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INTERGOVERNMENTAL PANEL ON climate change

Working Group III - Mitigation of Climate Change

Special Report on Renewable Energy Sources and Climate Change Mitigation

FIRST ORDER DRAFT (VERSION 1)

FOD

CONTENTS

December 22nd, 2009

Foreword to the First Order Draft of the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation

Dear SRREN Authors and Expert Reviewers,

The Intergovernmental Panel on Climate Change (IPCC) Working Group III (WG III) for the Mitigation of Climate Change is pleased to present the First Order Draft (FOD) 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), the first lead author meeting in São José dos Campos, Brazil (January 2009) and the second lead author meeting in Oslo, Norway (September 2009). 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 FOD 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 FOD is available on the internal website of the IPCC WG III via the following link: http://www.ipcc-wg3.de/internal/srren/fod. **Please note that this is a confidential document which must not be distributed, cited or quoted**. The FOD represents work in progress that needs to go through the process of scientific and governmental review and further refinements by the author teams and is therefore subject to change. 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 with Annex 1 of Appendix A to the Principles Governing IPCC Work[1] 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

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

review excel sheet (available on the same website as the FOD) for your comments. The expert review period will end Monday, **February 8th, 2010, Noon CET**. We kindly ask that you review the FOD and send your comments in the review excel sheet to the Technical Support Unit at contact@ipcc-wg3.de no later than that date. Please note that **all comments will be published** following the final approval and publication of the report. A revised SRREN timetable and outline is available at the beginning of the FOD. 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

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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
12-14.02.2011*(TBC)	3 days	CLA Preparatory Meeting	Final consideration of gov. comments on the SPM	CLAs
15-18.02.2011*(TBC)	1 week	WG3 Plenary Session	Approval of SPM and acceptance full report	WG3 Plenary + CLAs

*(TBC): Dates of final plenary are subject to be shifted by one week. Final dates are yet to be confirmed.

AUTHORIZED VERSION, 18 December 2009

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.

2. Current Version of the SRREN Table of Contents

Changes in the TOC are highlighted in light blue. If only the order of subchapters has changed, the numbering is marked, but the whole title is left unmarked. If the title has changed (or the subchapter has been added) the titles (and numbers) are highlighted accordingly.

0.1. Summary for Policy Makers

0.2. Technical Summary

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

(Pending formal approval at the upcoming IPCC Plenary, 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

2. Bioenergy (15%)

2.1. Introduction (traditional and modern use)

WMO UNEP

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. <u>Direct Solar Energy (10%)</u>

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. <u>Geothermal Energy (3-5%)</u>

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. <u>Hydropower (5-10%)</u>

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)

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%)

9.1. Introduction

9.2. Interactions between sustainable development and renewable energies

9.3. Environmental impacts: global and regional assessment

9.4. Socio-economic impacts: global and regional assessment (energy supply security)

9.5. Implications of (sustainable) development pathways for renewable energy

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%)

(Pending formal approval at the upcoming IPCC Plenary the titles of 10.2, 10.3, 10.4 and 10.7 will be amended according to the structure below. For a detailed explanation, please see notes to expert reviewers on page 1 of the FOD of Chapter 10)

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

11.2. Current trends: Policies, financing and investment

11.3. Key drivers, opportunities and benefits

11.4. Barriers to renewable energy implementation

11.5. Experience with and assessment of policy options (local, national, regional; innovation and deployment)

11.6. Enabling environment and regional issues (technology transfer, transition management, capacity building, finance & investment, quality standards, international trade regulations)

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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			
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	CAs:	Aviel Verbruggen, Jan Steckel			
Remarks:	First Order Draft				
Version:	11.1				
File name:	SRREN_Draft1_Ch01.doc				
Date:	22-Dec-09 14:11	Time-zone:	CET	Template Version:	12

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 40 pages: a total of 6 pages over the maximum (13 over the mean, respectively).

Expert reviewers are kindly asked to indicate where the Chapter could be shortened by 4-11 pages in terms of text and/or figures and tables to reach the mean length.

References highlighted in yellow are either missing or unclear.

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.

In addition, all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 1: Overview of climate change and renewable energy

CONTENTS

EXECUTIVE SUMMARY

Climate change is a major symptom of the more fundamental problem of unsustainable development. Utilizing the atmosphere as a dumping ground for heat trapping greenhouse gases (GHGs) such as carbon dioxide from burning fossil fuels, and methane from coal mining, production of natural gas and petroleum and natural gas transport and use is responsible for raising the temperature of the earth. Efforts to improve wellbeing through sustainable economic and social development will be severely compromised if they ignore the present and future economic impacts of acute climatic events (such as cyclones or floods) on economies, infrastructure and livelihoods, and the chronic effects of climate change on agriculture, fisheries, health, human settlements and other human activities.

IPCC AR4 demonstrated that climate change due to human activity (emissions of greenhouse gases especially carbon dioxide) is accelerating and that the warming 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 below preindustrial values. The AR4 indicates 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. Recent data suggest that global warming is accelerating faster than suggested in AR4, and that additional emission reductions will be needed to avoid exceeding a 2°C target.

Renewable energy (RE) in combination with end use efficiency is one of the few solutions that enable reducing CO_2 output while maintaining energy services and economic growth. Various forms of RE are universally available, and can readily be introduced in both developed and developing countries. However currently RE contributes only 18% of global energy use, of which 13% is from traditional use of biomass (firewood, dung and agricultural waste), much of which is both inefficient and ecologically unsustainable. On the other hand, the use of windpower and solar energy (PV) are both increasing rapidly from a low base: indeed in 2008 the investment in new 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.

