huge front-up costs, mostly to be paid by the public sector. Electric cars can be slowly phased in as plug-in hybrid electric vehicles, and battery electric vehicles with fuel extender. There will be considerable investments required whether informational or energy efficiency incentives to charge at night to minimize capacity requirements or charging stations (Shinnar, 2003; Romm, 2006). Investments into an hydrogen infrastructure are considered to be in the range of $200-500 billion USD_{2005} for the US (Hammerschlag and Mazza, 2005). Under uncertainty on the future benefits and costs, these investments could constitute a technological lock-in. Multiple equilibria, corresponding to different fuels, are possible; some of them could be far away from the global optimum. It has been warned that a hydrogen economy could be such a suboptimal equilirium (Keith and Farrell, 2003; Ogden, Williams *et al.*, 2004; Hammerschlag and Mazza, 2005). [More research needed].

11.5.6.5 Conclusions

A plethora of instruments address the inclusion of renewable fuels into the transport sector. Success of instruments crucially depends on the evaluation metric. Notably, renewable fuel standard - both volumetric and blending mandates – achieve a rapid augmentation in renewable fuel production and are the most important instrument evaluated in terms of quantity targets. However, renewable fuel standards have limited potential for GHG mitigation (the cheapest biofuels have often the highest life cycle emissions), and are rarely sustainable (competition with food production, rainforest loss). However, renewable fuels standards can be coupled with sustainability criteria. In contrast, low carbon fuel standards are so far less dominant but successfully incentivize low carbon fuels (example: biobuthanol refinery just opened in California). Furthermore, starting market penetration of alternative fuel vehicles, particularly, PHEVs and BEVs, gives leeway for electricity from renewable sources.

Renewable fuel transport policies are challenging for policy makers as a number of diverse and often interacting fuel supply chains, and existing and potential future infrastructure investments are or can be result in unwanted path dependencies. A clear recommendation here is to not support specific favourite fuels (‘fuel du jour phenomenon’, (Sperling and Yeh, 2009), but to chose policies that are technology neutral and provide a level playing field across all (renewable) fuels and focus on performance , e.g. global warming potential (GWP) or some measure of sustainability. Policies that fulfil these criteria are a) LCFSs, b) GHG standards for mobile sources, and c) emission trading schemes that include the transport and electricity sector. These instruments put a consistent price signal on fuels, and hence harmonize incentives.

A second related challenge involves sustainability issues of and emissions from the agricultural sector that are related to transport fuels. In contrast to other sector, emissions are geographically diffuse, vary significantly across production methods, and are plagued with indirect market force effects (ILUC). Similarly, agrofuels can have significant impact on food security, biodiversity and rainforest destruction, potentially compromising its sustainability. More than for other sectors, hence, it is unclear how to comprehensively address the agricultural sector. A way forward is the Californian LCFS which tries to measure ILUC and European sustainability standards. A combination of other instruments, including REDD and a forced transition to second and third generation biofuels may further ameloriate the issue.

A third challenge is the provision of infrastructures. Price signals and technology-neutral instruments deliver a level playing field at one point in time. However, this is not sufficient to achieve intertemporal optimality with respect to our target criteria (GHG emissions and sustainability). For example, a price signal can simply increase the slope of the learning curve of conventional technologies which have a temporal comparative advantages compared to alternative technologies. Measures to address this issue including R&D and protected nurturing areas for new technologies. [more research needed here].

11.5.7 Key Lessons for Policy Design and Implementation

The sections above have described the policy options. This section explains key lessons about their design.

Viable, clear and long-term government commitment and policy frameworks are critical.(International Energy Agency (IEA), 2008). This lesson is demonstrated by the recent history of wind power industries and markets in several countries. Langniss and Wiser (2003) concluded that the early success of Texas renewable policy was based on strong political support and regulatory commitment (Langniss and Wiser, 2003). Agnolluci (2006) pointed to the importance of the German political commitment to wind power development in its success (Agnolucci, 2006). In the case of Sweden, Soderholm et al. (2007) showed that policy uncertainties limited development for a time, in spite of an economically favourable set of policy instruments (Söderholm, Ek et al., 2007).

Ensuring that policies are investor grade will attract more private investment and free-up public finance for other purposes or mechanisms.

Effective and efficient RE policies are based on an extensive and balanced qualification of the diverse renewable sources and technologies, taking into account all relevant variables, including size and ownership (Verbruggen and Lauber, 2009). This means that incentives can decline over time. An appropriate incentive is one that guarantees a specific level of support that varies according to technology and level of maturity.

Policy-makers should try to learn from results of policy mechanisms and stay flexible, changing them when necessary.

A combination of policies will enable a wider group of participants.(Sawin, 2001; REN21, 2005; California Energy Commission and California Public Utilities Commission, 2008; REN21, 2008; van Alphen, Kunz et al., 2008; Sovacool, 2009) The combination of policies needed depends on the costs of the technologies used and their levels of maturity, as well as location and conditions, including local circumstances and available resources (Sawin, 2004b; International Energy Agency (IEA), 2008).

The effectiveness of policies in promoting RE will depend on their design, enforcement, how well they address needs and national circumstances, and the extent to which they are reliable and sustained (Sawin, 2004b; Lipp, 2007; REN21, 2008). Even government policies that are enacted to promote RE technologies can have negative impacts on RE and slow the transition to a low-carbon energy economy if they are not well formulated, inappropriate, inconsistent, or are too short-term (Sawin, 2001; Mendonça, 2007). Further, there must be coherence between RE policy and broader energy policies – for example, subsidies for fossil fuel production and use are incompatible with policies to promote RE (REN21, 2008).

11.6 Enabling Environment and Regional Issues

Energy systems are complex. They are made up of interrelated components. The process of developing and deploying new energy technologies follows systemic innovation “pathways”: innovation most often occurs in concert with several other associated or overlapping innovations. This pathway has been described as a succession of phases from R&D to full market deployment, but these phases are not linear.

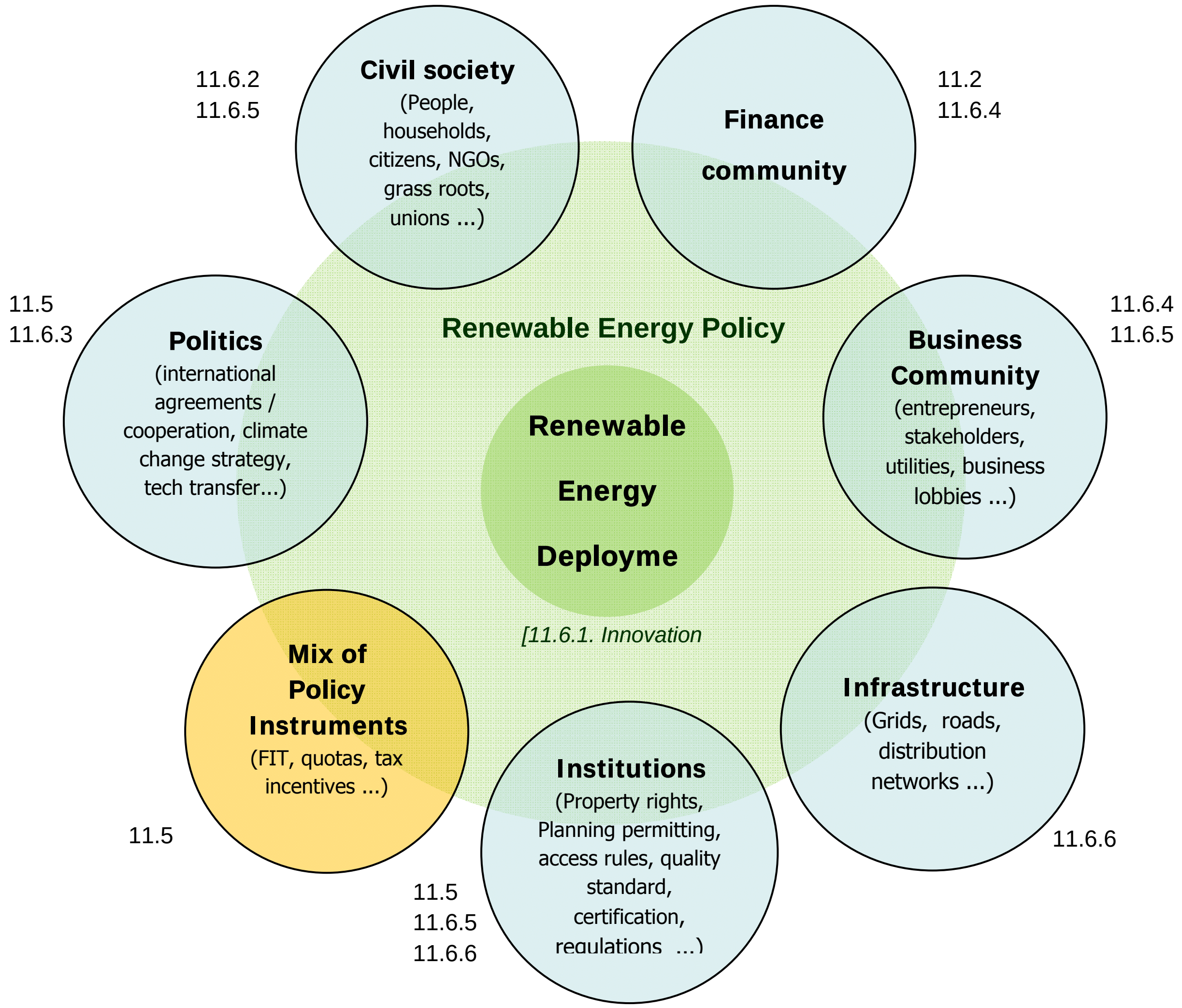

Figure 11.11 RE technology is embedded in an enabling environment, RE policy is one decisive dimension of this environment, but not the only one

The scale of technology development is conditioned by an “enabling environment”, which interlinks with RE policies (i.e. enables targeted RE policies to be more effective and efficient). The enabling environment includes institutions, regulations, the business and finance communities, civil society, material infrastructures for accessing RE resources and markets, and international agreements for facing the challenge of climate change or developing technology transfer (see Figure 11.11).

The Enabling Environment is defined as:

“A network of institutions, social norms, infrastructure, education, technical capacities, financial and market conditions, laws, regulations and development practices that in concert provide favorable conditions to create a rapid and sustainable increase in the role of renewable energies in local, national and global energy systems”

Section 11.5 has illuminated the importance of RE policies. These policies are necessary for RE to get deployed. They can be successful on their own in certain context. For instance, British Columbia and Norway provide examples of countries or jurisdiction with large endowments of renewable energy resource, that RE policies have brought on the way to high penetration of renewable energies (see Box 11.14) (British Columbia Ministry of Energy, 2007).

However, as renewable energy deployment increases, the enabling environment – whether gaining planning permission, gaining access to financing or to the grid – can make renewable energy deployment easier. On the whole, the barriers set out in various parts of the SSREN Report relate to one or several aspects of an enabling environment. If that enabling environment is in place then its related barriers should be overcome or reduced.

So, while RE policies can start very simply, with a mix of the various policy instruments discussed in section 11.5, successful experiences also suggest that developing such an enabling environment contributes to the emergence of well-designed policies and to their success, which in turn contributes to an increasing flow of private investment.

Box 11.14 Norway: Sustainable Hydropower and Balancing Variable RE

Hydropower, "the white coal of Norway" has been a strong driving force in the industrialization of the country (Skjold, 2009). Plants in isolated grids in the bottom of fjords gave rise to energy intensive industries in local fast growing communities. The later national hydropower system was designed for energy security and to deliver base load energy, but with the ability to peak when needed. In early 2010, installed capacity was about 29 GW and the average yearly generation is about 122 TWh, meeting 98-115 percent of Norway's annual electricity demand, depending on rainfall (Norwegian Water Resource and Energy Directorate (NVE) [Norges vassdrags- og energidirektorat], 2009). Reservoir capacity is about 84 TWh, accounting for nearly 50 percent of Europe's total (Norwegian Ministry of Petroleum and Energy (MPE), 2010; Stensby, 2010).

For about a century, hydropower was developed without a coordinated plan. After intense exploitation during the 1970s and 1980s, heightened environmental awareness led to a period of relative standstill in large hydro development and in 1973 the initial national protection plan was adopted. In 1986, the first version of a master plan for hydropower was passed; it categorizes potential projects according to economic and technical viability, but strongly emphasizes potential environmental and social conflicts (Thaulow, Tvede *et al.*, 2010). Approximately 400 rivers are now protected. Of the estimated feasible potential of 205 TWh of hydropower from Norway's rivers, 122 TWh are utilized, 46 TWh are protected, and about 37 TWh are sorted in acceptable/not acceptable projects in the National Master Plan for hydropower (Thaulow 2010). The last 30 years have seen improved environmental and social impact assessment (EIA/SIA) procedures, guidelines and criteria, increased involvement of stakeholders, better licensing procedures; all efforts to make hydropower more sustainable for the long term.

The perceived role of the Norwegian hydro system is now changing. This followed from the deregulation and establishment of the common Nordic market for electricity in the 1990s and establishment of the power exchange Nord Pool (Nord Pool Spot, 2009). Ambitious European goals for RE power generation will be achieved largely through the introduction of significant amounts of variable wind power into the European power system. A system with possibilities for energy storage and balancing services would enable a higher penetration of wind power in the system without compromising the security of supply (Sachverständigenrat für Umweltfragen (SRU), 2010). Today, especially for Denmark, storage hydro from Norway is a prerequisite for a high level of variable sources (>20 percent), and cabling from Norway (1 GW) makes this possible (Jørgensen 2010).

Preliminary investigations indicate that some power stations can already be converted from base load to peak load, giving an additional 7-8 GW peaking capacity. From a technical viewpoint, Norway has a long-term potential to establish pumped storage facilities in the 10 – 25 GW range, enabling energy storage over periods from hours to several weeks in existing reservoirs, and more or less doubling the present installed capacity of 29 GW (IEA-ENARD, 2010).

11.6.1 Innovation in the energy system

The threat of climate change and the need to change the energy system in the span of just a few decades means that the required energy transition is different from past transitions (Fouquet, 2008). It is thus important for policy makers to understand how energy systems change and to ensure that such change is encouraged.

11.6.1.1 Energy systems as socio-technical systems

Energy systems are socio-technical systems. They are made up of mutually dependent set of practices, skills, technologies, infrastructures, coalitions of actors and institutions (e.g. energy lobbies, rules, standards, ways of defining and framing problems ...).

Such systems are very stable because of their strongly interlinked elements. They support the existing technologies by making it easier and cheaper to develop and deploy them, or to develop technologies that do not require a profound transformation of the energy system (e.g. see chapter 8, the bio-fuel vehicle versus the electric vehicle) (Grubler, Nakicenovic *et al.*, 1999; Unruh, 2000)

Energy systems are not value-free. Actors, institutions and even the very structure of the economy end up depending to some degree on the existing technological pathways (Nelson and Winter, 1982). For instance, high fixed costs make large, incumbent firms resistant to technological innovations that might revolutionize the industry – even if these are generated within their own firm – because these might render obsolete their existing equipment, processes and infrastructure. Low carbon energy policies are not business as usual for those already established within the fossil fuel economy. Existing lobbies and vested interests need to be taken into account, because RE are integrating into a system that has built up around the characteristics of fossil fuels and nuclear power (e.g.(Verbong and Geels, 2007).

These reasons explain why changes of system take time, and it is systemic change rather than a linear change. It also explains why an important dimension of RE deployment is the implementation of an enabling environment which is conducive to change.

Policy-makers should thus expect unexpected consequences from their policy implementation rather than expect the transition to be smooth. The practical implication of this is that policy must take account of this by being flexible and reflexive: learn from what happens, experiment, look for best practice, re-evaluate and so on (Smith, Stirling *et al.*, 2005; Stirling, 2009).

The intricacies of technological change means that while all levels of government (from local through to international) can and should play an important role in encouraging RE development through policies, other actors are also important. Policy action is more efficient when state actors include non-state actors, networks and coalitions in building guiding visions, as well as in formulating and implementing public policy (Rotmans, Kemp *et al.*, 2001; van den Bergh and Bruinsma, 2008).

11.6.1.2 Accessing RE technology and capacity building

Even if all the RE technologies were offered free of charge today, most countries in the world – dozens of small developing countries – would not be able to effectively utilize them because of a lack of 'capacity'. In managing RE technological change, a useful meaning of capacity is the ability to make informed decisions regarding RE technology. The technological capacity of countries depends to a large extent on the National Innovation System (NIS). Such systems constitute the scientific and technological infrastructure of a country, and support their capacity to innovate. The state of the NIS includes the level of development of standards, norms, intellectual property rights, technical and scientific education, research financing, incentives, venture capital, foreign direct investment, foreign aid, personal mobility, business models, opening to the world, access to information, capital goods industry, policy, legislation, regulations, etc. Different countries have innovation systems at different levels of maturity and evolving at different paces. For specific RE technologies it is possible to measure the growth of capacity via learning curves over time(Trindade, 1994). And learning curves can be shortened by leapfrogging.

Studies on technology leapfrogging for RE and other low carbon technologies are just emerging. For example, a comparative evaluation of wind technology transfer in India and China, noted that both strong domestic policies, but also the corporate approach to technology transfer has significant influence on the speed and scale of technology advancement and growth of the locally owned business in both domestic and international markets (Lewis and Wiser, 2007). Taking advantage of a global network of subsidiaries allows more rapid technology advancement as well as expanding international sales (e.g. reverse technology transfer). In contrast, however, some argue that industrializing nations will be subject to Carbon Lock-In due to the substantial investment in traditional fossil fuel technologies and that leapfrogging may occur within specific technology or industrial areas, but at a scale insufficient to mitigate future climate change (Unruh and Carrillo-Hermosilla, 2006).

It is possible to reduce the time required to transform the energy system and attain a much increased RE deployment, if the above are taken into account and if long-term strategic thinking and commitment is exerted about the needs of a changing energy system, for example in relation to infrastructure. Developing countries without modern energy systems are undergoing significant change anyway, so ensuring its compatibility with RE provides greater flexibility.

Box 11.15: Lessons from Nepal: Importance of Up-front public investments in capacity development for scaling up RE

The National Micro-Hydropower Programme in Nepal aims to enhance rural livelihoods by accelerating the achievement of the Millennium Development Goals through, primarily, community-managed micro-hydropower systems (MHS). Field experiences under this programme during the 1996-2006 period revealed that capacity development is central to successfully scaling up decentralized energy access programmes and attracting private funding.

An analysis of the Nepalese programme found that upfront, long-term publically funded investment (from government and donors), is essential to developing the functional capacities needed to scale up rural energy programmes and to enable market transformation to occur. More than 90 percent of the early programme costs went to capacity development, which went far beyond traditional notions of typically defined by ‘training’ and/or ‘management’. Functional capacities included: planning, oversight, and monitoring; situational analysis; facilitation of stakeholder dialogue; training; implementation capacities and management support; and the provision of policy advice.

When capacity development is created by systematic interventions, programme successes and maturation over time, it can attract substantial funding from private sector sources in later stages. Indeed, the study found that the share of public financing for the micro-hydro programme gradually declined to about 50 percent. This indicates the important role of public investment in capacity development for attracting private financing sources, particularly decentralized sources among a project’s many users/beneficiaries. Communities provided cash, acquired bank loans, and supplied in-kind labour contributions—by digging channels for the MHS, for example—making up a significant portion of the overall financing needs.

Encouraging private sector participation requires promoting ownership of the MHS and productive use of the energy services it provides. In Nepal, productive uses fueled rural economies and increased the possibility for attracting private investments, including micro-finance. Fostering ownership also proved to be a necessary sustainability component, providing an incentive for users to use and maintain the technology properly.

The study also determined that although the functional capacity ‘policy development and advice’ made up only a small proportion of the total capacity development cost, it is a vital activity that plays a major role in informing policy and regulation development, supporting overall programme success and sustainability. Other steps taken in Nepal to support rural energy service delivery scale up include: the enactment of a rural energy policy in 2006; the development of a rural energy subsidy arrangement and delivery mechanism; the establishment of rural energy funds at different levels; and the exemption of mini-hydropower systems (up to 1,000 kW) from certain taxes, royalties, and licensing requirements.

11.6.2 Sustaining Social Innovation

An important dimension of the enabling environment is that related to ‘social innovation’ – meaning that individuals and institutions can play an important part in helping to make renewable energy deployment easier, quicker and greater in total (Kok, Vermeulen *et al.*, 2002).

Social innovation concern the ability of people and/or institutions to change the way in which they do things so as to adapt and to support the emergence and the deployment of RE technolgies. However, general lessons can be derived from these different areas about how policy can sustain and ultimately benefit from social innovation, as part of an enabling environment. These lessons relate to how institutions learn, or change; as well as to how policies and social aspects integrate to most effect.

11.6.2.1 How institutions learn and change

Collaborative approaches in policy making provide room for interaction between a multitude of stakeholders with diverging problem definitions. In such processes, it has been shown that knowledge is actively constructed through social interaction (Burningham & Cooper, 1999).

Over time, this learning is conducive to institutional capacity-building and policy learning at the level of policy design (i.e. choice and design of a policy instrument, as discussed in 11.5) but also at the deeper institutional level where numerous local decisions on siting and investments in energy schemes have to be made (Thelen, 1999, Breukers, 2007). Private actors (e.g. regional energy distributors, small wind power entrepreneurs) and the civil society develop social skills (e.g. management styles, informal contacts) and benefit from existing (or built-in) social conditions (e.g. trust or social coherence) in order to deal with prevailing institutional structure (i.e. electricity regulation, nature conservation norms; planning procedures) and get RE projects developed. The notion of “implementation capacity” (IC) (Agterbosch, Meertens *et al.*, 2009) has been proposed in order to point at this deeper and more diffuse institutional capacity that policy frameworks, such as planning frameworks, can sustain.

Overall, the capacity of the institutional environment (of any level whether international, national, local) to involve various parties into a common policy network makes it easier for the policy framework to (1) better respond to local political, economic, social and cultural needs and conditions; and (2) better ‘learn’ from outcomes and to incorporate them into ‘future’ policy-making (Breukers and Wolsink, 2007a) for Netherlands, United Kingdom and Germany; (Nadaï, 2007) or (Szarka, 2007) for France).

11.6.2.2 How policies and social aspects can integrate to most effect

The social structure of RE projects has been shown to underlay policy success in developing countries. For instance, community based micro-hydro systems accept lower financial returns (Chhetri, Pokharel *et al.*, 2009). Communities investing in these projects get a return on their money in many ways besides the financial interest they receive. In this context, the role of the civil society in making people aware of the benefits of RE technologies, their ease of implementation and management, is a large reason for growing acceptance of RE technologies in developing countries.

Technology cooperation within social networks is another way in which civil society can enhance policy success. Mallet has analysed the diffusion of passive solar heater (PSH) in Mexico city (Mallett, 2007). She has pointed at the ways in which technology cooperation characterised by a high level of consistent communication (continuous meetings, courses, an annual conference, etc.) within heterogeneous networks (academic, private and public-sector actors) has enhanced public policy.

If policy-makers align the enabling conditions for deployment of RE, for example, by ensuring increased awareness or knowledge of RE technologies [and associated infrastructure requirements], clarifying property rights to a RE resource, developing the necessary skills/capacity to deploy RE through education programmes or other means, or establishing technology standards and certification particular to RE, then evidence shows that broad public support has more chances to follow.

Box 11.16 Denmark’s Experience with Wind Power

Since the 1970s, wind power has developed into a mainstream technology in the Danish energy system, generating 20 percent of Denmark’s electricity by 2009. No other country has a higher level of wind power penetration. In 2009, the Danish wind industry was the country’s largest manufacturing industry, employing some 24,000 people (Danish Wind Industry Association

(Vindmølleindustrien, 2010). It accounted for 20 percent of the global market, and had manufactured every third turbine in operation worldwide (BTM Consult ApS, 2010).

At the time of the oil crises in 1973-74 and 1979, about 95 percent of Denmark's energy consumption was based on imported fuels, mainly oil. Concerns about security of energy supply made RE a top political priority, and over the decades since, a majority in the Danish Parliament has strongly supported wind power. In the 1980s and beyond, energy security, creation of domestic jobs and export markets were the major drivers for transformation of the Danish energy sector (Danish Ministry of Energy, 1981).

A combination of policy mechanisms, guided by national energy plans with long-term targets, has facilitated RE development. A publicly funded R&D programme began in 1976 with the goal to design and test megawatt-scale turbines. In 1979, the government introduced its first and most important policy to stimulate the market, based on a 30 percent investment grant to purchasers of "system approved" wind turbines. This programme ran for 10 years, with regular reductions in the grant level as technology improvements and economies of scale reduced costs. In 1985 the government enacted a per kilowatt-hour subsidy for all wind power fed into the grid, funded in part through a tax on CO_2. A voluntary feed-in tariff (equivalent to 85 percent of the retail rate) paid by utilities to wind producers was fixed by law in 1992 (Madsen, 2009{Sawin, 2001 #318)}.

The investment grants to end-users (private investors) created a small but strong industry with some 18 turbine producers by the early 1980s. Through the 1990s, private investors, often organized in small cooperatives, owned more than 80 percent of total installed capacity. This was largely due to a number of government policies, from special tax breaks to ownership limitations, to encourage individual and cooperative ownership. Investors had to live near their turbines, contributing to a general positive attitude toward wind power implementation (Madsen, 2009). In 1994, each municipality in Denmark became responsible for designating specific areas for wind power, eliminating uncertainty about siting while giving communities control over where projects were located (Sawin, 2001).

Also important were Ministry of Energy "contract policies", which required utilities to participate in wind power development. Under the first such contract, initiated in 1985, utilities were required to construct 100 MW of wind capacity over five years. The utility mandate was extended twice, and the first requirement for offshore capacity was issued in 1990 (Sawin, 2001).

Nearly three decades of consistent policy were interrupted in the early 2000s when leadership changed, the per-kWh subsidy was significantly reduced, and deregulation of the electricity sector created uncertainty (See Figure 11.12). Development was on hold with little new capacity added until 2008 because most projects were not economically feasible (except repowering, which received a premium tariff), and changes in planning structure delayed siting and installation of larger turbines (Madsen, 2009).

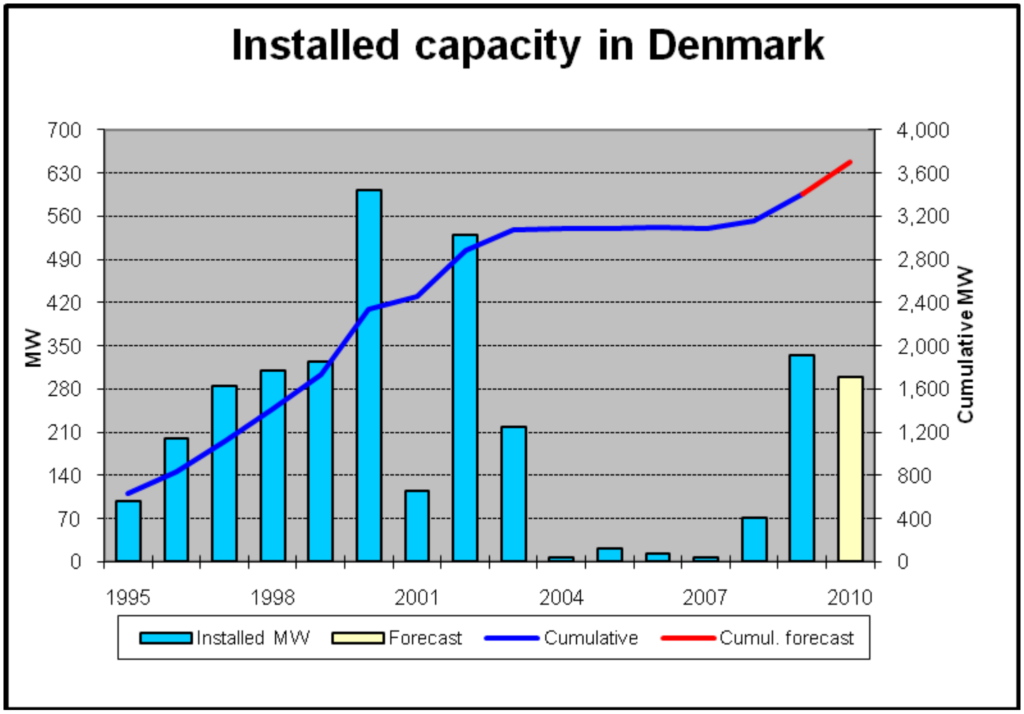

Figure 11.12 Annual and Cumulative Installed Wind Capacity in Denmark (BTM Consult ApS, 2010)

The government has since changed its position, announcing a political target of a "100 percent fossil free" energy system by 2050. As of 2009, Denmark aimed to get nearly 20 percent of total energy from RE sources by 2012 and 30 percent by 2020, with wind power playing a major role (European Union, 2009).

Consistent support for public R&D in Denmark played a critical role in the advancement of wind power technology, education of technical experts, and development of a manufacturing base. Market stimulation in the form of direct grants and later fixed feed-in tariffs, which reduced risk to investors, was essential for increasing installed capacity, reducing costs, and creating a strong domestic industry; but a significant policy changes and uncertainty stalled development for several years. Finally, Denmark's experience demonstrates that if people are involved directly as owners of the turbines, it is easier to implement substantial capacity in a country.

11.6.3 Managing Uncertainty

An important dimension of the enabling environment is its capacity to reduce the risk for RE investors. As risk is reduced, a larger number of projects become attractive in part because the lowering of risk reduces the cost of capital, thereby making the project more competitive. Ultimately, risk has to be reduced to such an extent that the appropriate level of investment, from a suitably diverse set of investors, can occur. Beyond well adjusted policy instruments, such a risk-reward ratio also depends on:

- political stability and commitment;
- institutional setting.

While there are multiple ways in which governments can commit their successors (e.g. by strategically managing public debt, founding independent agencies, amending written constitutions ...) (Persson, Tabellini *et al.*, 2000) , RE deployment has been more successful in the countries where governments have explicitly asserted and enacted strong political support and regulatory commitment to the deployment of renewable energies. Successful examples have been, for instance, Texas (Langniß and Wiser, 2003), Germany (Jacobsson and Lauber, 2006), Denmark approach to wind power policy or Brazil approach to ethanol policy (Teixeira Coelho et al. 2006). Symmetrically, the lack or delayed development of such long-range and stable political commitment (Meyer, 2003 & 2007 for Denmark recently; Soderholm et al., 2007 for Sweden), or the threat to existing political commitment (Agnolucci, 2006; Agnolucci, 2007)for Germany) has been shown to explain differences or slow down in wind power development in different countries.

Institutional settings, such as long-term contracts play a decisive role in stabilizing investors' expectations in the RE sector (Langniß and Wiser, 2003). Public institutions can get directly involved into public-private partnerships, as they did for wind power in Spain , where high investment risk in the first versions of the Spanish FIT was mitigated through the implication of a specific public agency acting as an investing partner into the wind power projects (Dinica, 2008).

Innovative business models (i.e., partnerships between global companies and government, local enterprises, donors or NGOs) have recently been tried in order to develop support for starting up and scaling up business activities that are aimed at the 4 billion poorest people in the globe (Hart and Christensen, 2002; Prahalad, 2006; Kandachar, 2008; Wilson, 2008). Recent cases show that multinational companies targeting these markets can contribute to poverty alleviation and to energy access (IIED, 2009). In certain contexts, community ownership is a way of reducing the risks for private household and micro-generation. Changing energy systems faces private household with uncertainty and budget constraints. Some developing countries (e.g. Vietnam, Nepal, Pakistan) have supported community ownership in micro-hydro power project management and operation as a way for people to share risk through collective decision. There are already a significant number of micro-hydro systems financially supported by local communities, local banks or local entrepreneurs (Pokharel, Chhetri *et al.*, 2008).

11.6.4 Easing Access to Financing

A broader enabling environment includes a financial sector that can offer access to financing on terms that reflect the specific risk/reward profile of a RE technology or projects. The cost of capital of such financing - the interest rates charged by banks or the return that investors require on their investments - depends both on the broader financial market conditions prevalent at the time of investment, and the specific risks of the technology, the project and the actors involved. The broader conditions generally determine the minimum cost of capital, which is then increased by a risk premium specific to the financing opportunity. The cost of capital has become more closely linked to financial markets with the shift from public to private sector investors.

Although the public sector has traditionally been the principal investor in energy supply infrastructure, usually through national utilities, in the RE sector investments have tended to originate from the private sector (Asian Development Bank, 2007). In 2005, the private sector accounted for well over 90 percent of all investment in the RE sector (UNFCCC, 2007).

11.6.4.1 Drivers for RE investments

The universe of private capital sources most relevant to the RE sector include corporate investors such as utilities, banks, institutional investors, and the capital markets more broadly. The development, expansion, and globalization of the capital markets since 1980 have created significant and growing pools of internationally mobile institutional investor capital. The managers of these institutional funds are under constant pressure to find high-quality investment opportunities that deliver adequate returns and manageable risks. Where institutional structures, regulation and incentives for RE technologies match the requirements of these institutional investors then the opportunity exists for capital deployment to the sector (Asian Development Bank, 2007). However the various classes of capital each have their own drivers, expectations and appetites for risk.

Non-RE specific issues that directly affect access to and cost of financing include political, country and currency risks as well as energy-sector related issues such as:

- Energy sector reform agendas: many countries have undertaken power sector reforms since the 1980s in an attempt to improve sector efficiency and to augment public resources with private sector financing. In most circumstances such reforms, particularly the establishment of independent regulatory institutions, have encouraged greater private sector participation and improved access to commercial financing (Asian Development Bank, 2007). However progress of these reforms has not always been smooth.
- Competition for investment – Investors that target the energy sector have, to date, tended to be drawn toward conventional energy investments as they have tended to yield a better return per unit of effort invested given the size of deals and, generally, clearer policy objectives and regulatory frameworks.
- Credit Risk – A fundamental determinant of the cost of capital for a project is the credit risk of the payment counterparty, that is, the customer. Often this is the state utility that may not be considered credit worthy by private investors.
- Ability to exit – Investors require identifiable exist opportunities to eventually sell-on their investments, usually either to a strategic investor like a utility or by way of a listing on a public stock market. Exit opportunities are usually more restricted in developing countries, both due to the macro financial conditions but also sometimes to specific policies. For example, governments may restrict the transferability of shares to protect domestic interests.

The fundamental principle of modern global capital markets is that private capital will flow to markets where policies and related regulatory frameworks that govern investment are well considered, clearly set out, and consistently applied in a manner that gives investors confidence over a time scale appropriate for their investment life cycle (Asian Development Bank, 2007).

11.6.4.2 The recent evolution of the RE financial sector

For the RE sector these conditions have been met in many countries, to varying degrees. Around 2004 the capital markets began to change the enabling environment for technological innovation in several RE sectors. Up until that time renewables, like most other technology sectors, relied on government and corporate R&D to drive innovation, and on large corporates to self-finance the commercialization of technologies that were market ready. In 2004 a number of solar and wind companies in Denmark, Germany and Japan began to generate significant revenues, in the hundreds of millions and eventually billions of dollars per year. These strong revenue figures signalled heightened interest from the investment community for the first time.