The potential energy supply from RE is very large. This report shows that it is economically feasible to develop RE to supply 270EJ by 2050, which is 31% of the global demand under a 'high-demand' scenario but 56% under a lower-demand scenario (i.e. one where energy efficiency is pursued more vigorously than has happened to date). However, this requires a shift in development strategy 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, enhancing energy security, employment creation and meeting Millennium Development Goals (MDGs). For example, use of modern energy services from renewable energy can contribute to freeing up household time in developing countries, and reducing smoke related diseases especially for women and children. This time can be reallocated to tending agricultural tasks, improving agriculture productivity, and develop micro-industries to build assets, increase income, and financial well-being of rural communities, thereby helping to alleviate poverty.

1.1 Background

1.1.1 Climate change

The industrial era has been fuelled by the burning of fossil fuels to provide energy for industry, transportation, heat and electric power. The trapping of radiant heat by carbon dioxide released during combustion of these fuels is now understood to be a major contributor to global warming and climate change.

In 2007, the Fourth Assessment Report (AR4) of IPCC expressed very high confidence (>90%) that the global average net effect of human activities since 1750 has been one of warming. There is a measured increase in global average temperature of 0.76°C (± 0.2°C) between 1850-1899 and 2001-2005, and the warming trend has increased significantly over the last 50 years. Although other greenhouse gases (GHGs) contribute to this warming, CO_2 from fossil fuels accounts for some 60% of the underlying radiative climate forcing, and by 2008 concentrations had increased from preindustrial levels of 280 ppm to 385 ppm (Solomon et al, 2009). Recent studies have demonstrated that climate change is accelerating, that the warming may be significantly greater and the consequences more severe and irreversible than previously realized. Solomon et al. report that "climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop." Additional carbon dioxide and some methane is released from coal mining, oil and gas production and natural gas transmission and distribution leaks, forest clearing and burning and by land use change. Analysis also suggests that additional warming from carbon black may be adding to radiative forcing (Ramanathan, 2009) along with other changes in the albedo or reflectivity of the earth's surface.

AR4 [WG1] 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 which of the SRES socio-economic scenarios best fits actual future GHG emissions. More recent projections, by Prinn et al. (Prinn, 2009), indicate a warmer range of 3.5 to 7.4°C. 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 AR4 [WG2]. A very recent report summarizes multiple trends and concludes that climate change is accelerating on every front from glacial melting to temperature and sea level rise (Copenhagen Diagnosos, 2009) The severity of the consequences of reaching irreversible tipping points temperature rises have lead many governments to advocate limiting temperature rises to 2°C above preindustrial values.

It is the total concentration of GHGs in the atmosphere that directly affects the global temperature. GHG emission rates from fossil fuels currently exceed the ability of natural sinks to absorb them, so 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. If global emissions continue to increase (upper curve of Figure 1.1), then global average temperature will increase by 3-5°C by 2100. (The upper curve is the mid-range A1B scenario (IPCC, 2007), but emissions since 1990 are trending above this curve.)

To limit the average temperature increase to 2°C requires emissions to decrease sufficiently to stabilise CO_2 concentration below 450 ppm (lower curve of Figure 1.1). This in turn implies that global emissions will have to decrease by 50-80% below current levels by 2050 and to begin to decrease instead of their current projected rapid increase by about 2020 (IPCC, 2007 AR4 Synthesis Report, Table SPM-6).

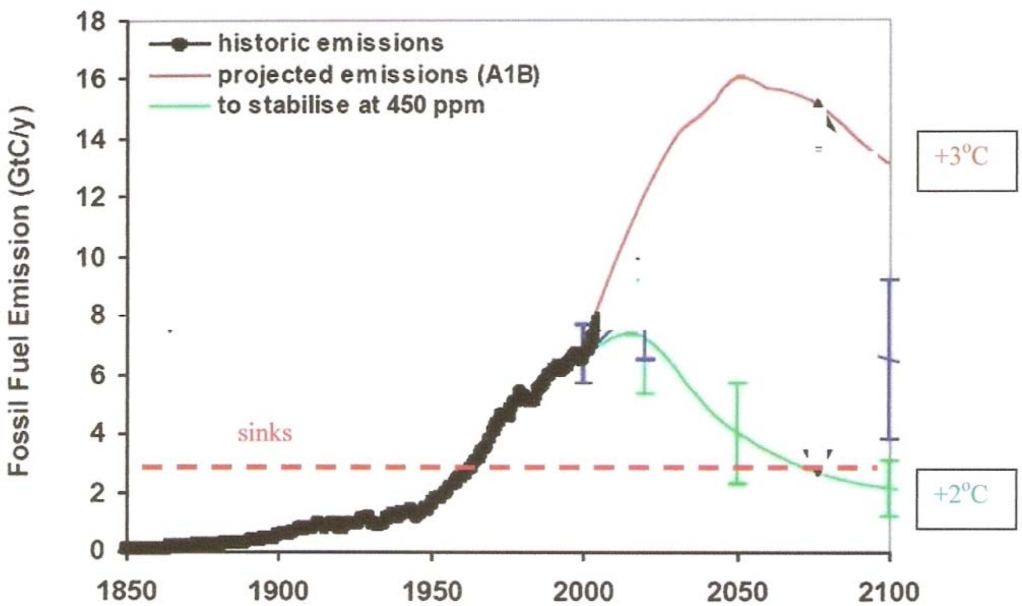


Figure 1.1. Alternative missions scenarios. If global emissions continue to increase as they have done since 1990 (upper curve), then global average temperature will increase by at least 3-5°C by 2100. If emissions decrease sufficiently to stabilise CO_2 concentration at about 450 ppm (lower curve), then the average temperature increase will be limited to ~2°C. (Diagram adapted from IPCC AR4 Synthesis Report Figure SPM-11 and charts from the Global Carbon Project; sinks data from IPCC AR4 WG1 Table TS-1).