With financiers now keen to engage, RE entrepreneurs could raise financing more easily from the capital markets than from the large corporates which they were so dependent on previously. This change meant that between 2004 and 2006 much of the RE technology leadership shifted from large diversified corporates to dedicated renewable-only companies. Easy access to venture capital to finance technological development, to equity financing to build manufacturing facilities, and to cheap debt to finance projects meant that the very capital intensive RE sector was about as enabled as it could be from the financial point of view. In other words, access to finance was not a problem for any well prepared project or technology opportunity. This situation changed in 2008/2009, when the financial and broader economic crisis cut off the access to debt financing, particularly for long term, capital intensive investments like renewables.

However, policies support and strong government interferences helped lots of companies to survive the hardest year. For example, in US, the government introduced the Investment Tax Credit, to replace the (at least temporarily) dysfunctional Production tax Credit, which was facing huge difficulties due to the lack of any large financial institutions that needed to shield hundreds of millions of dollars from tax. In Europe, government grants and policy driven banks helped to finance some of the projects. Utilities also financed some new projects off their own balance sheets (UNDP, 2006; Deutsche Bank, 2009). .

11.6.5 Planning, Permitting and Participation

Few areas in the world are truly devoid of/lack traditional uses, conservation values or existing commercial interests. As a result, the growing deployment of RE technologies may create tensions. Rules are needed to resolve conflicts over access to RE resources. This section addresses the general lessons learned from the planning and permitting of renewable energies. Technology issues for planning are in the relevant technology chapters

Evidence shows that spatial planning (land / sea space, landscape) processes are social processes. They can bring parties into negotiation and open public consultation. In doing so, they enhance social wishes and contribute in clarifying social acceptance or conflicts of usage. Planning runs the risk of making administrative procedures more complex but an appropriate planning framework can reduce hurdles at the project level, making it easier for RE developers, communities or households to access the RE resource and succeed with their projects.

11.6.5.1 Planning challenge and hurdles

A main challenge for policy makers is to design a balanced planning regulation that broadly supports the deployment of RE technology while at the same time establishes procedures that ensure public insight and environmental protection. This, in many countries, calls for institutional reforms as well as changes in planning practices at different levels of decision making.

This holds for large-scale RE technologies (e.g. wind turbines, ocean energy technologies, concentrated solar power...) and for smaller scale technologies (e.g. individual solar panels, small-scale biomass...) even if the environmental and social impacts and corresponding planning issues vary a lot between different types of RE (See Table 11.5).

Table 11.5 Environmental and social issues that planning and planning and permitting face

Renewable energy	**Environmental and social impact in relation with spatial planning**
Biomass	Emissions from combustion Visual impact of energy crops
Biogas plants	Smell (distance)
Solar	
• Installation on buildings	Aesthetics and architectural design
• Large solar plants	Land use & landscape aesthetics challenges
Hydro	
• Large scale	Social impact and impact on local ecosystems
• Small-scale	Impact on local ecosystems
Geothermal energy	Air and water pollution Local seismicity
Marine energies	Impact on marine life Conflict of usage
Wind power	Visual impact and landscape aesthetics Noise Impact on birds and marine life (offshore)
New supporting infrastructure (often in remote areas) Electricity grids District heating pipelines	Visual impact, landscape aesthetics, conflicts of usage

Lengthy permitting processes, high applications costs, lack of data or low access to data, lack of local or regional capacity, or local public opposition can make planning and permitting processes can become prohibitively long. This has favoured proposals for streamlining planning and permitting procedures (California Energy Commission and California Public Utilities Commission, 2008); OPTRES, 2007). While some project developers may regard this system as a 'barrier', for others it provides protection against overenthusiastic developments that may not be beneficial to the local community or local environment at all. Hence, planning and permitting, even if it is sometime assimilated to mere administrative barriers, also has a potential as social a process (Ellis, Cowell *et al.*, 2009).

11.6.5.2 *Why planning and permitting can support the sustainable deployment of RE technologies*

The sustainable deployment of RE technologies is a long-term transition process. It involves (radical) changes in the relationship between (energy) technology and society, and raises questions about how people can become engaged in and committed to these systemic changes (Guy and Shove, 2000)(Hodson et al, 2007). Spatial/land use planning plays an important role, because they structure the socio-technical and political processes that enable changes in our spatial environment (including the deployment of RE technologies).

It is often in the process of preparing, designing, planning, deciding and implementing a specific project, that differences in perspectives, expectations and interests become manifest. The system of spatial/land use planning provides for a framework - a set of legal, formal rules and procedures - to address these differences and mediate conflicting interests and values (Owens and Driffill, 2008; Ellis, Cowell *et al.*, 2009). This framework is in line with the political culture of a country and reflects historically evolved 'ways of doing' – e.g. traditions of administrative coordination between levels of government, with more or less autonomy for local governments in taking decisions on local land use. Renewable energies, because of their often decentralized dimension, face planning institutions with issues as regards to the allocation of decision making (Kahn, 2003; Söderholm, Ek *et al.*, 2007; Bergek and Jacobsson, 2010) for wind power and decentralized institutions in Sweden; (Nadaï, 2007) for wind power and centralized institutions in France).

Planning systems are thus historically and culturally embedded. There are wide differences between countries. The same goes for permitting procedures. Whether conflict is likely to occur depends very much on the specific context and on the type of project development under consideration. For instance, where landscape amenity is a cultural-historical value this may be a huge issue for a wind project (e.g. (Cowell, 2010; Nadaï and Labussière, 2010), this may be less the case in countries where this is not the case (Toke, Breukers *et al.*, 2008).

The *sustainable* deployment of RE technology means that social acceptance and commitment are sought for. While the articulation between the national and the local level seems decisive in achieving this (e.g. (Smith, Stirling *et al.*, 2005; Nadaï, 2007; Bergek and Jacobsson, 2010), universal procedural fixes – e.g. "streamlining", speeding-up legislation or directive measures – are unlikely to resolve conflicts between stakeholders at the level of project deployment (Breukers and Wolsink, 2007b; Agterbosch, Meertens *et al.*, 2009; Ellis, Cowell *et al.*, 2009)because they would discard the place - and scale specific conditions. However, it is still useful to point out those conditions that have shown to be favourable for arriving at a sustainable deployment of RE technologies in various studies.

11.6.5.3 *How planning and permitting can support the sustainable deployment of RE technologies*

For each condition, we indicate how spatial planning can create/support this favourable condition.

Aligning stakeholder expectations and interests

Several case studies have shown the importance of alignment of interests between various stakeholders (Warren et al., 2010; Devine Wright, P., 2005). This can be done through several ways such as adopting procedures for project development that are judged fair by the different parties (Gross, 2010) or by identifying (creating, negotiating) in the ‘pre-application process’ multiple benefits that a RE project may bring for different stakeholders (Ellis et al 2010:538 ; Heiskanen et al, 2008).

Learning about the context

A more pro-active effort could be taken to learning about the local societal context in which a RE project is going to be proposed (Breukers and Wolsink, 2007a); Raven et al, 2008). In particular, the recent case of wind power opposition has proved that opposition cannot be dismissed as ignorant or misinformed instead it must be acknowledged that objectors are often very knowledgeable (Ellis et al., 2007). Public attitudes and responses to wind power should not then be examined in order to mitigate potential future opposition, but rather in order to understand the social context of renewable energy (Aitken, 2010; Gee, 2010).

Adopting benefit sharing mechanisms

Benefits can be social (e.g. local control, ethical and environmental commitment, feeling of positive contribution to society ...), environmental (e.g. contribution to global environment...) or financial /economical (e.g. creating local revenues, market for local wood, agricultural wastes ....) (Rogers, 2008; Walker, 2008; Madlener, 2007). However, in the current state of affairs, benefits related to RE projects mostly accrue to the global community as whole – CO2 reduction – and to the project developer – financially (e.g. Bell et al. 2005). An acknowledgement that benefits, costs and risks are unequally distributed can be followed by efforts to arrive at a more equitable distribution. Evidence shows that when local economic involvement is high the overall opposition to developments tends to be lower (Jobert, Laborgne *et al.*, 2007; Maruyama, Nishikido *et al.*, 2007).

Benefits sharing encompasses mechanisms for the local communities to participate in the benefits generated by the development. They may include: co-ownership (Meyer, 2007 for Danish wind power ; Walker, 2008 ; Deepchand, 2002 for the Bagasse Transfer Price Fund and Sugar Investment Trust in Mauritius); local employment by making use of / setting up local contractors and services (Faulin et al., 2008 for wind power in Navarre, Spain; Heiskanen et al, 2008; Agterbosch and Breukers, 2008); benefits in kind through direct re-investment of part of the benefits by the developers in local community infrastructures (Upreti, 2004 , for glasshouse development in relation to the Elean Power Station in Ely, Cambridgeshire, UK) ; transfer of benefits through lump sum or business tax to local communities (Faulin et al., 2008; Nadaï, 2007 for wind power in France) ; energy price reduction (e.g. Deepchand, 2002), environmental compensation (Cowell, 2003 negotiation about an amenity barrage across the Taff-Ely estuary in Cardiff).

Timing: pro-active national and local government

Clear procedural rules (e.g. requirements for permitting, ground for court appeal, allocation of responsibilities and timing of the process ...) are important to reduce risks for the developer and to ensure legal security for stakeholders.

National planning policies sometimes lag behind initiatives of those deploying innovative technologies and therefore hamper these innovations. Legislative changes or case by case approach might be required. In the UK, recent legislative changes have been adopted in order to ease micro-renewables development (McAllister, Scott *et al.*, 2009). In many countries, marine energy projects at an early commercial stage find themselves in a “Catch-22” situation, where regular permitting regime requires project impact data that could only be produced if a temporary authorization was granted to them (IEA, 2009a) : project license lease, pilot development zones or specific site agreements have been used as tailored solutions.

Local governments are also often caught by surprise when a project developer presents a RE project proposal (Agterbosch and Breukers, 2008; Breukers and Wolsink, 2007; Nadaï & Labussière, 2010). Organising local participation in the development of comprehensive plans, where main siting areas can be identified before any project is planned makes it easier to create an open and non-polarised discussion (Sussman, 2008).

Last, the articulation between the local and national level is often decisive for the way in which RE project get politicized at the local level. Lack of political support to RE from the national level can favour local polarization by making RE impact be perceived as a private rather than a public issue (Bergek and Jacobsson, 2010).

Building collaborative networks

The success of a RE technology project depends on multiple actors and conditions. Building collaborative networks is part of the sociotechnical change process towards a more sustainable energy system. Involving relevant stakeholders and making them part of the solution is more likely to result in long-term acceptance and lasting commitment than taking an approach that overlooks and excludes them. Networks are furthermore important ‘vehicles’ for exchanging experience and knowledge and hence support learning processes (Breukers and Wolsink, 2007; Heiskanen et al, 2008; Negro et al, 2007; Suurs and Hekkert, 2009; Dinica, 2008; Mallet, 2007). They can also support radical innovation in “ways of doing” such as the renewal of landscape values or bird protection approaches in relation to wind power (e.g. Nadaï in Ellis et al., 2009; Nadaï & Labussière, 2009 and 2010).

Mechanisms for articulating conflict and negotiation

The deployment of a RE project usually will not serve everyone’s’ interest. Existing formal avenues to voice opposition usually only offer room to object to a ready-made project proposal (Wolsink, 2000). Such decide-announce-defend strategy, which is traditionally associated with technocratic decision-making, is both questionable on democratic grounds and counterproductive (Healey, 1997). Discussions tend to get stranded in polarised pro-contra controversy, leaving little room for constructive deliberation. It is useful to create room for the articulation of conflicting perspectives in order to be able to subsequently jointly seek for solutions or compromises (Cuppen et al, 2010).

11.6.5.4 Pro-active, positive, place - and scale-sensitive planning and permitting approaches

Overall, the lessons learned stress the extent to which sustainable energy transitions and spatial and urban planning are interwoven. It point towards the need for evolving planning and permitting towards a pro-active, positive, place - and scale-sensitive systems. It also points at the lasting benefits of social innovation, as a strategy developed and implemented within and together with society. Such a planning and permitting strategy includes:

The development of planning policy that reflects on the various democratic mechanisms in place and crosses sectoral boundaries (energy, agriculture, transport, etc) in order to foster a more integrated approach towards energy transitions and facilitates the aligning of interests at a supra-local level - e.g. by providing support to foster collaborative networks between spatial planners, technology developers, technology implementers, end users, and other societal stakeholders –;.

The development of strategic planning upstream from project development at scales which fit the specificities of each RE technology and the differences in local and national contexts.

The fostering of institutional capacity, with the required resource (finance, knowledge, know-how ...) and power endowments at the level(s)(national and local) where projects are planned, decided and sited, in order to create institutions that are able to: anticipate and sustain the emergence of new RET projects; set timely local participation for collaborative networking and co-construction of plans; identify multiple benefits and benefits sharing mechanisms in relation to local needs, concerns, ambitions and expectations.

Additional knowledge is needed, especially, in relation with the experiences in developing and transition countries, where RE policies are in place, deployment can be already significant (e.g. China, India) but context-specific understanding of planning processes has not been analyzed.

11.6.6 RE Access to Networks and Markets

RE needs to be sited and then its output used, whether on-site or sold. In the latter case, RE projects need to connect to networks in order to sell their electricity or heat. Once connected, the generation or heat has to be sold or 'taken' by the network. These two requirements: connection and then sale of energy are two different requirements. The ease, and cost of fulfilling them, is central to the ability for projects to raise finance and get a chance to be developed. Chapter 8 approaches these dimensions by focusing on cross-cutting integration issues. This section discusses these issues in relation with different dimensions of the enabling environment such as its institutional (e.g. spatial and energy planning) and infrastructural (e.g. grid development) framing, but only for electricity.

11.6.6.1 Connection charging and network access

RE projects often need to be located in areas where the electricity grid is weak. This raises difficulties in connection as, once planning consents are achieved, RE projects can often be constructed in shorter timescales than that of the associated infrastructure reinforcement. In addition variable-output RE such as wind requires back-up in the form of flexible conventional generation, giving rise to the need for RE and conventional generation to "share" available grid capacity, depending on whether renewable resource is available or not. The deployment of RE therefore challenges traditional concepts of grid management; a new paradigm is required to deliver flexibility in design, operation and market rules.

In the EU, the Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources, states that EU Member States must ensure that transmission and distribution system operators guarantee grid access for electricity generated by RE (EU, 2001). This is both connection and off-take. In general, but not always, the fundamental design feature of FITs is a project's connection to grid, and the off-take of the electricity, according to a defined process and cost. As a result of the EU Directive, some European countries, particularly those which have FITs, have implemented connection regulations that guarantee access to the grid. These regulations ensure that transmission and distribution system operators guarantee grid connections for RE electricity.

However, despite the EU Directive requirement of providing 'priority access' for RE, some countries (i.e. the UK) have argued that they have fulfilled the Directive through its market mechanism without ensuring both connection (and its cost) and off-take of the renewable generation (Baker, Mitchell *et al.*, 2009). Connection to the grid in the UK is a very time-consuming and costly requirement, which acts as a significant barrier to RE deployment (Baker et al, 2009).

'Priority' grid access is, at it says, when RE generation is given priority access to the grid, before other forms of generation. This requires a purchase obligation, which requires grid operators, energy supply companies, or electricity consumers to buy the power generated from RE at the moment it is offered. It has been argued that such a requirement is not compatible with the market because it requires electricity purchase independent from demand (Ragwitz, Held *et al.*, 2005). Others argue that RE (other than dispatchable resources like biomass and some dam hydropower) should receive priority access because the short-term marginal cost is close to zero (Jacobsson, Bergek *et al.*, 2009; Verbruggen and Lauber, 2009).

11.6.6.2 Increasing Resilience of the System

One of the biggest challenges for the integration of renewable electricity into the system is to deal with the variability, given that the output varies with the availability of the resource of some RE technologies such as wind, solar, run-of-river hydro, and ocean. The resilience of an energy system is its capacity to integrate variable energy output while keeping matching the energy demand. Again, this is the focus of Chapter 8 and we do not replicate the much deeper discussion there. However, we put forward a few key policies related to integration and market access to highlight the importance of institutional adjustment in this area.

As the percentage of renewable energy increases there is an increasing requirement of resilience within the energy system (UKERC, 2009b). Smoothing the effects of the variability can be improved through: aggregation, forecasting and integration in the market (IEA, 2008a). Spain has chosen to promote this as a means to encourage RE by requiring the mandatory aggregation of all wind farms in Delegated Control Centres which are in on-line communication with the National Renewable Energy Control Centre (Tongsopit, 2010). The introduction of variable-output RE will also increase the volatility of energy prices, particularly in those markets that do not reward capacity explicitly. This could impact particularly on investment in high capital-cost low carbon generation such as CCS and also flexible conventional generation required in the medium term for back up purposes. Increasingly volatile energy prices may therefore bring forward the need for further direct support measures in order to deliver the capacity required (GB Treasury, 2010; Ofgem, 2010).

As variable output RE such as wind cannot forecast output with any accuracy until close to the event, it cannot be expected to participate in the traditional forwards market model. Electricity markets will need to develop intra-day trading, shorten gate-closure timescales and provide efficient, liquid and cost reflective balancing arrangements to ensure the most effective use of RE . An increasingly flexible approach to trading reduces the impact of forecast errors and will encourage demand-side participation, thereby reducing the need for additional fast response power plants, interconnection or storage (IEA, 2008a). The different uses of flexibility resources will determine the flexibility of the system (IEA, 2008). Measures, such as the increase of the interconnection capacity within systems or demand side management measures would help to integrate more wind power, for example, especially in extreme situations (Alonso, Revuelta *et al.*, 2008).