Recent analysis of the economic cost of damages and mitigation to avoid those damages has also influenced thinking concerning potential mitigation options (Stern, 2006; 2009; UCS, 2009, McKenzie, 2008). There are many issues in any analysis of mitigation costs including debates over appropriate discount rates (Nordhaus, 2008) whether one utilizes a top down (usually more costly) or bottom up (usually less costly) analysis. The influence of these more recent studies has been to shift the perception that mitigation costs may be less than estimated in earlier studies or may in fact lead to significant direct and indirect savings for many sectors (Ackerman, 2009).

The main renewable energy (RE) technological options for reducing the growth of greenhouse gases in the atmosphere are described in sec. 1.1.4, and in the appropriate chapters of this report.

1.1.2 What is renewable energy and what is its role in addressing climate change?

Renewable energy (RE) is any type of energy produced from geophysical or biological sources that are naturally replenished. As long as the rate of extraction of this energy does not exceed the natural energy flow rate, then the resource is sustainable. 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 in which case, these “renewable” resources are unsustainable. By contrast, the rate of utilization of solar energy has no bearing on the rate at which it reaches the earth.

The renewable energy sources examined in this report are categorised as bioenergy (ch.2), direct solar (ch.3), geothermal (ch.4), hydro (ch.5), ocean energy (ch.6) and wind (ch.7).

Most renewable energy technologies have the advantage of not producing any (or very low) carbon dioxide emissions, and can be utilized in a manner which is in principle inexhaustible. Biomass can be utilized so as to be responsible for significant GHGs, or can be a low carbon fuel. Each RE technology does have a specific set of associated environmental impacts, as discussed in the 'technology' chapters of this report. Most of these impacts are very modest compared to those of fossil and nuclear systems, although a few RE technologies can have substantial environmental impact, notably large dams and unsustainable use of biomass.

The use of renewable energy by humans goes back to the discovery of fire and the use of wood for cooking and heating. Beginning with the domestication of animals for motive power and transportation, humans have relied on photosynthesis and the stored energy in green plants to fuel "animal machines." These original forms of renewable energy still provide the principal sources of energy for more than one billion people in the world and account for an estimated 10 percent of world energy use. Vegetable oils were the original choice of Otto Diesel for his early engine and Henry Ford selected grain ethanol to power his first vehicles.

These biofuels were largely replaced by abundant coal, petroleum and natural gas during the 20th century. However, volatile petroleum and natural gas prices, national security concerns about the geopolitical availability of these fuels and the drive to reduce human induced climate change are creating demands for a return to biofuels for the rapidly growing transport sector, which is largely dependent on fossil liquid fuels The discovery that mechanical energy could be extracted from the wind and from the kinetic energy of falling water and ocean tides, waves and currents was made independently in many parts of the world over the past millennium and in modern technological forms are currently experiencing a resurgence of interest and investment. Passive solar energy has been used for heating and light in ancient Greek and Roman buildings and many societies have made use of the heat from natural hot springs, which now produce both heat and electricity. The development of solar photovoltaic panels that can convert sunlight directly into electricity opened new opportunities for producing electricity, while the development of thermal systems now produce both heat and electricity (Moomaw, 2008).

In 2007, Denmark produced 21% of its electricity from wind power, and nearly 20% of their total energy comes from renewables. Brazil met more than half of its non-diesel transportation energy with bioethanol in 2008, and China's installed wind capacity has grown 5-fold between 2005 and 2008, and it will soon exceed its nuclear capacity at current growth rates. China also leads the world in solar domestic hot water installed capacity (Sawin and Moomaw, 2009; REN 21, 2009a,b).

Despite these impressive gains by renewable energy technologies, fossil fuels remain the dominant form of energy production for heat, electric power and transportation, and their use continues to grow rapidly increasing carbon dioxide (Figure 1.1 and Figure **1.2**).