11.6.7 Integration of RE policies with other sector policies

RE policies interact with many other sector policies. Some of these have been described within the discussion of the enabling environment in this section, for example RE and planning policies. RE also interacts with climate change policies (See Box 11.17). General RE integration issues are addresses in Chapter 8.

Box 11.17 The economic implications of interactions between climate change mitigation policies and renewable energy support policies

The logic for renewable energy policy in addition to carbon policy

It is well-understood that climate change involves two major market failures (Stern, 2006). First, polluters do not pay for the damage caused by greenhouse gas emissions, so government intervention is required to put an explicit or implicit price on emissions (Pigou, 1932). Second, research and development, innovation, diffusion and adoption of new low-carbon technologies creates wider benefits to society than those captured by the innovator (Jaffe, 1986; Griliches, 1992; Jaffe, Newell *et al.*, 2003; Edenhofer, Bauer *et al.*, 2005; Jaffe, Newell *et al.*, 2005; Popp, 2006a), so without government intervention there will be too little low-carbon innovation. With at least two market failures, it follows that at least two broad policy approaches are required (Tinbergen, 1952), namely carbon pricing (by carbon trading, carbon taxes, or implicitly through regulation) and support for research and development and diffusion of low-carbon technology. Otherwise, the two objectives have to be traded off against each other, and one of the objectives would have to be sacrificed to some extent. For instance, carbon pricing on its own is likely to under-deliver investment in R&D of new technologies (Rosendahl, 2004; Fischer, 2008).

In this context, there are three broad reasons that may be advanced for support of renewable energy (RE) alongside climate-change policy. First, governments have not yet implemented “ideal” carbon pricing or “ideal” low-carbon technology support. Carbon prices are often non-existent or lower than estimated social costs (Stern, 2006)Tol, 2009), and have not provided a sufficiently credible basis for a large-scale shift towards low-carbon investment (Helm et al, 2003). As such, there is role for additional “second best” government intervention, including RE policies, to better address the climate externality.

Second, even if governments were to implement “ideal” carbon pricing and “ideal” research and development support, there are a range of other relevant market failures, including financial market failures, oligopoly and imperfect competition, information failures and labour market failures (Sjögren, 2009) that might justify additional intervention. For instance, if fossil energy is provided by a cartel which extracts rents from consumers, carbon taxes might merely shift rents from fossil energy producers to governments, without changing producer prices and without reducing emissions. To take another example, financial market failures may imply that perceived risks of RE investment are greater than actual risks, resulting in too little investment. These other market failures can imply that additionalis (Sjögren, 2009) policies, such as RE policies, may be justified to complement climate-change policies.

Third, RE yields a range of other non-market benefits, including reductions in local air pollution, heath benefits, safety benefits, and job creation relative to fossil-fuel based energy production.

Without government policy to account for these benefits, the supply of RE will be too low even if carbon prices are "ideal". These benefits might be internalised by other policies (e.g. local pollution regulations), but if they are not, direct support for RE is an alternative way of achieving these objectives.

In the presence of multiple market failures, a variety of models suggest that an optimal portfolio of policies can reduce emissions at a significantly lower social cost than any single policy (Popp, 2006a; Popp, 2006b; Grimaud and Lafforgue, 2008; Acemoglu, Aghion *et al.*, 2009; Schmidt and Marschinski, 2009). The policy portfolio might include an emissions price, an R&D subsidy, a RE subsidy, and potentially also fossil-fuel taxes and emissions or energy performance standards. It appears that an optimal policy mix would use emissions pricing to incentivise the bulk of the emissions reductions (Fischer, 2008; Fischer and Newell, 2008; Otto, Löschel *et al.*, 2008; Richels and Blanford, 2008).

Potential perverse outcomes from RE and climate-change policy

These reasons suggest a role for policy providing support for RE in addition to climate-change policy. However, given the close relationship between RE policy and climate-change policy, policies need to be designed carefully. Perverse outcomes are possible from RE or climate-change policies alone, before considering their interactions.

First, both climate-change and RE policies create risks of "leakage". RE policies in one jurisdiction reduce the demand for fossil-fuel energy in that jurisdiction, which *ceteris paribus* reduces fossil-fuel prices globally and hence increases demand for fossil energy, to some extent, in other jurisdictions. Similarly, climate-change policies in one jurisdiction increase the relative cost of emitting in that jurisdiction, providing firms with an incentive to shift production from plants facing carbon prices or regulation to plants in countries with weaker climate change policy (Ritz, 2009).

The scope of offset provisions within a carbon cap-and-trade system (the Clean Development Mechanism or Joint Implementation, for example) can also affect the renewable objective by reducing the incentive to deploy renewables technologies within the borders of the renewable mandate (del Río González, Hernández *et al.*, 2005).

Second, both climate-change and RE policies apply over long periods and require careful consideration of "dynamic effects". The prospect of future carbon price increases may encourage fossil fuel owners to deplete current resources more rapidly, undermining policy-makers' objectives for both the climate and the spread of renewables technology (Sinn, 2008). If this holds true, the optimal carbon price trajectory is not a steady rise at the rate of interest, or the discount rate plus the rate of decay of greenhouse gases in the atmosphere, often assumed in models of optimal climate-change mitigation policy (Paltsev, Reilly *et al.*, 2009). Rather, a downward time profile of carbon prices would persuade resource owners at least to delay extraction (Sinn, 1982; Sinclair, 1992; Sinclair, 1994).

However, this result may not hold for several reasons. First, Edenhofer et al. (2010) note that Sinn's model rests on the assumption that all fossil resources are extracted, yet an emissions trading scheme could set a cap that restricts the total extracted. There is an time profile for carbon taxes that will have the same effect (Kalkuhl and Edenhofer, 2008). Second, as an empirical matter it is unclear whether fossil fuel resource owners would rush to deplete their resources. Pindyck (1999) found that the standard model of exhaustible natural resource pricing

(Dasgupta and Heal, 1980), which underlies Sinn's argument, applies reasonably well to behaviour in oil markets, but less well for coal and natural gas. Other theories of behaviour – such as those emphasising geopolitical and fiscal factors, particularly the need to finance public spending – may be appropriate, especially when the owners are sovereign governments (Slaibi, Chapman *et al.*, 2005). Third, it is possible to construct general dynamic models accounting for these effects, which still show optimal carbon prices first rising before eventually declining (Ulph and Ulph, 1994; Hoel and Kverndokk, 1996).

Interactions between RE policy and climate-change policies

If both climate and RE policies are administered simultaneously, their impacts are unlikely to be the same as expected of each alone (de Miera, del Río González *et al.*, 2008; de Jonghe, Delarue *et al.*, 2009) and while they can potentially work together (Popp, 2006b; Popp, 2006a; Grimaud and Lafforgue, 2008; Stankeviciute and Criqui, 2008; Schmidt and Marschinski, 2009), they can also undermine the efficiency of each other (Sorrell and Sijm, 2003; Rathmann, 2007).

For instance, if a RE quota-based scheme is combined with a carbon market, and one market is notably more stringent than the other, the price in the weaker scheme could fall to zero (Unger and Ahlgren, 2005; De Jonghe et al., 2009). Conversely, if one price-based (e.g. RE subsidies) and one quantity-based measure (e.g. emissions trading) are combined, the price instrument could affect the market price of the trading scheme. For instance, RE subsidies added to an existing carbon cap-and-trade scheme would be unlikely to reduce emissions, but would instead reduce carbon prices, thereby deterring private investment in non-RE abatement technologies (Blyth et al., 2009). This suggests that impacts of RE policies should be factored into setting the carbon cap. More generally, it implies that RE and carbon policies should be carefully coordinated both at the initial stages and subsequently as circumstances change (De Jonghe et al., 2009; Rathmann, 2007; Blyth et al., 2009; Verbruggen and Lauber, 2009).

11.6.8 Conclusion and key messages

The scale of technology development is conditioned by an enabling environment. As renewable energy deployment increases, the enabling environment – whether gaining planning permission, gaining access to financing or to the grid – can make renewable energy deployment easier.

Many countries in the world – including dozens of small developing countries – do not currently have the necessary 'capacity' for RE policy-making, financing and implementation.

Energy systems are complex socio-technical systems which are very stable, because of their strongly interlinked elements, and are not value-free. As a result, system change takes time, and is systemic rather than linear.

Because of the complexity of the energy system, Policy-makers should expect unexpected consequences from their policy implementation rather than expect the transition to be smooth, and counter the unexpected consequences by being flexible and reflexive

An important dimension of the enabling environment is that related to social innovation Social innovation concern the ability of people and/or institutions to change the way in which they do things so as to adapt and to support the emergence and the deployment of RE technologies. Policy can sustain and ultimately benefit from social innovation, as part of an enabling environment.

An enabling environment can reduce the risk for RE investors. Risk has to be reduced to such an extent that the appropriate level of investment, from a suitably diverse set of investors, can occur and the financial sector can offer access to financing on terms that reflect the specific risk/reward profile of a RE technology or projects.

Rules are needed to resolve conflicts over access to RE resources. Spatial planning (land / sea space, landscape) processes are social processes. They can bring parties into negotiation and open public consultation. In doing so, they enhance social wishes and contribute in clarifying social acceptance or conflicts of usage. Planning runs the risk of making administrative procedures more complex but an appropriate planning framework can reduce hurdles at the project level, making it easier for RE developers, communities or households to access the RE resource and succeed with their projects.

Non-on-site RE electricity and heat projects may need to connect to a network in order to sell their energy. Once connected, the energy has to be sold within a market or 'taken' by the network. These two requirements: connection and then sale of energy are two different requirements. The ease, and cost of fulfilling them, is central to the ability for projects to raise finance and get a chance to be developed.

RE policies interact with many other sector policies, as well as with climate change policies and its important to ensure, by careful co-ordination, that they complement each other rather than lead to perverse outcomes.

11.7 A Structural Shift

This section closes Chapter 11 with some broader considerations about the implications for policy, financing and implementation if a rapid and large-scale deployment of RE is to be enabled.

Section 11.5 of this chapter has set out the available policies and evidence about their success and failures. Section 11.6 has explained the enabling environment which is required to maximise the success of those policies. Together, 11.5 and 11.6 illuminate the ‘best practice’ policies available and their requirements for success. Any country which puts in place both those ‘best practice’ policies and enabling environment could expect success in delivering renewable energy deployment.

RE is a rapidly increasing source of energy around the world. However, in most places, RE is still viewed as a ‘new’ source of energy from a few ‘new’ technologies and provides only a small percentage of the energy used (see Chapter 1). Chapter 10 illuminates the very wide range of expectations for renewable energy deployment over the next decades, including at the higher end (ie 80% of primary energy by 2050) a similar level to fossil fuels now. Even at the lower levels (15-34% in BAU or lower end of scenarios by 2050) RE deployment is predicted to increase greatly from today. This section focuses on how RE can make the transition to where it is considered in the same way as fossil fuels currently are. If this were the case, then RE would be perceived as a ‘standard’ or ‘normal’ form of energy. Addressing this issue allows this section to explore what is required, not only in terms of policy, but also in terms of political and institutional change; economic goals; societal and individual values and so on.

In particular, this section 11.7 explores:

- What the implications are for energy systems if the barriers to RE (set out in Chapter 1 and 11.4) are overcome
- the wider requirements, beyond renewable energy policies and their enabling environments, to enable a structural shift in energy provision to RE and what this means for societal activities, practices, institutions and norms
- some of the key choices that policymakers, companies, investors and consumers face;
- whether, to implement policies which ‘breakthrough’ or enable ‘bricolage’

Section 11.7.1 illuminates what an energy system without barriers to renewable energy would like: 11.7.2 explores what a structural shift would look like and how to do it; 11.7.3; explores what the fundamental factors are in a number of scenarios to a low carbon economy using low CO2 emitting RE; Section 11.7.4; explores incremental versus step change as a way to make the transition; 11.7.5 briefly looks at ways to change societal values and attitudes as a means to move to a low carbon economy; 11.7.6 looks at 100% renewable energy communities, what they have in common and their challenges; 11.7 7 explores what key choices and implications his seems to imply for policy makers and what altered roles this may mean for other actors, such as companies, investors, communities and individuals; and 11.7.8 sums up the key messages from section 7.

11.7.1 An energy system without barriers for RE

Chapter 1 briefly describes the barriers to RE and 11.4 describes the barriers specific to putting in place a RE policy, including its design. An energy system where RE is thought of in the same way as fossil fuels implies that the majority of the barriers to their deployment have been overcome, and taking the categories of Chapter 1, this implies the following:

- Informational and awareness issues will have been overcome - there is an understanding within policy makers; planners and so on about what the characteristics of RE is; how they work; how they should best be integrated into the energy system; and also about the value of RE in relation to climate change emission reduction, access to energy and poverty reduction
- The socio-cultural aspects of RE acceptance and utilisation has altered so that renewable energy is accepted as not only being a ‘normal’ part of life, but an important one which is adding to societal benefit; but also there is an understanding of how individuals connect and adapt to societal requirements
- Technical and structural barriers have been removed because R&D and other support mechanisms have been undertaken; skills and capacities have developed so that it is possible to implement RE
- The economic barriers to RE have been negated or dismantled so that costs of RE have come down relative to other sources of energy because the social costs of fossil fuels and nuclear power have been incorporated; because subsidies or tax breaks for fossil fuels are removed; so that markets and network access complement RE characteristics; so that carbon markets function well; so that the risk of investment have become on a par with other investments within the energy system and financiers

- The institutional barriers are removed

11.7.2 Energy Transitions and Structural Shifts

Transitions from one energy source to another have characterized human development (Fouquet, 2008). A shift from the current energy system to one that includes a high proportion of RE also implies a number of structural changes (Unruh, 2000; Smith, Stirling et al., 2005; Unruh and Carrillo-Hermosilla, 2006; Mitchell, 2008; van den Bergh and Bruinsma, 2008; Verbruggen and Lauber, 2009).

Movements from one energy source to another have occurred as each new source of energy provided a new and desired service which displaced and augmented the services available from the previous ‘standard’ energy source (Fouquet, 2008). The timescales of these energy transitions and their linked infrastructure replacements or developments varied by countries but occurred over several decades (Fouquet, 2008). A transition to a low carbon economy using low carbon emitting RE is different from past transitions because the time period available is restricted, and relatively short compared to the timescales of previous transitions. Further RE is trying to integrate into a system (including policies, regulations and infrastructure) that was built to suit fossil fuels (which have a number of continuing useful qualities such as energy density and portability) and nuclear power. While RE provides different benefits, services are similar. Because of this movement towards the transition has to be deliberate (Stirling, 2009).

There are different approaches to analysing this complex area of how transitions, or innovations, occur. For example the economics of innovation (Freeman and Soete, 2000; Freeman, 2001); innovation systems (Jacobsson and Carlsson, 1997); transition management (Rotmans, Kemp *et al.*, 2001); and business approaches (Winsemius and Guntram, 2002) . Some of these approaches are linear and rational and others argue that policy-making is more ‘based on such things as visions and values, the relative strengths of various pressure groups and on deeper historical and cultural influences’ (Jacobsson and Lauber, 2004). A plausible approach is that socio-technical system occurs by a complex non linear series of adjustments between three different ‘levels’ or ‘settings’ within a country.: that of (1) the landscape of a country (which is made up of the political system; society’s mindset; the underlying economic system; institutions; the broad geographies and infrastructure, such as cities); that of (2) the energy system in place (made up of certain policies, technologies, the enabling environment; the infrastructure, such as networks and power plants); and (3) the level of niches, where innovations within society, companies and institutions occur, and often wither.

Thus, while an energy system can change (if there are sufficient policies and an enabling environment in place) enabling a structural shift to an energy system with fundamentally different characteristics, requires an alignment between these three levels or setting. This requires three, not inconsiderable, steps, set out in Figure 11.13 below:

- First, an understanding of what is needed at the niche or innovative level for a transition, For example, this report is exploring the potential of low carbon dioxide emitting renewable energy technologies to meet the energy services of people in both developed and developing countries. Thus, the understandings set out in this report are one step to fulfilling this knowledge at a global level. More and more understanding is required for all countries

- Second, a translation of this understanding into policies and enabling environments at the energy system level to make it happen (as set out in 11.5 and 11.6); and
- Third, that this understanding at the energy system level becomes aligned at the landscape or country level (ie the political paradigm of the country has to accept RE as the new energy as ‘standard’; the economic development model has to match it; the infrastructure – such as cities – has to reflect it; and it has to become part of society, so that individuals, communities, companies and institutions fuse within a new society ‘mindset’).

Only when this alignment has occurred between the three levels of a country will the structural shift have occurred. At that point, RE would be treated in the same way as fossil fuels currently is and the linkages between the three levels foster a continuing process of adjustments.

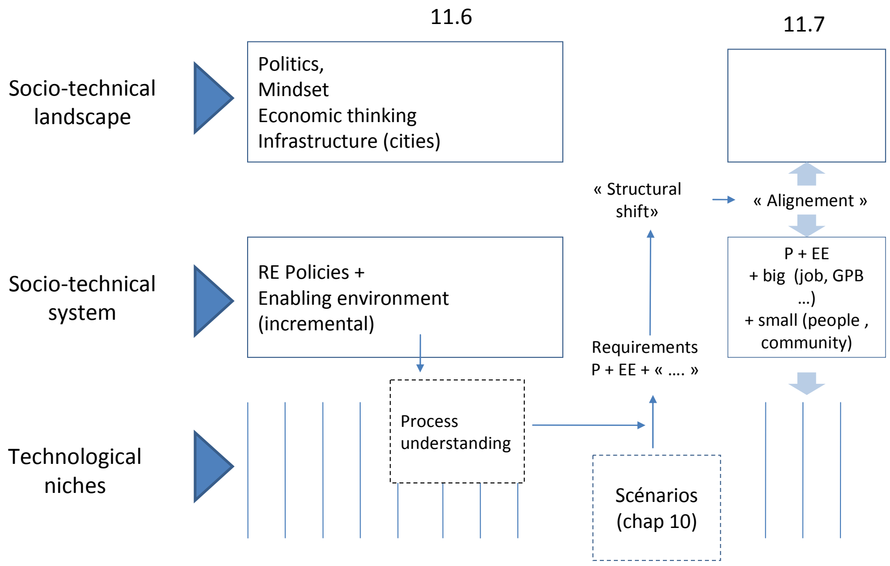

Figure 11.13 Socio-technical requirements of a structural shift.

11.7.3 Exploration of Scenarios

Scenarios create logical future worlds, so that the use of resources and their consequences can be explored, and so that the process understanding of what is required for a transition is understood in greater detail. This report (Chapter 10) reviewed 165 scenarios which represented the most recent integrated modelling literature. It then analysed in depth 4 scenarios, which are representative of those 165 scenarios. From these scenarios, it becomes clear that different desired outcomes, for example a 450 ppm atmosphere in 2050 globe or a global average income level in 2050, require different policy choices and raise critical issues of feasibility in terms of climate change mitigation.

One description of these tensions is given in a recent set of scenarios from Tellus (Tellus, 2010) argue that ‘within a conventional economic development paradigm, implementing remedial technologies and policies at the required pace and magnitude would be daunting, indeed, like trying to go up a down escalator. A 21st century world of rising population, consumerism and universal convergence towards affluent lifestyles would create incessant pressure for ever more energy and materials, land and food' (page 14) [TSU: (See 11.3)?].

The importance of policy choices on our future lives is clearly shown in a recent IEA report (IEA, 2009c) RE cities and communities) which set out two imaginary visions of a future: Bleak House and Great Expectations. In these visions, the first reflects a world where the concerns of climate change had not been heeded and technological R&D has not been undertaken. The other is one where concerns of climate change have been heeded and technological R&D has been undertaken. The latter includes a wide range of technologies, including smart information technologies, as well as implementing energy efficient policies. The requirement of individuals to independently change their behaviour and lifestyles is minimised – in other words as much as possible is done for individuals to make the move to a sustainable as easy as possible, although lifestyle and behaviour change is required, and is indeed pushed by the technologies themselves. The IEA report presented these visions to stimulate the reader to contemplate what sort of world they may want to inherit (IEA, 2009) but also to illuminate how technology and behaviour are intimately linked and should be viewed positively together.

These scenarios and vision illuminate central choices for policy makers:

- whether they support a continuation of the current model of economic growth around the world, fuelled by low carbon technologies? And if so, where the energy and resources would come from for it?
- whether policy decisions remain centralised or devolved down to local levels to enable and encourage more local, community and individual involvement in energy system decisions
- whether policy makers will accept a greater amount of global co-ordination to ensure the meeting of global targets - which includes the transfer of financial flows from developed to developing countries, and whether that co-ordination is possible?
- whether policy makers conclude that a more values led movement of society is beneficial to change; and whether that change is possible?

When broken down these scenarios of Chapter 10 and the IEA visions either reflect a technology optimistic route – where low carbon technologies enable a somewhat similar lifestyle across the globe to that enjoyed in developed countries and which don't need much change in societal values or behaviours – or reflect a behaviour optimistic route – where changing individual and societal values are central to the development of a sustainable low carbon emitting economy. The scenarios and models reviewed in Chapter 10 differ greatly in their arguments of which works 'best'; whether by going down one path, negates going down another and so on. Nevertheless, the socio-techno paths are very different; imply real differences for societal values; energy company practices; and institutions; institutional arrangements and government policies.

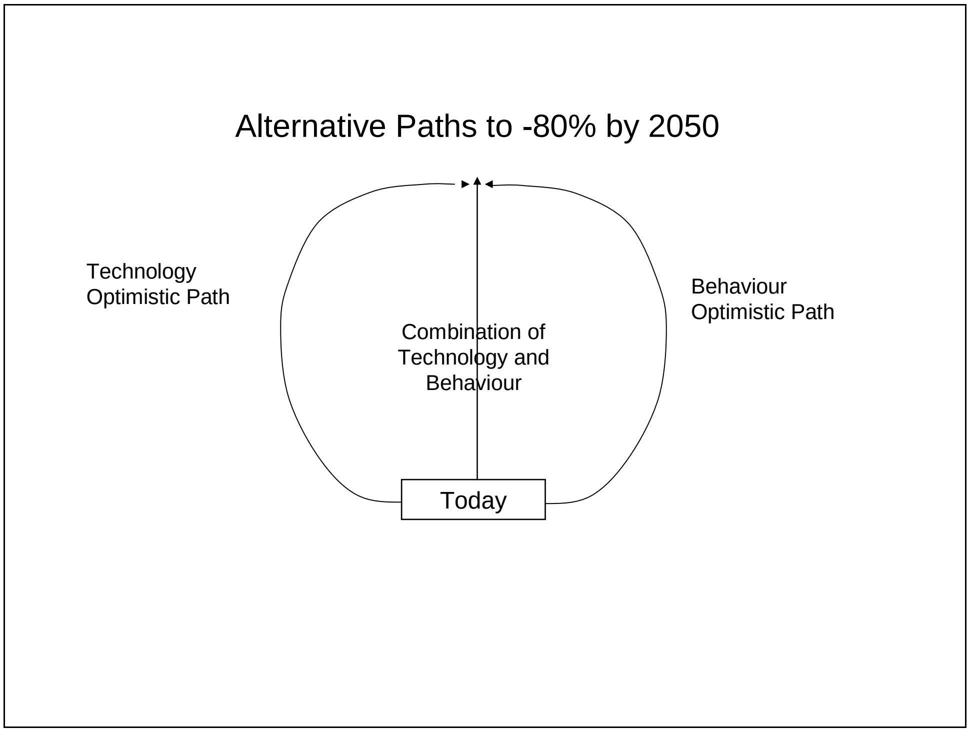

Figure 11.14 Alternative pathways to RE on the standard energy provider

11.7.4 Bricolage versus Breakthrough

When undertaking the transition, and making the choice of which pathway to the low carbon economy to follow, policy makers are able to choose policies which attempt a technological ‘breakthrough’ or ‘step-change or policies which lead to a series of incremental steps, which over time results in a structural shift. As set out in 11.5.2 (Garud and Karnøe, 2003) have termed this choice ‘bricolage or breakthrough’. They define bricolage to connote resourcefulness and improvisation on the part of involved actors while breakthrough is taken to evoke an image of actors attempting to generate dramatic outcomes. They argued that ‘breakthrough’ policies can result in ‘dampening the learning processes required for mutual co-shaping’ of technology development’. Bricolage on the other hand preserves emergent properties and is a process of moving ahead on the basis of inputs of actors who possess local knowledge but who through their interactions are able to gradually transform emerging paths to higher degrees of functionality (Tellus, 2010; Jacobsson and Lauber, 2004).

This complements the argument that ‘agency’ or the ability to do something is distributed across actors rather than based in one key actor alone (Bijker et al, 1987). As has been shown, enabling the development and deployment of RE requires all sorts of inputs and changes whether skills, finance and so on (See figure 11.6). Thus, an energy system following a technological path cannot be attributed to one actor, one technology, one policy; or one ‘economic’ situation. Price, while important, is not sufficient on its own to harness the inputs of distributed actors involved in the development of new technologies (Garud and Rappa, 1994; .

The conclusion to be drawn from this section by policy-makers, business, investors and individuals is that a transition may best be enabled by small, directed steps, building on those taken before. However small the change adds to that structural shift. Thus while the bricolage approach is comforting for policy-makers; it does have to be ‘directed’ towards unlocking or removal of barriers and overcoming of hurdles by combinations of policies (International Energy Agency (IEA), 2008; van den Bergh and Bruinsma, 2008; Praetorius, Bauknecht *et al.*, 2009; UNFCCC, 2009).

11.7.5 Changing societal values and attitudes

This chapter has described policies that create obligations or alter incentive structures for innovation and diffusion (e.g., regulation, price mechanisms, and R&D support). As described above, the value of changing behaviour and values in moving to a low carbon economy is an important element to many of the scenarios reviewed in Chapter 10. This section doesn’t review that literature again, but it does address our understanding of how a social mindset could alter, thereby complementing and helping a structural shift to a low carbon economy occur.

Public education on RE is typically targeted at a general audience through mass media channels. It seeks to change values through moral persuasion or to raise awareness of an issue (Gardner & Stern 2002). Impacts on behaviour are diffuse, long-term, and hard to measure because values towards the environment generally correlate weakly with behaviour (Gatersleben, Steg *et al.*, 2002; Poortinga, Steg *et al.*, 2004). Values exert influence through specific beliefs and then personal norms by which individuals take on the responsibility to act in order to protect the things they value (Stern, Dietz *et al.*, 1999).In contrast, information provision is typically targeted at decision points or at particular population segments. It seeks to reinforce positive attitudes or activate personal norms. Both are precursors to behaviour (Ajzen, 1991)(see Ajzen 1991 and (Oskamp, 2000) respectively). Positive attitudes are further reinforced by public commitments and targeted feedback (Staats, Harland *et al.*, 2004).

A number of recent reviews discuss the role of information and attitudes in behavioural models and settings relevant to the environment (Halpern, Bates *et al.*, 2004; Jackson, 2005; Wilson and Dowlatabadi, 2007). A key finding applicable to RE is that the effectiveness of education and information-based policies is limited by contextual factors. Favourable attitudes only weakly explain behaviour if contextual constraints are strong (Guagnano, Stern *et al.*, 1995; Armitage and Conner, 2001).Systems of energy provision and use are deeply embedded in household routines and social practices (Shove, 2003). This characteristic of energy technologies as “congealed culture” with choices “partially limited by ritual and lifestyle” (Sovacool, 2009) cautions a naïve reliance on information and education-based policies to affect change. But neither does it mititate against their use as relatively low cost, uncontroversial, and potentially empowering instruments of autonomous choice, favoured over coercion from an individual standpoint (Attari, Schoen *et al.*, 2009).

Social norms towards RE rely on ‘social’ visibility. This is not a physical attribute (although literal visibility can help), but rather the extent to which people’s attitudes and behaviour towards RE is communicated through social networks (Schultz, 2002). This type of social communication is central to the diffusion process for innovations including many examples of distributed RE (Archer, Pettigrew *et al.*, 1987; Rogers, 2003; Jager, 2006). The literal visibility of residential wind or solar may help RE become a normative talking point (Hanson, Bernstein *et al.*, 2006) and the converse is true of poorly visible technologies such as micro-CHP. Demonstration projects help promote social visibility and allow potential adopters to observe, learn and communicate about, and test RE technologies vicariously. With solar PV for example, demonstration projects helped breed familiarity and reduce perceived risks for Dutch homeowners and U.S. utility managers alike (Kaplan, 1999; Jager, 2006).

For RE, a key element of context is the residential customers' past experience, habit and life style (Brennan 2007). As systems of energy provision and use are deeply embedded in household routines, social practices and life styles (Sovacool 2009), collective action (e.g. through social norms) and systemic approach is an often times more efficient, but more complex, medium for change than individual action (e.g. through individual values, personal attitudes or personal norms ...) (Wilson 2008; Nolan et al. 2007). Favourable attitudes only weakly sustain behaviour change if the contextual constraints are strong (e.g. access to financing, permitting procedures ...) (Guagnano & Stern 1995; Armitage & Connor 2001), so transforming attitudes in behaviours often times calls for coordinated policy action at the level of the system.

11.7.6 100% renewable energy societies

A few towns, local authorities, or communities have moved considerably toward sourcing 100% of their energy from RE (Droeghe, 2009; IEAs Cities Towns and RE; see Box 11.18). On the one hand, those locations that have made this transition offer limited potential for learning because they are at the forefront of energy system. Yet their experiences can provide very useful insights by illuminating how and why such change occurred. The key lesson of whether, and how, these city's and communities were able to do this ultimately depended on the *spatial, environmental, social and economic capacities to implement RE* – and this would only be possible if the concerns of the three main actors – state, market and civil society - are addressed together (Droeghe, 2009). This is the practical representation of the arguments for structural change set out in 11.7.2 – an alignment has to occur between the State; the social mindset and institutions. Issues raised by the 100% communities are:

- only a limited number of cities and communities have shifted, or are in the process of transitioning to, 100%. But this transition was almost unimaginable even a few years ago. These places have been able to achieve the shift rapidly and have seen significant additional advantages result, such as jobs or economic development, and which have become important, reinforcing factors in themselves
- they are technically-literate places – while the technologies are often small scale, the system itself is linked to a greater or less degree to 'active' or 'smart' technologies
- The positive aspects from the case studies reinforce each other once a certain point in the transition has been reached: new companies entering the market place, more jobs, lower costs, better quality of life.
- past scenarios would not have predicted that such step changes were possible (or perhaps economically feasible).

Box 11.18 The Road to 100% RE: Güssing, Austria and Rizhao, China

A small but increasing number of cities, towns and communities from Europe to Asia have started down the path to 100 percent RE. This is the story of two of them.

Güssing in Austria was the first town in the European Union to reduce its carbon emissions by 90 percent (below 1992 levels) and today is a model for environment-friendly energy production based on energy saving, self-sufficiency and environmental protection. Thirty RE plants—solid biomass, biodiesel, biogas and photovoltaic facilities—operate within 10 kilometers of Güssing and meet the town's fuel demands for transportation, residential heating, and electricity. Electricity produced locally and sold into the grid has increased local revenue, with profits reinvested into the community and its RE projects. By 2009, Güssing's renewable profile had attracted 60 companies wanting to run on clean energy, creating at least 1000 new jobs.

The town's transformation began in the late 1980s when a massive fuel debt prompted the local mayor to enforce energy-saving measures and begin phasing out fossil fuel use, replacing it with locally supplied RE. Within two years, energy expenditures were reduced drastically. Policies were implemented to manage and sustain local farms and forests to produce raw material for generating bio-energy. Several local and regional public and private research institutions provided technological assistance. Güssing's specialised centre on RE has helped to raise public awareness about clean energy and energy efficiency as well as broader conservation and climate protection goals. Grants from the European Commission, regional authorities and the national government assisted with the construction of new infrastructure, such as the district heating system. By 2001, Güssing was 100 percent self-sufficient and operating on RE.

In northern China, the city of Rizhao has attracted an increasing level of foreign investment, tourism and migration thanks to RE and efficiency policies that have helped to enhance the city's environmental profile while improving living standards. The local government has mandated the integration of clean energies, especially solar, into all development and modernisation projects in the region. As a result, 99 percent of all buildings in urban areas, and more than 30 percent of houses in rural areas, have installed solar water heaters; almost all outdoor public lighting (traffic signals, street and park lights) is PV-powered.

By supporting local supplier start-ups (through tax breaks and/or preferential land allocation) and subsidising R&D, rather than end users, the city has enabled RE industries to increase efficiency and reduce per unit costs. This is considered more cost-effective than funding the entire city population. To source raw material for bioenergy production, waste minimization policies assist and encourage industries to recycle wastewater and solid wastes for drying processes, or to generate heat and electricity. An urban-rural planning framework ensures equal attention is paid to the self-sufficiency of regional areas, and municipal-run energy advisory centres provide advice for consumers and potential energy providers.

The result has been millions of RMB yuan generated annually from the electricity sold, alongside a considerable reduction in urban water, power, steam and food consumption. Rizhao's eco-agricultural model has helped improve the rural ecology and the livelihood of farmers through organic farming based on RE tapped from local bio-digesters, small-scale hydro and wind power.

11.7.6.1 Factors in Common

Common to both places were the following themes: government leadership; community involvement; access to funding and market incentives; awareness; and research and development (R&D) support. Strong local government leadership was critical, authorities in both cases had to actively facilitate, educate, and promote market transformation of local energy supplies. Clear energy goals were established that were based on fulfilling community needs and addressing local problems such as high energy costs, low living standards, unemployment, old infrastructure and pollution. Policies had to ensure the competitiveness of renewable energy (RE) markets through preferential policy for RE companies, such as tax breaks, feed-in tariffs, fossil fuel tax, or preferential land allocations for RE manufacturers. A local planning framework that involves the cooperation of the state, private businesses and civil society into the decision process was also necessary. Energy and environmental awareness required changes in the local curricula from local schools to technical colleges. External expertise was needed to assist governments with taking stock of the region's social, environmental and spatial capacity to generate and supply renewable energy – an energy mix that would help overcome fluctuations in energy supply due to changing climatic conditions. Sourcing raw material was for example, were reflected into policies enforcing the recovery of local and regional waste material (from farms, landfills or industry) for the generation of clean energy. Naturally, the modernisation of the local infrastructure and the need to mandate energy efficiency and renewable energy integration though policies on urban regeneration or the construction of new development, was also essential. Although the availability of financial assistance from regional and national authorities was key, funds were largely directed towards R&D of renewable energy technology, rather than subsiding end-users in the form of rebates or the like.

11.7.6.2 Key Challenges

The key challenges 100% RE societies face ranged from (Droege, 2009):

- operational difficulties associated with out-of-date planning and funding approval processes,
- to societal scepticism or the lack of awareness by all in understanding the economic, social and spatial implications of changing the town's energy base to sustainable sources.
- Existing processes take up considerable periods of time, more particularly in relation to applying for grants for renewable energy projects, and/or applying for development approval for their actual construction.
- Funding processes sometimes require cities to comply with particular rules (for example such as those set out by the EU) in order to qualify for financial assistance. Timeframes often differ depending on whether funds are sourced locally, regionally or nationally.
- Structural changes to planning regulations, due to changing governments or market fluctuations, or conflict between national and local policies, also cause a slowing down or stagnation in the approval processes.
- A non-competitive market for RE and energy efficiency measures, coupled with high upfront installation costs and the changing values of feed-in tariffs, adds to the prevailing reluctance amongst companies and governments to invest into such projects due to the uncertainty.
- Energy research and technological expertise was required to ensure a town's transformation and to maintain its success; but often this has not been possible due to the lack of funds or general passive resistance from town planners to external, academic advice.
- Becoming energy producers would mean communities themselves undergoing some form of training.