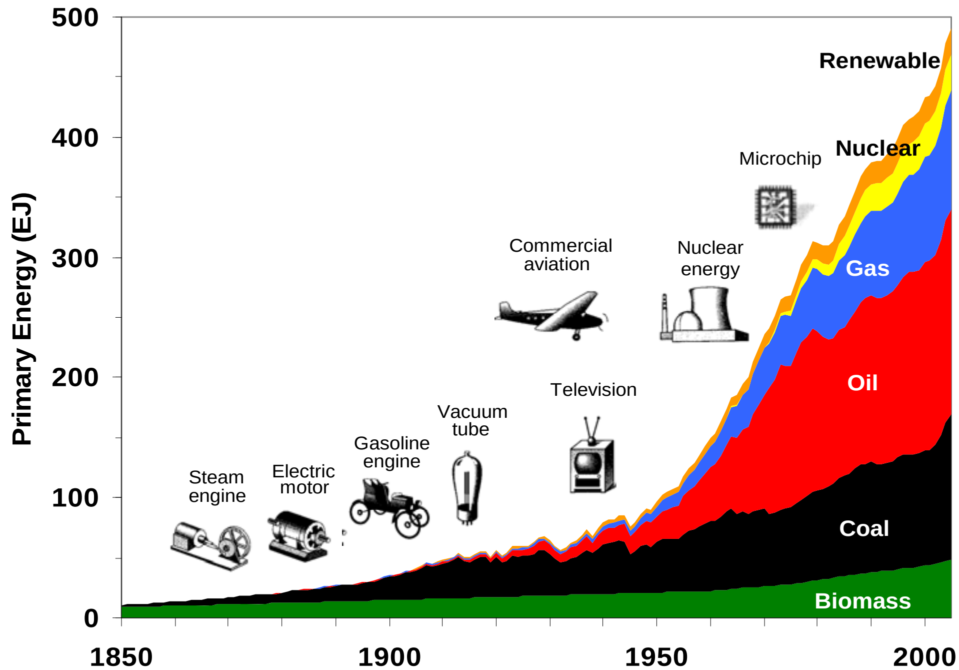


Figure 1.2. Energy supply by source 1850-2005. [TSU: Source?]

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) (Kaya, 1990). The absolute (a) and percentage (b) changes of global CO_2 emissions decomposed into the Kaya factors are shown in Figure 1.3, (Edenhofer et al, 2010).

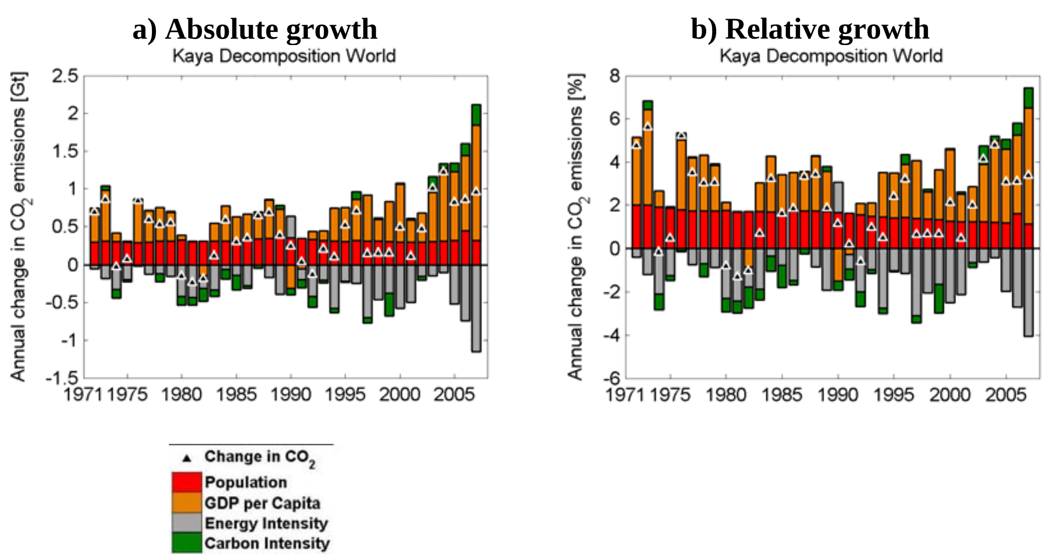


Figure 1.3. Kaya decomposition of global energy related CO_2 emissions by population (red), GDP per capita (orange), energy intensity (grey) and carbon intensity (green) from 1971 to 2007. Total annual changes are indicated by a black triangle. Part (a) Absolute changes; Part (b) percentage changes. 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. Since the early 2000s the energy supply has become more carbon intense, thereby amplifying the increase resulting from growth in GDP/capita.

It is possible to extend the standard Kaya decomposition so that changes in carbon intensity can be assigned to different energy carriers. Figure 1.4 shows the influence of different energy carriers on emission growth induced by carbon intensity (Edenhofer et al, 2010). 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.

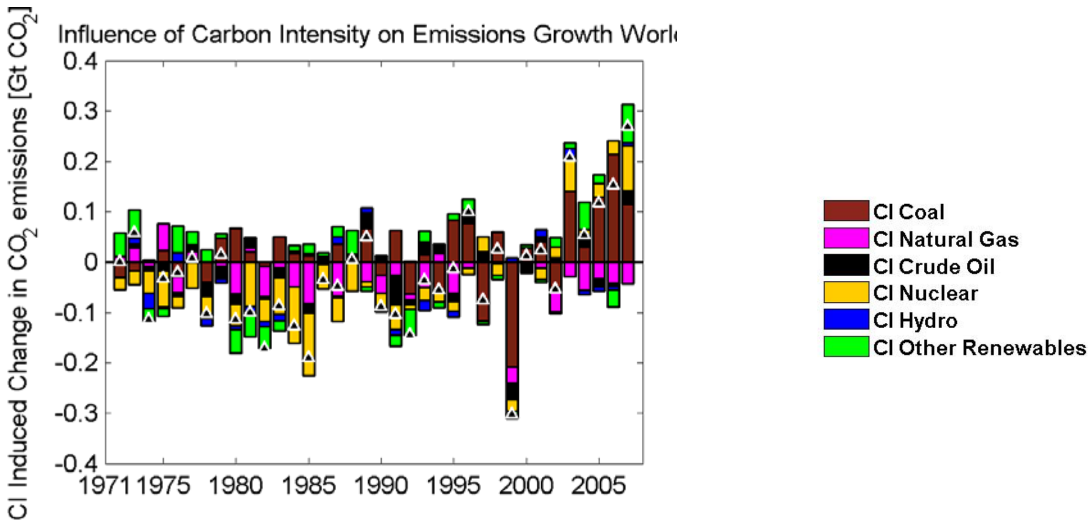


Figure 1.4. The influence of different energy carriers on the carbon intensity induced changes on CO2 emissions. The contribution of carbon intensity to the change in annual CO_2 emissions can be attributed to changes in the relative contribution of the energy carriers coal, natural gas, crude oil, nuclear, hydro and other renewables. Note that in case of decreasing shares of carbon-free technologies (renewables, hydro, nuclear), an increase of carbon intensity and thus CO_2 emissions is induced. Data Source: IEA (2009b). [TSU: Title partly missing, Cl not defined]