- Existing planning methods require some restructuring, and specific goals in relation to renewable energy and energy efficiency must be clearly expressed in local energy plans – an aspect often missing from local sustainability objectives. For many cities around the world, energy is still addressed only in relation to the provision of infrastructural services. Locally drafted land-use plans often do not address the energetic implications of each land-use typology, be it industrial, residential or commercial (in relation to its environmental footprint or emissions output). They often fail to express the energy-generating potential of sites, nor do they help guide the conversion of buildings associated with each land-use into more energy-efficient, self-sustaining built forms.
- Other critical factors include social attitudes and lifestyles, as fears still prevail amongst industry that new sustainable energy businesses will cause their demise, while communities around fear that they would have to do without. A lack of awareness that generally hinders the take-up of energy efficiency and renewable energy measures, communities often waiting for instructions from the local government before any form of action takes place.

11.7.7 Key Choices and Implications

This section has illuminated the key requirements and choices that policy makers face and which have significant implications for society (Smith, 2000; Unruh, 2000; Garud and Karnøe, 2003; Szarka, 2006; Unruh and Carrillo-Hermosilla, 2006; Smith, 2007; Szarka, 2007; International Energy Agency (IEA), 2009; Praetorius, Bauknecht *et al.*, 2009). Governments are required to orchestrate the deliberate move from fossil fuels to RE use. As is argued in the IEA's Deploying Renewables (2008), success in delivery occurs where countries have got rid of non-economic barriers and where policies are in place at the required level to reduce risk to enable sufficient financing and investment (International Energy Agency (IEA), 2008). In addition, this section has set out that

- RE Policies, the enabling environment and more structural shifts are all on a continuum towards a transition to an energy system with more and more RE.
- A ‘breakthrough’ or a ‘bricolage’ policy approach to technology development and system change is a key choice
- Another key choice is the policy priority of whether to support a technology optimistic pathway ; a behaviour optimistic pathway or one that combines both
- the degree to which policies are devolved down from national to local governments, and open to individual choice
- the degree to which the State, the market and civil society are brought together to address, and create, sufficient spatial, environmental, social and economic capacities to enable a move to a low carbon economy

The choices will affect the actors described above so that societal activities, practices, institutions and norms can be expected to change. Thus, choice of policies is central to the success of policies.

11.7.8 Conclusions

This section, chapter and report comes to a number of fundamental principles about RE deployment, financing and implementation:

1**.** **Targeted RE policies accelerate RE development and deployment**. Targeted policies should address barriers to RE, including market failures, and appropriate market signals are crucial to trigger significant RE growth, but are not sufficient.

2. **Multiple RE success stories exist around the world and it is important to learn from them**. They demonstrate that the right policies have an impact on emissions reductions and the enhanced access to clean energy. They also demonstrate the importance of learning by doing, including learning from mistakes, to achieving success.

3. **Economic, social, and environmental benefits are motivating Governments and individuals to adopt RE.** In addition to mitigation of climate change, benefits include economic development and job creation, increased security of energy supply, greater stability and predictability of energy prices, access to energy, and reduced indoor air pollution. In general, climate change mitigation is a primary driver for developed countries whereas developing countries focus more on energy access and energy security through RE. In low-lying developing countries, RE's potential for climate change mitigation becomes an issue of economic and physical survival.

4. **Multiple barriers exist and impede the development of RE policies to support development and deployment.** These primarily relate to the degree of awareness, and acceptance, of climate change policies; a lack of knowledge of how RE can mitigate the problem and a lack of sufficient public governance capacity to elaborate and make RE policies operational; the momentum of the existing energy system, including policies that were enacted to advance or support the existing fossil-based system and that now undermine RE policy; and a lack of understanding on the part of policy-makers of the needs of financiers and investors.

5. **'Technology push' coupled with 'market pull' creates virtuous cycles of technology development and market deployment**. Public RD&D combined with promotion policies have been shown to drive down the cost of technology and sustain its deployment. Steadily increasing deployment allows for learning, drives down costs through economies of scale, and attracts further private investment in R&D.

6. **Successful policies are well-designed and -implemented, conveying clear and consistent signals.** Successful policies take into account available RE resources, the state and changes of the technology, as well as financing needs and availability. They respond to local, political, economic, social, financial, ecological and cultural needs and conditions. RE deployment policies can immediately start in every country with simple incentives, evolving toward stable and predictable frameworks and combinations of policies to address the long-term nature of developing and integrating RE into existing energy systems.

7. **Policies that are well-designed and predictable encourage greater levels of private investment than those that are not**, thereby reducing the amount of public funds required to achieve the same levels of RE development and deployment.

8. **Well-designed policies are more likely to emerge and to function most-effectively in an enabling environment**. An enabling environment integrates technological, social, cultural,

institutional, legal, economic and financial dimensions, and recognizes that technological change and deployment come through systemic and evolutionary (rather than linear) processes. Also important is coordination across policies, the dimensions of the enabling environment and, where relevant, different sectors of the economy including broader energy policy, transportation and agriculture.

9. **The global dimension of climate change and the need for sustainable development call for new international public and private partnerships and cooperative arrangements to deploy RE. RE deployment is a part, and a driver, of sustainable development**. New suitable finance mechanisms on national and international levels, involving cooperation between the public and private sectors, work to stimulate technology transfer and worldwide RE investment as well as advancing the necessary infrastructure for RE integration. New partnerships would recognize the diversity of countries, regions and business models.

10. **Structural shifts characterize the transition to economies in which low CO_2 emitting renewable technologies meet the energy service needs of people in both developed and developing countries**. When RE is treated as the norm, as fossil fuels are today, a structural shift will have occurred. Political will and effective policies to promote RE deployment, in concert with decreasing energy intensity, are an integral part of the needed energy transition. Further, transitions require important changes in societal activities and practices, business conditions and institutions.

11. **Better coordinated and deliberate actions can accelerate the necessary energy transition for effectively mitigating climate change**. The now required transition differs from previous ones in two primary ways. First, the available time span is restricted to a few decades. Second, RE has to develop within the existing energy system (including policies, regulations and infrastructure) that generally were built to suit fossil fuels and nuclear power. Thus it is important to align attitudes and political actions with the known requirements for effectively mitigating climate change. Critical are combinations of strategic and directed policies established to meet interim and long-term RE targets and advance the required infrastructure. Long-standing commitment is essential alongside the flexibility to adapt policies as situations change.

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INTERGOVERNMENTAL PANEL ON climate change

Annex I

Glossary

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Errors in formatting, spelling etc. will be corrected in the publication phase of the report.

ANNEX I GLOSSARY

- **Adaptation:** The process of altering infrastructure or practices to respond to climate change.
- **Asset Finance**: A consolidated term that describes all money invested in generation projects (i.e. projects/corporate finance, bonds), whether from internal company balance sheets, from debt finance or from equity finance.
- **Barrier** Any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy, programme, or measure. Barriers to renewable energy deployment range from intrinsically natural properties of particular RE sources (for example intermittency and diffuse incidence of solar radiation) to artificial, unintentionally or intentionally constructed, impediments (for example badly oriented, shadowed roof surfaces; tilted power grid access conditions for independent generators).
- **Barrier removal:** Correcting market failures directly or reducing the transactions costs in the public and private sectors by e.g. improving institutional capacity, reducing risk and uncertainty, facilitating market transactions, and enforcing regulatory policies.
- **Baseline:** The reference scenario for measurable quantities from which an alternative outcome can be measured, e.g. a non-intervention scenario is used as a reference in the analysis of intervention scenarios. A baseline may be an extrapolation of recent trends; assumne frozen technology or costs; or be described as “buisness as usual.”
- **Bioenergy:** Energy derived from biomass
- **Biofuel:** Any liquid, gaseous, or solid fuel produced from plant or animal organic matter. E.g. soybean oil, alcohol from fermented sugar, black liquor from the paper manufacturing process, wood as fuel, etc. Second-generation biofuels are products such as ethanol and biodiesel derived from ligno-cellulosic biomass by chemical or biological processes.
- **Biomass:** The total mass of living organisms in a given area or of a given species usually expressed as dry weight. Organic matter consisting of, or recently derived from, living organisms (especially regarded as fuel) excluding peat. Biomass includes products, by-products and waste derived from such material. Cellulosic biomass is biomass from cellulose, the primary structural component of plants and trees.
- **Black carbon:** Dark soot particles are released by burning biomass fuels and from diesel engines and chimneys of power plants and some industrial processes. These particulates cause lung and eye damage, and when they fall on snow or ice, absorb heat that accelerates melting and significantly reduce albedo (reflectivity).
- **Capacity factor:** For any energy supply technology, the ratio of actual energy output over a period of time (typically a year) over its name plate capacity for the same period of time.
- **Corporate Finance:** debt obligations provided by banks to companies using ‘on-balance sheet’ assets as collateral. Most mature companies have access to corporate finance, but have constraints on their debt ratio and, therefore, must rationalise each additional loan with other capital needs.
- **Enabling environment:** combines economic, technological, social and cultural, institutional and financial dimensions, including both the public and private sectors.

- **Energy**: The amount of work or heat delivered. Energy is classified in a variety of types and becomes useful to human ends when it flows from one place to another or is converted from one type into another.
    - **Primary energy:** Primary energy (also referred to as energy sources, or as Total Primary Energy Supply, TPES) is the energy embodied in natural resources (e.g., coal, crude oil, natural gas, uranium) that has not undergone any anthropogenic conversion. It is defined either in terms of the initial heat derived from that source (Physical Content Method) or in terms of the secondary energy, heat, electricity or mechanical energy delivered (Direct Substitution Method) or as the Direct Equivalent Method. Primary Energy is transformed into **secondary energy** by cleaning (natural gas), refining (oil in oil products) or by conversion into electricity or heat. When the secondary energy is delivered at the end-use facilities it is called
    - **Total Final Consumption (TFC)** (e.g., electricity at the wall outlet), where it becomes **an energy service** (e.g., light). Daily, the sun supplies large quantities of energy as rainfall, winds, radiation, etc. Some share is stored in biomass or rivers that can be harvested by men. Some share is directly usable such as daylight, ventilation or ambient heat. See Appendix II for a full discussion of the different means of accounting for primary energy.
    - **Renewable energy:** Renewable energy (RE) is any form of energy from geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes non-carbon dioxide emitting technologies such as solar energy, hydropower, wind, tide and waves and geothermal heat, as well as renewable fuels such as biomass. In this context, energy flow must exceed energy demand from that flow to be considered renewable and sustainable. For a more detailed description see specific renewable energy types in this glossary, e.g. biomass, solar, hydropower, ocean, geothermal and wind. Sometimes renewable technology and primary energy are referred to as RE or as renewables.
    - **Embodied energy:** is the energy used to produce a material substance (such as processed metals or building materials), taking into account energy used at the manufacturing facility (zero order), energy used in producing the materials that are used in the manufacturing facility (first order), and so on.
    - **Energy density:** the amount of energy stored per unit of volume or mass of the system.
    - **Energy Efficiency**: The ratio of useful energy output of a system, conversion process or activity to its energy input.
    - **Energy Intensity:** The ratio of energy use to economic output. At the national level, energy intensity is the ratio of total domestic primary energy use or final energy use to Gross Domestic Product. See also **specific energy use**
- **Energy Services:** Energy services are the tasks to be performed by energy. A specific energy service such as lighting may be supplied by a number of different means from day lighting to oil lamps to incandescent, fluorescent or light emitting diode devices. The range of energy needed to provide a service may vary over a factor of ten or more, and the corresponding GHG emissions may vary from zero to a very high value depending on the source of energy and the type of end use device.

- **Energy Security:** The various security measures that a given nation, or the global community as a whole, must carry out to maintain an adequate energy supply. Measures encompass safeguarding access to energy resources; enabling development and deployment of technologies; building sufficient infrastructures to generate, store and transmit energy supplies; ensuring enforceable contracts of delivery; access to energy at affordable prices for a specific society.
- **Externality / External cost / External benefits:** Externalities arise from a human activity, when agents responsible for the activity do not take full account of the activity's impact on others' production and consumption possibilities, while there exists no compensation for such impact. When the impact is negative, so are external costs. When positive they are referred to as external benefits.
- **Geothermal Energy:** Thermal energy that originates within the earth from radioactive decay of nuclear isotopes. Some portions of heat may come near or to the earth's surface as molten lava from volcanos, as hot water or steam in geysers or hot springs. Other thermal reservoirs lie deep within the earth as "hot dry rock," which may be accessed by drilling from the surface and using a heat transfer fluid. This form of thermal energy differs from "ground source heat" that is stored solar energy in soils and ground water.
- **Greenhouse Gases chemical formulas:** The following chemical formulas describe the indicated GHG.
    - Carbon Dioxide - CO2
    - Hydriofluorocarbons HxFyCz
    - Methane - CH4
    - Nitrous Oxide - N2O
    - Perflurocarbons - CzF(2z+2)
    - Sulfur hexafluoride - SF6
- **Greenhouse gases associated with renewable energy**
    - **direct GHGs** – those GHGs emitted directly by the technology; e.g., GHGs released by decomposition of organic material (submerged biomass) in a reservoir behind a dam, exhaust gases released by geothermal plants, combustion of biomass
    - **indirect GHGs:** emissions generated elsewhere as a result of supply generation; e.g., increased production of fertilizers, fuels and the like with the increased agricultural activity needed to generate biofuels.
    - **avoided GHGs:** emissions reduced due to the utilization of the renewable energy. This is likely to regionally specific and definitionally challenging in that it is not always evident what is being displaced (marginal supply, baseload supply, imported or exported energy, etc.).
- **Hydropower:** The potential energy of falling water that is converted into mechanical energy through a turbine or other device that is either used directly or more commonly to operate a generator that produces electricity. The term is also used to describe the kinetic energy of streamflow that may also be converted into mechanical energy of a generator through an in-stream turbine to produce electricity. A distinction is often made between large scale hydro greater than 10 MW, and small scale installations. Minihydro is typically less than 1 MW and micro as less than 0.1 MW

- **Likelihood**: The likelihood of an occurrence, outcome or result, where this can be estimated probabilistically (see **risk, uncertainty**), is expressed in IPCC reports using a standard terminology (IPCC, AR4 WG3,2007):

Particular, or a range of, occurrences / outcomes of an uncertain event owning a probability of	>99%	are said to be:	Virtually certain
	>90%		Very likely
	>66%		Likely
	33 to 66%		About as likely as not
	<33%		Unlikely
	<10%		Very unlikely
	<1%		Exceptionally unlikely

- **Learning impacts and learning / experience curves**
  - **Learning** occurs to improve technologies and processes over time due to experience, as production increases and / or with increasing research and development.
  - **Learning / experience curves** are the mathematical correlation between cost and performance. It provides an indication of the degree to which learning and experience affects the costs associated with the production of the technology.
- **Market pull:** incentives for achieving economies of scale in manufacturing, such as Renewable Energy Portfolio Standards or feed-in tariffs
- **Mitigation:** A human intervention to reduce the *sources* or enhance the *sinks* of *greenhouse gases* to reduce the extent of climate change. There are several ways to mitigate climate change including reducing heat trapping gas emissions through low or zero emitting technologies, fuel switcheing to lower emitting fossil fuels, increasing the uptake of carbon dioxide by plants and soils, end use efficiency improvement, increasing albedo to reflect more sunlight, behavior changes including consumer choices, lower population growth rates and geoengineering.
- **Narrative Structure:** Is the organization and structure of the report
- **Ocean Energy:** Energy that is produced by the ocean. These include energy from the tides, ocean currents, thermal and saline gradients.
- **Offsets:** Greenhouse gas reductions that occur elsewhere as the result of their displacement by an alternative generation source or by absorption of gases such as carbon ioxide through tree planting or enhanced carbon buildup in soils.
- **Payback gap**: A payback gap exists when private investors and micro-financing schemes require higher profitability rates from innovative distributed projects than from established ones. Imposing a x-times higher financial return on RE investments is equivalent to imposing a x-times higher technical performance hurdle on delivery by novel RE solutions compared to incumbent NSE expansion
- **Payback time - Economic**: the period of time over which a return on an investment in an energy supply technology is equivalent to the initial cost of the investment.
- **Payback time - Energy**: the period of time required for an energy supply technology to generate as much energy as was used in the life cycle of it's production (see Energy – embodied energy).