These analyses demonstrate the necessity of shifting from carbon intensive fossil fuels to alternative low carbon sources in the provision of energy services. In order to meet the stringent CO_2 emission reduction requirements to 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 renewable energy sources in combination with energy efficiency to meet the GHG reduction goals set by policy makers to reduce the extent of future climate change.

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, in association with energy efficiency, renewable energy sources can make a substantial contribution to climate change mitigation as early as 2030 and an even large contribution 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 broader 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:

Renewable resources by region and impacts of climate change on these resources;

Mitigation potential of renewable energy sources;

Linkages between renewable energy growth and co-benefits in achieving sustainable development by region;

Impacts on global, regional and national energy security;

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. How accelerated deployment might be achieved in a sustainable manner.

1.1.4 Options for mitigation

It is often assumed that economic growth is tied to energy use, and since 85% of primary energy comes from fossil fuels, to CO_2 emissions. Historically, energy consumption per capita has been very roughly proportional to GDP per capita, but this connection was broken in many economies following the oil price shocks of the 1970s. This lowered the energy intensity of economic growth, decreasing the ratio of energy use/ GDP thereby slowed the growth of GHG emissions. Indeed the energy/ GDP ratio declined by 33% between 1970 and 2004 (IPCC, 2007), Fig. SPM-2). Energy supply appears adequate to supply most energy services in most of the developed countries. 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 reduces energy consumption, and with low carbon technologies that minimise CO_2 emissions. All the long-term energy scenarios expect high growth rate of energy consumption in developing countries, so that energy supply with low or zero CO_2 emissions and low energy intensity are indispensable.

We caution against 'mitigation' options that cast climate change as the sole problem when it is really just one symptom of the more fundamental problem of unsustainable development. Thus, 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 which is 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 is likely to increase the amount of 'acid rain' and will not address the increasing acidification of the oceans by CO_2 or the choking of cities by the increasing number of motor cars on the road (Robock et al., 2009).

More constructively, Figure 1.6 shows a potential framework of options for achieving "low carbon growth". These include end use efficiency improvements, more efficient energy conversion technologies, more stringent standards and market based measures, and renewable energy. Renewable energy and energy efficiency represent two of the major options available. Renewable energy in combination with end use efficiency is potentially one of very few solutions that enable the world to actually reduce CO_2 output while maintaining energy services and economic growth.

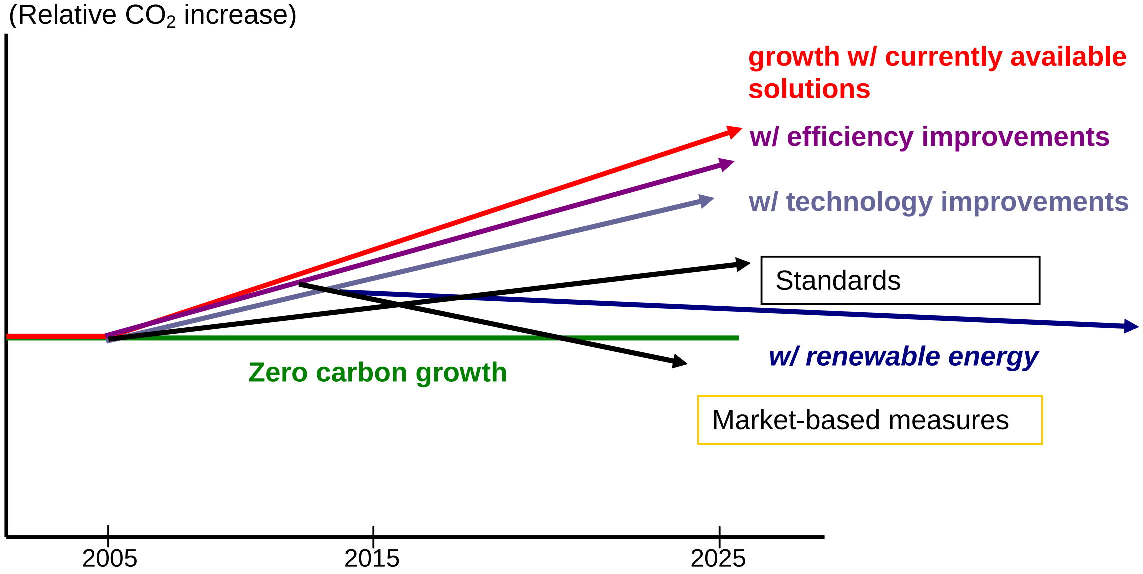


Figure 1.6. A potential framework for reducing carbon output. [TSU:Source?]

There are numerous specific responses to climate change (Pacala and Socolow, 2004; IPCC AR4, 2007), notably

- Renewable energy technology substituting for fossil fuels
- End use energy efficiency gains and production efficiency through newer technologies and/or improved operational practices
- Carbon Dioxide Capture and Storage (CCS) from fossil fuel or biomass combustion
- Fossil fuel switching to lower carbon fuels such as substituting natural gas or biomass for coal
- Nuclear power substituting for coal and natural gas
- Forest, 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)
- Geoengineering such as albedo adjustments, and ocean fertilization

This report will focus on the first of these options: the role that renewable energy can play in reducing the heat trapping gases, carbon dioxide, and methane and will examining the synergies between RE and 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 by up to 50% in many applications. 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, 2009). Avoiding international style glass box construction of high-rise buildings in tropical countries could dramatically reduce emissions at a substantial cost saving for cooling.

Renewable energy 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. Biofuels become more feasible for aircraft as efficiency improves

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. Substantial efficiency gains and CO_2 emission reductions have also been achieved through the use of hybrid electric systems, battery electric systems and fuel cells. The first two are now in production, but fuel cells are still too expensive to be commercially competitive.

Two additional approaches to energy efficiency are combined heat and power systems (Kasten, 2008), and recovery of otherwise wasted thermal or mechanical energy (Bailey and Worrell, 2005).

These principles are also applicable to enhancing the overall delivery of energy from renewable energy as in capturing and utilizing the heat from PV or biomass-electricity systems.

Technological improvements can and will continue to make tremendous progress reducing greenhouse gases through efficiency. However – technology alone can only take us so far. The forecasted growth in population and the demand for energy could well outpace the pace of technological innovation and emissions will continue to grow, without changes in lifestyles especially in the richer countries.

1.1.5 Role of renewable energy in addressing co-issues of climate change (energy security, employment, MDGs and sustainability goals)

Two primary concerns motivate the consideration of renewable energy: price and environmental effects. The latter is a growing concern, with generally increased public and government expectations for environmental performance. Energy security is also a major driver. For example in the U.S, the military (Secretary of the Air Force, 2009) has led the effort to expand and diversify fuel supplies for aviation and cites improved energy supply security as the major driving force for renewable fuels. Apart from climate change mitigation, renewable energy can play a significant role in meeting sustainable development goals, enhancing energy security, employment creation and meeting Millennium Development Goals (MDGs).

Securing a reliable, constant and sustainable supply of energy requires a diversification of energy sources. Renewable energy offers promise as a possible alternative for replacing petroleum based products; since most of the resources are domestically based, they can be used in any country (German Federal Ministry for Environment 2008). Despite the worldwide economic recession of 2008-2009, oil prices will likely continue to rise with economic recovery in the absence of other market drivers. A diversified and expanded supply of energy may act to lower prices and/or reduce volatility. Increasing the energy supply via production of alternative fuels is expected to have a positive effect for all energy users by reducing the long-run price of all fuels including conventional petroleum products. Associated price reductions could result in significant savings (on the order billions of dollars annually). 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.

Production and utilisation of renewable energy can also spur rural and economic development, providing opportunities for farmers and entrepreneurs to produce feedstocks for renewable energy production and participate as owners of production facilities across all types of renewable energy. Given that 50% of the world’s population is still agrarian, the scale up of renewable energy offers significant economic opportunities for rural communities around the world (WIREC 2008). The opportunities culminate in improved income, job creation, and improved education, health care, distributive computing, telecommunications and public services.

But we must take care to ensure that even an RE “solution” is truly sustainable. For example, when considering biofuels, they should be made from crops that do not take up arable land that could be used to produce food and do not require excessive use of water, chemicals or threaten biodiversity.

Furthermore, renewable energy sources represent an important opportunity for developing countries, since access to energy is a key factor in combating poverty. A large proportion of the population in these countries live in rural areas. The lack of transmission grids makes conventional energy supply impossible in such locations. The decentralised nature of renewable energy means they are able to provide a basic energy supplies through an off grid system (German Federal Ministry for the Environment 2008). In this way, renewable energy 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.

Renewable energy is also central in achieving MDGs and targets. For example, regarding MDG goal 1 of eradicating extreme poverty and hunger, use of modern energy services from renewable energy can contribute to freeing up household time, in particular for women. This time can be reallocated to tending agricultural tasks, improving agriculture productivity and develop micro-industries to build assets, increase income, and financial well being of rural communities (UNDP 2005). Chapter 9 looks at the relation between greenhouse mitigation and sustainable development.

1.1.6 Trends in renewable energy

The international community's role in advancing renewable energy goes back three decades to the fuel crisis of the 1970s, when many countries began exploring alternative energy sources. Since then, various attempts have been made to ensure renewable energy featured prominently on the international environment and development agenda 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;
2. the 1992 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 renewable energy;
4. 2002 World Summit on Sustainable Development (WSSD) in Johannesburg-South Africa, when several Renewable Energy Partnerships were signed;
5. Bonn Renewable Energy Conference 2004, which addressed best practices, research and policy development, energy services, and MDGs;
6. Beijing Renewable Energy Conference (BIREC) 2005;
7. Washington Renewable Energy Conference (WIREC) 2008.