- **Photovoltaics (PV)**: Solid state devices that convert light energy directly into electricity by mobilizing electrons in the solid.
- **Potentials**
    - **Market potential:** the amount of RE output expected to occur under forecast market conditions, shaped by private economic agents and regulated by public authorities. Private economic agents realize private objectives within given, perceived and expected conditions. Market potentials are based on expected private revenues and expenditures, calculated at private prices (incorporating subsidies, levies, and rents) and with private discount rates. The private context is partly shaped by public authority policies.
    - **Economic potential:** the amount of RE output projected when all – social and private – costs and benefits related to that output are included, there is full transparency of information, and assuming exchanges in the economy install a general equilibrium characterized by spatial and temporal efficiency. Negative externalities and co-benefits of all energy uses and of other economic activities are priced. Social discount rates balance the interests of consecutive human generations.
    - **Sustainable Development potential**: the amount of RE output that would be obtained in an *ideal setting* of perfect economic markets, optimal social (institutional and governance) systems and achievement of the sustainable flow of environmental goods and services.
    - **Technical potential**: the amount of RE output obtainable by full implementation of demonstrated and likely to develop technologies or practices. No explicit reference to costs, barriers or policies is made but when adopting *practical constraints* analysts implicitly take into account economic and socio-political considerations.
- **Private Equity investment:** Capital provided by investors and funds directly into private companies for setting up a manufacturing operation or other business activity. (Can also apply to Project Construction)
- **Project Finance:** Debt obligations (i.e., loans) provided by banks to distinct, single-purpose companies, whose energy sales are usually guaranteed by power purchase agreements (PPA). Often known as off-balance sheet or non-recourse finance, since the financiers rely mostly on the certainty of project cash flows to pay back the loan, not the creditworthiness of the project sponsors.
- **Public Equity Investment:** Capital provided by investors into publicly listed companies most commonly for expanding manufacturing operations or other business activities, or to construct projects.
- **Regions**, **Geographic:** North America, South America, Europe, Africa, Asia, Oceana.
- **Regions, Economic (IEA):** Often the literature provides different categories such as economic regions as Developed Countries, Large Developing Countries, Other Developing Countries.
    - OECD North America
        - Comprise Canada, Mexico and the United States regional groupings.
    - OECD Europe
        - Comprise EU19 and Other OECD Europe regional groupings.
    - OECD Pacific

        - Comprises Australia and New Zealand, Japan and Korea regional groupings.
    - E. Europe/Eurasia
        - Comprises Asian Eastern Europe/Eurasia, Europe 8, Non-EU Eastern Europe/Eurasia and Russia regional groupings.
    - Non-OECD Asia
        - Comprises China, India, Indonesia and Other non-OECD Asia regional groupings.
    - Africa
        - Comprises North Africa and Other Africa regional groupings.
    - Latin America
        - Comprises Brazil and Other Latin America regional groupings.
    - European Union
        - Comprises Europe 19 and Europe 8 regional groupings
    - Pacific Island Nations
- **Renewable Energy**: See Energy
- **Risk**: A probabilistic calculation or estimation of the occurance of a specific negative event. It is the outcome of a specific outcome times the probability that this outcome will occur. See also **likelihood** and **uncertainty**.
- **Scenario:** A plausible description of how the future may develop, based on a coherent and internally consistent set of assumptions ("scenario logic") about key relationships and driving forces (e.g., rate of technology change, prices) on energy and GHG emissions. Note that scenarios are neither predictions nor forecasts.
- **Solar Energy:** Energy from the sun that is captured either as heat, as light that is converted into chemical energy by natural or articicial photosynthesis or by photovoltaic panels and converted directly into electricity. Concentrating solar power refers to systems that use either lenses or mirrors to capture a larger amount of solar energy and focus it down to a smaller region of space. The higher temperatures produced can either operate a thermal steam turbine or else be used in high temperature industrial processes. Direct solar energy refers to the use of solar energy as it arrives at the earth's surface before it is stored in water or soils.
- **Specific energy use:** The energy used in the production of a unit of mass of material, product or service.
- **Sustainable development (SD):** The concept of sustainable development was introduced in the World Conservation Strategy (IUCN 1980) and had its roots in the concept of a sustainable society and in the management of renewable resources. Adopted by the WCED in 1987 and by the Rio Conference in 1992 as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations. SD integrates the political, social, economic and environmental dimensions.
- **Technology push:** Targeted development of specific technologies through support for research, development and demonstration

- **Transmission and distribution:** The network that transmits electricity through wires from where it is generated to where it is used. The transmission system distribution system refers to the lower voltage system that actually delivers the electricity to the end user.
- **Uncertainty:** An expression of the degree to which a value or outcome is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values calculated by various models) or by qualitative statements (e.g., reflecting the judgment of a team of experts). See also **likelihood** and **risk.**
- **Valley of Death:** The phase in which a technology is generating a large and negative cash-flow. In this phase, development costs increase but the risk associated with the technology are not reduced enough to entice private investors to take on the financing burden
- **Venture Capital:** A type of private equity capital typically provided for early-stage, high-potential, technology companies in the interest of generating a return on investment through a trade sale of the company or an eventual listing on a public stock exchange.
- **Wind Energy:** The kinetic energy from air currents that arise from uneven heating of the earth's surface. Wind turbines are designed to convert the kinetic energy of the wind into mechanical energy that is either used directly (e.g. water pumping) or more commonly to run an electrical generator.

Annex II

Methodology

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Errors in formatting, spelling etc. will be corrected in the publication phase of the report.

ANNEX II METHODOLOGY

A.II.1 Introduction

Parties need to agree upon common data, standards, supporting theories and metodologies. Appendix II summarizes a set of agreed upon conventions and methodologies. These include the establishment of metrics, determination of a base year, definition of methodologies and consistency of protocols that permit a legitimate comparison between alternative types of energy in the context of climate change phenomena. In this section we define or describe these fundamental definitions and concepts as used throughout this report recognizing that the literature often uses inconcistent definitions and assumptions.

A.II.2 Metrics for analysis in this report

There are a number of metrics that can simply be stated or are otherwise relatively easy to define. Appendix 1 provides a set of agreed upon choices. Those which require further description are found below. Here we list units to be used and some basic parameters pertinent to the analysis of each RE type in this report:

- Standards and units (SI)
- Metric Tonnes CO_2, CO_2e
- Discount rates = 3% (public), 7%, 10% (private)
- Technical and economic life time
- Currency values, $US 2005 (no PPP, conversion rates and equivalencies provided in appendix)
- Capacity: GW thermal, GW electricity
- Capacity cost $US/kW (peak capacity)
- Capacity factor
- Primary energy values in Exajoules (EJ)
- IEA energy conversion factors
- Energy cost in 2005 $US/kWh or 2005 $US/EJ
- Transparent energy accounting (e.g., transformations of nuclear or hydro to electricity)
- Baseline year = 2005 for all components (population, capacity, production, costs)
- Note that more recent data may also be included as well, e.g. 2008
- Target years: 2020, 2030, 2050
- WEO 2008 fossil fuel price assumptions

A.II.3 Life cycle assessment and boundaries of analysis

The metrics defined in 1.6.9 and in the appendix provide the basis from which one can compare one renewable resource type (or project) to another. To make projects or resources comparable, at least in terms of costs, we reduce costs that may occur at various moments in time (e.g., in various years) to a single number anchored at one particular year, the reference year (2005).

A.II.3.1 Constant (Real) Values

The analyses of costs are in constant or real[1] dollars (i.e., excludes the impacts of inflation) based in a particular year; in our case, the base year 2005 in US$. Specific studies on which this document depends may use Market Exchange Rates as a default option or use Purchasing Power Parities, but where these are part of the analysis, they will be stated clearly and, where possible, converted to 2005 $US.

When the monetary series in the analyses are in real dollars, consistency requires that also the discount rate should be real [free of inflationary components]. This consistency is often not obeyed; studies refer to "observed market interest rates" or "observed discount rates", which include inflation or expectations about inflation. "Real / constant" interest rates are never directly observed, but derived from the ex-post identity:

$$(1+n) = (1+i) * (1+f) \qquad (1)$$

where

n = nominal rate (%)

i = real or constant rate (%)

f = inflation rate (%)

The reference year for discounting and the base year for anchoring constant prices may differ in studies used in the various chapters; where possible, we attempted to harmonize the data to reflect discount rates applied here.

A.II.3.2 Discounting and NPV

Private people assign less value to things further in the future than to things in the present because of a "time preference for consumption" or to reflect a "return on investment". Discounting reduces future cash flows by a number less than 1.

Applying this rule on a series of net cash flows in real $US, one can ascertain the net present value of the project and, thus, compare it to other projects using:

$$NPV = \sum_{j=0}^{n} \frac{Net\ cash\ \ flows(j)}{(1+i)^j} \qquad (2)$$

where

n = life time of the project

i = discount rate

As a matter of consensus, analysts have used the three values of discount rates (i) to provide a range of cost evaluations. These discount rates reflect typical rates used when one considers the a public interest perspective (3%), a private perspective more reflective of the cost of capital (7%) and a discount rate that includes a risk premium (10%). The latter is, of course, open to much discussion and no clear parameter or guideline can be suggested as an appropriate risk premium. Analytical studies of effective or implicit discount rates revealed when one critiques consumer choices indicates values much higher than these. We do not address this discussion here pointing out that the goal is to provide an appropriate means of comparison between projects, renewable energy types and new vs. current components of the energy system.

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[1] The economists' term "real" may be confusing because what they call real does not correspond to observed financial flows ("nominal", includes inflation); "real" reflects the real purchasing power of the flows.

A.II.3.3 Levelized Cost

Levelized prices are used in the appraisal of conventional power generation investments, where the outputs are quantifiable MWh generated during the lifetime of the investment. The Levelized Cost is the unique break-even price where discounted revenues (quantities)[2] equal to the discounted net expenses:

$$LC = \frac{\sum_{j=0}^{n} \frac{Expenses_j}{(1+i)^j}}{\sum_{j=0}^{n} \frac{Quantities_j}{(1+i)^j}} \qquad (3)$$

where

LC = levelized cost

n = life time of the project

i = discount rate

Alternatively, levelized costs can provide a point of comparison for a fixed unit of product-generating capacity. Because all supply provides a unit of energy for use, either in terms of thermal or electric carriers (GW installed) an assessment of costs of installation can be made and comparisons reviewed. This forms only one of the units of comparison and is not to be considered a definitive criterion for choosing one renewable energy form over another.

$$LC_{GW} = \frac{CC * \frac{i}{1-(1+i)^{-n}} + OC + EC + o}{Capacity_{GW}} \qquad (4)$$

where

LC = levelized cost

CC = installed capital cost

OC – annual operating and maintenance costs

EC – annual energy costs

i = discount rate

n = life time of the project

o = other annual costs (e.g., co-benefits, intangible costs)

Capacity – installed name plate capacity

This calculation assumes that annual operating costs and energy costs are real and do not vary over the period. There are a number of other costs or benefits, represented by “o” in equation 4 that may require some review or assessment. For example, one could assign significant benefits to hydro generation if one assumes a value to attendant features such as flood control, irrigation or recreation opportunities. On the other hand, one can estimate a cost associated with the loss of scenery, the flooding of valleys, silt entrapment or a change in flora and fauna. For many of the various renewable energy forms, both positive and negative attributes exist, each of which may bear a cost. Each chapter will attempt to define such costs and provide background to their attributes and values. While levelized costs can provide some comparison of two projects or two renewable energy types, it may not capture issues related to the utilization of capacity, for example. In order to compare projects or renewable energy types, one needs to calculate the levelized cost as listed in equation 4.

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[2] This is also referred to as Levelised Price. Note that, in this case, MWh would be discounted.

A.II.3.4 Valuation of renewables (direct and indirect avoided costs)

From the above we see that, when evaluating the costs and benefits of renewable energy, one can assess values based on a number of characteristics of the process / technology. The first involves a simple calculation of costs to supply the energy and incorporates capacity (capital) and its installation costs, operation costs, maintenance costs, energy costs (if any) and other costs that may be incurred (including estimations of co-benefits or intangible costs if known; see levelized cost above). One can modify these costs to reflect other characteristics of the renewable energy type. For example, different renewable energy capturing processes / technologies show different capacity factors, a variation that is captured in the levelized price of formula 3. Some, like geothermal energy, have a capacity factor of 100 (less any down time associated with maintenance schedules) while others, like wind, have capacity factors that are much lower, dependant on when the resource is available. Solar energy capturing technologies constrained to the earth surface would have an annual capacity factor less than 50% by definition. Each of the following chapters 2-7 describe an energy resource and provides an analysis of such direct costs.

There are other characteristics associated with renewable energy that will also affect the costs of that form of renewable energy. Dispatchability, like the capacity factor, has value. Resources that can be dispatched at any time provide a value to the system. Dispersion of the energy source over a region has an impact on transmission and distribution costs. Known as distributed generation, costs incurred on sophisticated and often complicated transmission and distribution systems can be avoided. On the other hand, costs to harmonize multiple sources of power increase system operation costs. Here again, each chapter provides the costs and benefits associated with such characteristics. Many of these costs are dealt with in the chapter on integration, chapter 8.

In the context of GHG issues and climate change, there are other costs and benefits associated with renewable energy generation: impacts of costs of carbon, opportunity cost associated with displacement of other, often fossil (or other renewable), energy sources, avoided costs, other intangible costs that include land use, aesthetics and social or socio-economic concerns (e.g., the “not-in-my-back-yard” syndrome). Each of these will have a cost impact that, in fact, is highly dependant on the system in which each of these renewable supply sources and technologies find themselves.

A.II.4 Resource assessment

If one discusses the potential of renewable energy in the total energy system, one sees that many of the various renewable energy resources are sufficient in and of themselves to provide all of humankind’s energy needs (see Table 1.1). A review of the AR4 (IPCC, 2007) makes it clear that many renewable resources, while potentially abundant, would be insufficient or unable to provide for all energy needs. Thus, we need to ensure that estimates of a resource are reliable in and of themselves and relatively consistent between renewable energy types. Each of the renewable energy supplies of chapters 2-7 provide their evaluation of the total absolute potential, technically possible and total achievable supply of that resource type.

Just as quantities of fossil fuels are categorized broadly as “total resource” and “ available reserves”, so renewable energy supply can be understood to have quantities economically available (reserve) as a subset of total potential (resource). The quantity of the reserve depends on the economics of the energy system while the resource is a measure of potential availability not dependant on price but more often related to that which is technologically accessible.

Resources (and reserves) can also be evaluated on other criteria including spatial (regional differences in availability), local conditions (one must consider icing when installing a wind generator in the arctic), direct and indirect land use, impacts of climate variability (climate change affects hydrologic cycles and so alter hydrologic and biomass sources of energy), proximity to end use, or other characteristics. These are defined in each chapter.

A.II.5 Primary Energy Accounting in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)

Different energy analyses use a variety of accounting methods that lead to different quantitative outcomes for both reporting of current primary energy use and energy use in scenarios that explore future energy transitions. Multiple definitions, methodologies and metrics are applied. Energy accounting systems are utilized in the literature often without a clear statement as to which system is being used (Lightfoot, 2007; Martinot *et al.*, 2007). An overview of differences in primary energy accounting from different statistics has been described (Macknick, 2009) and the implications of applying different accounting systems in long-term scenario analysis were illustrated by Nakicenovic *et al.*, (1998).

Three alternative methods are predominantly used to report primary energy. While the accounting of combustible sources, including all fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e. nuclear energy and all renewable energy sources except biomass. These methods are:

- *the physical energy content method* adopted, for example, by the OECD, the International Energy Agency (IEA) and Eurostat (IEA/OECD/Eurostat, 2005),
- *the substitution method* which is used in slightly different variants by BP (2009) and the US Energy Information Administration, each of which publish international energy statistics, and
- *the direct equivalent method* that is used by UN Statistics (2010) and in multiple IPCC reports that deal with long-term energy and emission scenarios (Nakicenovic and Swart, 2000; Morita *et al.*, 2001; Fisher *et al.*, 2007).

For non-combustible energy sources, the *physical energy content method* adopts the principle that the primary energy form should be the first energy form used down-stream in the production process for which multiple energy uses are practical (IEA/OECD/Eurostat, 2005). This leads to the choice of the following *primary* energy forms:

- heat for nuclear, geothermal and solar thermal; and
- electricity for hydro, wind, tide/wave/ocean and solar PV.

Using this method, the primary energy equivalent of hydro energy and solar PV, for example, assumes a 100% conversion efficiency to “primary electricity”, so that the gross energy input for the source is 3.6 MJ of primary energy = 1 kWh electricity. Nuclear energy is calculated from the gross generation by assuming a 33% thermal conversion efficiency[3], i.e. 1 kWh = (3.6 ÷ 0.33) =10.9 MJ. For geothermal, if no country-specific information is available, the primary energy equivalent is calculated using 10% conversion efficiency for geothermal electricity (so 1 kWh = (3.6 ÷ 0.1) =36 MJ), and 50% for geothermal heat.

The *substitution method* reports primary energy from non-combustible sources in such a way as if they had been substituted for combustible energy. Note, however, that different variants of the substitution method use somewhat different conversion factors. For example, BP applies 38% conversion efficiency to electricity generated from nuclear and hydro whereas the World Energy Council used 38.6% for nuclear and non-combustible renewables (WEC, 1993; Nakicenovic *et al.*,

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[3] As the amount of heat produced in nuclear reactors is not always known, the IEA estimates the primary energy equivalent from the electricity generation by assuming an efficiency of 33%, which is the average of nuclear power plants in Europe (IEA, 2009).

1998) and EIA uses still different values. Macknick (2009) provides a more complete overview. For useful heat generated from non-combustible energy sources, other conversion efficiencies are used.

The *direct equivalent method* counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, i.e. 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. This method is mostly used in the long-term scenarios literature, including multiple IPCC reports (Watson *et al.*, 1995; Nakicenovic and Swart, 2000; Morita *et al.*, 2001; Fisher *et al.*, 2007), because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources.

In this Special Report on Renewable Energy (SRREN), IEA data are utilized, but energy supply is reported using the *direct equivalent method*. The major difference between this and the *physical energy content method* will appear in the amount of primary energy reported for electricity production by geothermal heat, concentrating solar thermal, ocean temperature gradients or nuclear energy. **Table A1** compares the amounts of global primary energy by source and percentages using the *physical energy content, the direct equivalent* and a variant of the *substitution method* for the year 2007 based on IEA data (IEA, 2009). In current statistical energy data, the main differences in absolute terms appear when comparing nuclear and hydropower. Since they both produce about the same amount of global electricity in 2007, under both *direct equivalent* and *substitution methods*, their share of meeting total final consumption is similar, whereas under the *physical energy content method*, nuclear is reported at about three times the primary energy of hydro.