Since 1990, global energy consumption almost doubled, rising to around 503EJ in 2007, with renewable energy's share at 13.0% (IEA 2009). (Figure 1.7)

Global primary energy consumption

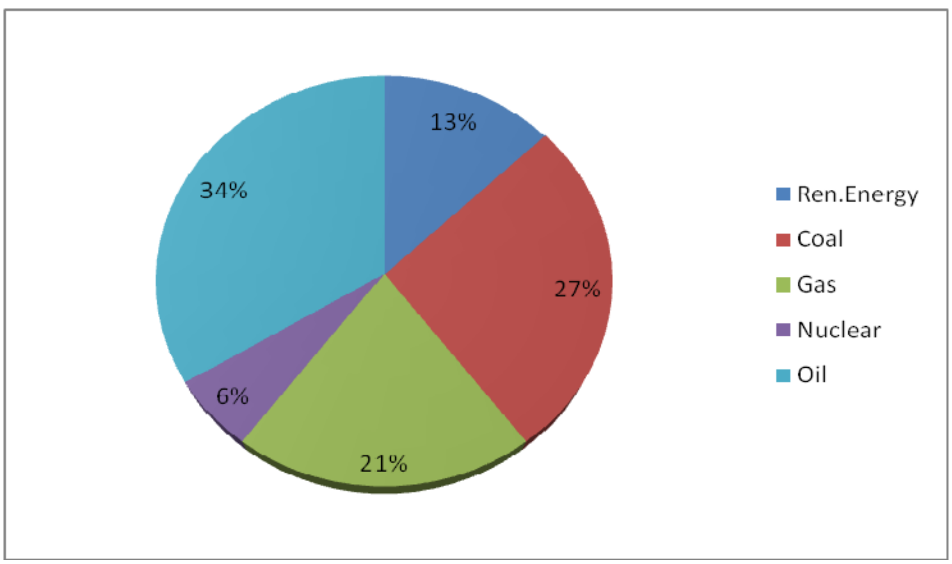


Figure 1.7. Global primary energy consumption(IEA, 2009a).

The 13.0% renewable energy is distributed as solid biomass (9.6%), large hydroelectric power (2.2%), geothermal (0.4%), liquid biomass (0.2%), and new renewables embracing wind solar and marine energy (0.1%). Traditional biomass accounted for the "lion's" share of global primary energy consumption, at 47.0% for Africa, due to its wide spread traditional use particularly in for cooking and lighting. At the global level, on average, renewables have increased by 1.8% per annum between 1990-2007(IEA, 2009b), 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 renewable energy 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, 2009b). Biomass and waste as a share of primary energy consumption is particularly high in Africa (Figure 1.8).

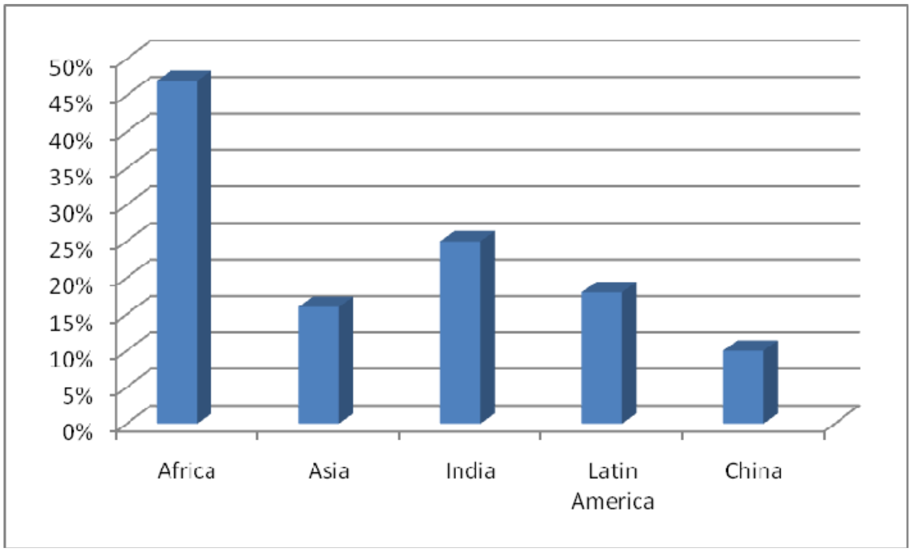


Figure 1.8. Biomass as a share of Primary Energy Consumption (IEA, 2009b)

Africa has a share of 47.0%, Latin America 18.03%, Asia 16.0%, India 25.0% and China 10.0%. Africa's high share is due to traditional use of biomass, which is not sustainable in the long run. Basic forms of cooking and heating impair health through use of open fires, and lead to deforestation (Brew-Hammond, 2008).

UNEP finds that global investment in renewable energy 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 estimates that an additional $15 billion was invested in energy efficiency during the year (UNEP, 2009). 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 with the U.S. second, Germany third, Spain fourth and India fifth (REN 21, 2009a). In 2008, investment in renewable electric supply exceeded that for coal and natural gas for the first time. Much of this investment was in the United States, China and Europe (UNEP, 2009; REN 21, 2009b)

This investment milestone suggests the possibility that renewable energy could play a much more prominent role in both developed and developing countries over the coming decades. New policies in the United States, China and the EU are supporting this effort, and one country, Germany has proposed a goal of 100% renewable energy by 2050 (German Federal Ministry, 2009).

1.2 Summary of renewable energy resources

1.2.1 Resource advantages of renewable energy

Renewable energy is a resource that is available and is delivered by natural processes to a technological receiver. These resources are far more uniformly distributed among all nations than fossil fuels and uranium. Thus, from an energy security perspective, they are more reliable than other energy resources for fossil-fuel poor countries.