Table A1 Comparison of global total primary energy supply in 2007 using different primary energy accounting methods (data from IEA (2009)).

	Physical content method		**Direct equivalent method**		**Substitution method**[4]	
	EJ	**%**	**EJ**	**%**	**EJ**	**%**
Fossil fuels	411.09	81.62	411.09	85.27	411.09	79.41
Nuclear	29.69	5.90	9.81	2.04	25.79	4.98
Renewables	62.47	12.40	60.81	12.61	80.40	15.53
Bioenergy	48.31	9.59	48.31	10.02	48.31	9.33
Solar	0.40	0.08	0.40	0.08	0.49	0.10
Geothermal	2.05	0.41	0.39	0.08	0.78	0.15
Hydro	11.08	2.20	11.08	2.30	29.17	5.63
Ocean	0.00	0.00	0.00	0.00	0.01	0.00
Wind	0.62	0.12	0.62	0.13	1.64	0.32
Other	0.39	0.08	0.39	0.08	0.39	0.08
Total	503.64	100.00	482.10	100.00	517.67	100.00

The alternative methods outlined above emphasize different aspects of primary energy supply. Therefore, depending on the application, one method may be more appropriate than another. However, none of them is superior to the others in all facets. In addition, it is important to realize that total primary energy supply does not fully describe an energy system, but is merely one indicator amongst many. Energy balances as published by IEA (2009) offer a much wider set of indicators which allows tracing the flow of energy from the resource to final energy use. For instance, complementing total primary energy consumption by other indicators, such as total final

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[4] For the substitution method conversion efficiencies of 38% for electricity and 85% for heat from non-combustible sources were used. BP uses the conversion value of 38% for electricity generated from hydro and nuclear sources. BP does not report solar, wind and geothermal in its statistics; here, we also use 38% for electricity and 85% for heat.

energy consumption (TFC) and secondary energy production (e.g. electricity, heat), using different sources helps link the conversion processes with the final use of energy.

For the purpose of the SRREN, the *direct equivalent method* is chosen for the following reasons.

- It emphasizes the secondary energy perspective for non-combustible sources, which is the main focus of the SRREN analysis in the technology chapters 2 to 7.
- All non-combustible sources are treated in an identical way by using the amount of secondary energy they provide. This allows the comparison of all non-CO_2 emitting renewable energy and nuclear energy sources on a common basis. Primary energy of fossil fuels and biomass combines both the secondary energy and the thermal energy losses from the conversion process. When fossil fuels or biofuels are replaced by nuclear systems or other renewable technologies, the total of reported primary energy decreases substantially (Jacobson, 2009).
- Energy and CO_2 emissions scenario literature that deals with fundamental transitions of the energy system to avoid dangerous anthropogenic interference with the climate system over the long-term (50-100 years) has used the direct-equivalent method most frequently (Nakicenovic and Swart, 2000; Fisher *et al.*, 2007).

Table A2 shows the differences in the primary energy accounting for the three methods for a scenario that would produce a 550 ppm CO_2 equivalent stabilization by 2100.

Table A2 Comparison of global total primary energy supply in 2050 using different primary energy accounting methods based on a 550 ppm CO2-equivalent stabilization scenario (Loulou et al., 2009).

	Physical content method		**Direct equivalent method**		**Substitution method**	
	EJ	**%**	**EJ**	**%**	**EJ**	**%**
Fossil fuels	581.56	55.24	581.56	72.47	581.56	61.71
Nuclear	81.10	7.70	26.76	3.34	70.43	7.47
Renewables	390.08	37.05	194.15	24.19	290.37	30.81
Bioenergy	119.99	11.40	119.99	14.95	119.99	12.73
Solar	23.54	2.24	22.04	2.75	35.32	3.75
Geothermal	217.31	20.64	22.88	2.85	58.12	6.17
Hydro	23.79	2.26	23.79	2.96	62.61	6.64
Ocean	0.00	0.00	0.00	0.00	0.00	0.00
Wind	5.45	0.52	5.45	0.68	14.33	1.52
Total	1052.75	100.00	802.47	100.00	942.36	100.00

While the differences of applying the three accounting methods to current energy consumption are modest, differences grow significantly when generating long-term lower CO_2 emissions energy scenarios where non-combustion technologies take on a larger relative role. (**Table A2**). The accounting gap between the different methods becomes bigger over time (**Figure A1**). There are significant differences of individual non-combustible sources in 2050 and even the share of total renewable primary energy supply varies between 24 and 37% across the three methods (**Table A2**). The biggest absolute gap for a single source is geothermal energy with about 200 EJ difference between the direct equivalent and the physical energy content method, and the gap between hydro and nuclear primary energy remain considerable. The scenario presented here is fairly representative and by no means extreme. The chosen 550 ppm stabilization target is not particularly stringent nor the share of non-combustible very high.

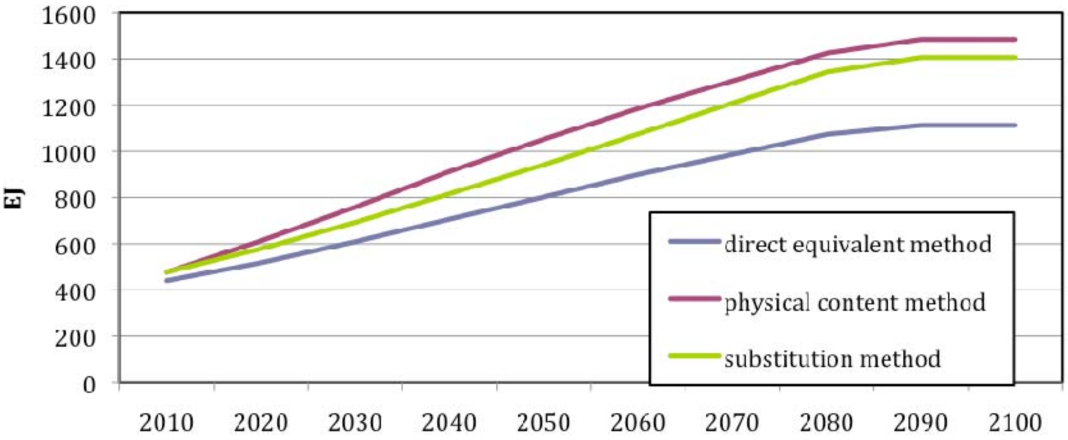

Figure A1 Comparison of global total primary energy supply between 2010 and 2100 using different primary energy accounting methods based on a 550 ppm CO2-equivalent stabilization scenario (Loulou et al., 2009).

A.II.6 General conversion factors for energy

To:	**TJ**	**Gcal**	**Mtoe**	**MBtu**	**GWh**
From:	*multiply by:*				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

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INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Annex III

Cost Table

Chapter:	Annex III				
Title:	Cost Table				
(Sub)Section:	All				
Author(s):	CLAs:				
	LAs:	John Nyboer, Steffen Schlömer, Aviel Verbruggen, Ryan Wiser			
	CAs:	Dan Arvizu, Ånund Killingtveit, Walt Musial, Luis Gutiérrez-Negrín, Gerardo Hiriart, Arun Kumar			
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Annex III Cost Table

The tables in this Annex contain information on cost and performance parameters for several renewable energy technologies, based on information provided in the respective technology chapters. The ranges provided in Tables 1 and 2 are based on assessments of various studies and represent roughly the mid 80% of values found in the literature, hence, excluding outliers. A range of levelized cost of energy (LCOE) has been calculated for three different discount rates (3%, 7% and 10%) based on the methodology described in Annex II. LCOE information based on the values stated here appears in Chapters 1 and 10 of the main report. Chapters 2-7 present more detailed information on current and future costs of each respective technology.

Table 1. Cost-performance parameters for RE power generation technologies[i]

Resource	Technology	Typical size of the device in MW installed capacity	Capital cost in 2008 (2005 US$/kW)[ii]	Fixed annual operating cost (2005 US$/kW)	Variable operating cost (2005 US$/MWh)	Capacity factor (%)	Financial/ economic lifetime (years)	Learning Rate (LR)[iii] (%)	References[iv]
Direct Solar Energy	PV - residential rooftop	0,004 – 0,01	6370 – 7280	27,3 – 36,4	0	12 – 20	20 – 30	11 – 26	
	PV - commercial rooftop	0,02 – 0,5	5460 – 6825	18,2 – 27,3	0	12 – 20	20 – 30	11 – 26	
	PV - utility scale, fixed tilt	0,5 - 100	3640 – 4550	13,7 – 18,2	0	15 – 21	20 – 30	11 – 26	
	PV - utility scale, 1-axis	0,5 - 100	4095 – 5005	22,8 – 27,3	0	15 – 27	20 – 30	11 – 26	
	CSP	50 - 250[v]	6400 – 7300[vi]	64 – 82	na	35 – 42[vii]	20 – 30	5 – 15	Solar Vision Study (not released)
Geothermal Energy	Geothermal energy (condensing-flash plants)	10 - 100	1778 – 3556[viii]	152 – 187	24 – 30[ix]	60 – 90[x]	25 – 30[xi]	na	For capex: Bromley et al., 2010. For O&M: Hance, 2005.
	Geothermal energy (binary-cycle plants)	2 - 20	2133 – 5244[viii]	152 – 187	24 – 30[ix]	60 – 90[x]	25 – 30[xi]	na	
	Enhanced Geothermal System (EGS)[xii]	na	na	na	na	na	na	na	-
Hydropower	All	< 0,1 - 20000[xiii]	1000 – 3000[xiv]	30 – 66[xv]	0	40 – 60[xvi]	40 – 80[xvii]	na[xviii]	see below [TSU: reference unclear]
Ocean Energy	Wave	na	2620 – 16071	123	na	38	20	na	Prevesic, 2004; Carbon Trust and Callaghan, 2006
	Tidal Current	na	8571 – 14286	na	na	na	na	na	Carbon Trust and Callaghan, 2006
	OTEC	10 – 100	4200 – 12300[xix]	na	na	na	na	na	Vega, 2002
	Salinity Gradient	na	-	na	na	na	na	na	
Wind Energy	Wind Energy (On-shore, Large Turbines)	5 - 300[xx]	1200 – 2100[xxi]	na	12 – 23	20 – 40[xxii]	20[xxiii]	10 – 17[xxiv]	References are provided in Chapter 7
	Wind Energy (Off-shore, Large Turbines)	20 - 120[xx]	3200 – 4600	na	20 – 40	35 – 45[xxii]	20[xxiii]	Na[xxv]	

[TSU to reviewer: It is intended to add data on bioenergy to this table to the extent possible based on the information available in chapter 2.]

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[i] For bioenergy and ocean energy (more detailed) information on cost are given in chapter 2 and 6 respectively.

[ii] In case 2008 data are not available or misleading (e.g. due to temporary price fluctuations), the closest and most adequate data available is stated here. For ocean energy capital costs may deviate from 2005 US$.

[iii] LRs are estimated for different periods in time, different regions and for different performance measures (cost of electricity vs. cost of generating device). These factors can have a significant impact on the derived LR.

[iv] The complete references are listed in the respective chapters' list of references.

[v] Project sizes of CSP plants can minimally match the size of a single power generating system (e.g. 25kW dish/engine system). However, the range provided is typical for projects being built or proposed today. "Power Parks" consisting of multiple CSP plants in a single location are also being proposed at sizes of up to 1GW (4x250MW).

[vi] For parabolic trough plant with 6hrs thermal energy storage. Costs are based on 2009 costs. Used chemical engineer composite cost index to convert to $2005. Total installed cost includes direct plus indirect costs where indirects include EPC markup, owners costs, land, and taxes.

[vii] Capacity factor for parabolic trough plant with 6hrs TES for solar resource classes typical of southwest U.S.

[viii] Data for new (greenfield) projects taken from new Table 4.7 to be included in the SOD version of Chapter 4. For expansion projects (i.e., new plants in the same geothermal field) capex can be 10-15% lower.

[ix] Variable O&M cost are calculated from fixed O&M costs using a capacity factor of 71%. Hence, fixed and variable O&M costs as stated here are not additive.

[x] Current (data for 2008-2009) worldwide capacity factor (CF) for condensing (flash) and binary cycle plants in operation is 71%. Excluding some limit cases, the lower and upper bounds can be estimated as 60% and 90%. The worldwide CF average is expected to increase to 75% in 2015, 80% in 2020, 85% in 2030, and 90% in 2050 (Table 4.9 in the SOD version of Chapter 4).

[xi] 25-30 years is the common lifetime of geothermal power plants worldwide. This payback period allows for refurbishment or replacement of aging surface plant, but is not equivalent to economic resource lifetime, which is typically more than 50 years, e.g. Larderello, Wairakei, The Geysers.

[xii] Other geothermal technology expected to be developed in the near-middle term (2015-2020), is Engineered Geothermal Systems (EGS). There are no observed costs or LCOE data for EGS and then it is not included in this table. Some projections have been made using two different models for several cases with diverse temperatures and depths (Table 9.5 in Tester et al., 2006). The obtained LCOE values for the MIT EGS model range from 100-175 US$/MWh for relatively high-grade EGS resources (250-330°C, 5 km depth wells) and a productivity of 20 kg/s per well.

[xiii] Hydropower projects come are usually very site specific and designed to use the flow and head at each site. Therefore, projects can be very small, down to a few KW in a small stream, and up to several thousand MW, for example 18000 MW for the Three Gorges project in China.

[xiv] Lowest cost for hydropower projects can be down to 4-500 $/KW but most realistic projects today lie in the range from 1000 up to 3000 $/KW.

[xv] O&M cost are usually given as a percentage of investment cost. Typical values range from 1% to 4%, as an average we use 2.5%.

[xvi] Capacity factors will be determined by hydrological conditions, installed capacity and degree of regulation. For power plant designs for energy production (base load) and with some regulation, capacity factors will be from 40 to 60%. A typical value can be 45%. For peaking type power plants the capacity factor will be much lower, down to 20%, but then the stations are designed with much higher capacity than needed for energy production.

[xvii] Hydropower plants in general have very long life-time. There are many examples of hydropower plants that have been in operation for more than 100 years, with regular upgrading of E&M systems but no major upgrades of the most expensive civil structures (dams, tunnels etc). For large hydropower plants the lifetime can safely be set to at least 40 years (IEA recommends 80 years). For small hydro the typical lifetime can be set to 40 years, in some cases even less.

[xviii] Hydropower is a mature technology so there are no major changes in cost. Some type of cost, for example related to Environmental conditions is gradually increasing, other like for example costs for tunneling, dam construction, etc are gradually decreasing. These two trends may balance each other, so future cost will probably be aproximately like today for the whole project.

[xix] Size of the power plant and distance from shore are stated as major cost determinants.

[xx] Typical size of device is taken as power plant (not turbine) size. For on-shore wind energy, 5 - 300 MW plants were common from 2007-09, though both smaller and larger plants are prevalent. For off-shore wind energy, 20 - 120 MW plants were common from 2007-09, though much larger plant sizes are expected in the future. As a modular technology, a wide range of plant sizes is common, driven by market and geographic conditions.

[xxi] Lowest cost plants have been installed in China, with higher costs experienced in the US and Europe. Range reflects majority of wind power plants, but plants installed in China have average costs that are even below this range (US$1,000-1,350/kW is common in China).

[xxii] Capacity factors depend on the strength of the underlying wind resource, which varies by region and site.

[xxiii] Modern wind turbines that meet IEC standards are designed for a 20-year life, and turbine lifetimes may even exceed 20 years if O&M costs remain at an acceptable level. Wind power plants are typically financed over a 20 year time period.

[xxiv] Learning rates for on-shore wind energy come from the published literature as reported in Chapter 7 (see Table 7.6), focusing on those studies completed in 2004 and later and that present learning rates based on total investment cost and global cumulative installations; the remaining range is explained by differences in model specification, variable selection and assumed system boundaries, data quality, and the time period over which data are available; the resulting studies are therefore not strictly comparable.

[xxv] Reliable historical learning rates for off-shore wind energy are not available.

Table 2. Cost-performance parameters for RE heating & cooling technologies[i]

Resource	Technology	Typical size of the device in MW$_{th}$ installed capacity	Capital cost in 2008[ii] [ii] (2005 US$/kW$_{th}$)[ii]	Fixed annual operating cost (2005 US$/kW$_{th}$)	Variable operating cost (2005 US$/GJ) (2005 US$/kWh$_{th}$)	Capacity factor (%)	Financial/ economic lifetime (years)	Learning Rate (LR)[iii] (%)	References
Geothermal Energy	Geothermal (building heating)	0,1 – 1	1595 – 3940	na	8.33 – 11.1 (0.03 – 0.04)	30	20	Na	Lund and Boyd, 2009.
	Geothermal (district heating)	3,8 – 35	571 – 1566	na	8.33 – 11.1 (0.03 – 0.04)	30	25	Na	Balcer, 2000; Radeckas and Lukosevicius, 2000; Reif, 2008; Lund et al., 2010
	Geothermal (Greenhouses)	2 – 5,5	500 - 1000	na	5.56 – 8.33 (0.02 – 0.03)	50	20	Na	Lund et al., 2010
	Geothermal (Aquaculture ponds, uncovered)	5 – 14	50 - 100	na	8.33 – 11.1 (0.03 – 0.04)	60	20	Na	Lund et al., 2010
	Geothermal Heat Pumps (GHP)	0,01 – 0,35	938 – 3571	na	7.8 – 8.9 (0.028 – 0.032)	30	20	Na	Lund and Boyd, 2009.

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[i] For bioenergy-based technologies and solar heating & cooling see chapters 2 and 3 respectively.

[ii] For geothermal heat pumps (GHP) the bounds of capital costs include residential and commercial or institutional installations. For these latter, costs include drilling costs, but for residential installations drilling costs are not included.