1.2.1.1 Cost certainty and distribution

While distant sources such as off-shore wind and remote wind and hydro will require long distribution limes, distributed systems will not. Renewable technologies such as rooftop solar PV produce electricity that is mostly utilized on site, so even if these distributed systems are grid connected there is no additional transmission or distribution system required and no transmission or distribution line losses. Over half of the capital investment in the electric power sector is in transmission and distribution costs (IEA, 2009b), The cost of renewable energy "fuel" and its delivery to the production site (wind, solar, hydro, geothermal and ocean) is free, and the capital costs for extracting and converting it are known up front, hence there is certainty over future fuel prices. For the world's poor who utilize wood, dung and crop residues for cooking and heating the biofuels can be gathered with their own labour. As discussed in the next section, more advanced technologies for capturing renewable energy are often capital intensive. Even so, financing systems for technologies such as solar PV for small-scale use in developing countries have been developed that make the cost of improved energy services comparable to kerosene, batteries and oil lamps (Enersol, 2009).

1.2.1.2 Scalability of renewable energy technology

The issue of scaling up particular technologies is an issue, and 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 meet the needs for growing energy demand.

But the rapid introduction of natural gas fired turbines during the past 20 years in North America and Europe suggests an alternative conclusion. The rapid adoption of gas turbines has been due to three factors. The first is that such turbines have become exceptionally efficient (50-60%), the second is that because of economies of scale, their unit cost is low, and thirdly, they can be produced quickly in modules of 50 -100 MW and installed within a short time-frame. This latter aspect has meant low cost of capital, a better match to incremental demand growth and immediate production of incremental power upon installation. Finally, it is interesting to note that the total engine power of vehicles sold in the US each year exceeds the total electric power generation capacity of the country. Another testament to the capacity of modular scaling to produce sufficient modestly sized energy units to meet a large scale demand.

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.

At current rates it appears that wind, solar and biomass have all demonstrated that they can be manufactured at a rate that is comparable to large-scale projects. 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.

1.2.2 Resource disadvantages of renewable energy

One problem with many renewable resources used for electric power is that they are variable and may not always be available for dispatch when needed. Renewable resources may be characterized into two categories: those that have inherent energy storage and those that are variable. The former include hydropower, geothermal, and biomass. Variable sources include solar and wind power. The need for management of variable sources or the use of energy storage systems increases the complexity and cost of these systems. As will be discussed in chapter 8.2 of this report, Germany has recently demonstrated a virtual renewable base load power plant by utilizing a "hybrid" set of renewable sources.

Some sources are matched to demand such as solar electricity and air conditioning loads. Energy services such as water pumping, purification or desalination can be provided whenever the energy source is available. Smart grid advocates including Amory Lovins who was an early proponent, propose utilizing the electricity storage capacity of electric battery vehicles and battery hybrid vehicles to provide interactive storage for solar or wind produced electricity (Moomaw, 1994, RMI, 2008).

The energy density of many renewable sources is relatively low, so that available power levels may be insufficient for meeting certain purposes. These may include very large-scale industrial facilities or dense urban settlements. In most cases, at least some portion of these demands can be met by a combination of renewable energy sources, as will be discussed elsewhere in this report.

The cost of energy capture technology can be quite expensive and it may be difficult to pay for the initial capital investment. Addressing this problem is really no different than meeting the capital costs of other capital-intensive investments such as nuclear power plants and large coal power plants or large scale hydropower facilities.

1.2.3 Resource potential

The theoretical potential for renewable energy 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 renewable energy and a comparison with fossil fuel reserves and annual consumption of approximately 500 Exajoules/year are provided in Table 1.1.

Table 1.1. Renewable energy fluxes

Renewable source	Annual flux or use	Ratio Annual flux or resource/ 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	- - -
Total conventional fossil fuel reserve	396 EJ/y*	104	46,700 EJ

Renewable source	Annual flux or use	Ratio Annual flux or resource/ annual demand	Total reserve
Total unconventional fossil fuel reserve	0.06 EJ/y**	42	18,800 EJ
Total Uranium reserve	31 EJ/y***	6.7 - 23	3,000- 10,500 EJ
Current global energy use	448 EJ/y (2004)* Conv. Biofuels adds ~45 EJ/y	1	- - -

Source: World Energy Assessment, 2000 and 2004, ***IEA, 2006, ** OGJ, 2004.

A summary of the renewable energy supply technical potential estimates in ExaJoules from each of the technical chapters is provided in Table 1.2. Geothermal and wind estimates are assumed to remain constant from the present to 2050. No useful estimate for oceans has been developed. Note that the technical potential exceeds even 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 end use efficiency gains are endogenous ones rather than being policy driven. See Section 1.3 for how a substantial increase in energy efficiency for both supply and demand could lower the total demand even further.

Table 1.2. Technical potential for renewable energy (EJ) The data are a summary of the findings of the technology chapters. See Glossary for a definition of Technical Potential. No consistent method is available for estimating ocean potentials,

Technology	2005	2020	2030	2050
Biofuels	46	530	1,000	1,500
Solar	1,440	17,640	34,200	50,400
Geothermal	661	661	661	661
Electric	30	30	30	30
Thermal	631	631	631	631
Hydropower	12	16	17	23
Oceans	-	-	-	-
Wind	396	396	396	396
Total Renewable production	2,555	19,242	36,274	52,979
Projected global demand, 450 Scenario*	502	586	601	712
Projected global demand, BAU*	502	628	712	928

Source: IEA, 2009c.

1.3 Meeting energy service needs and current status

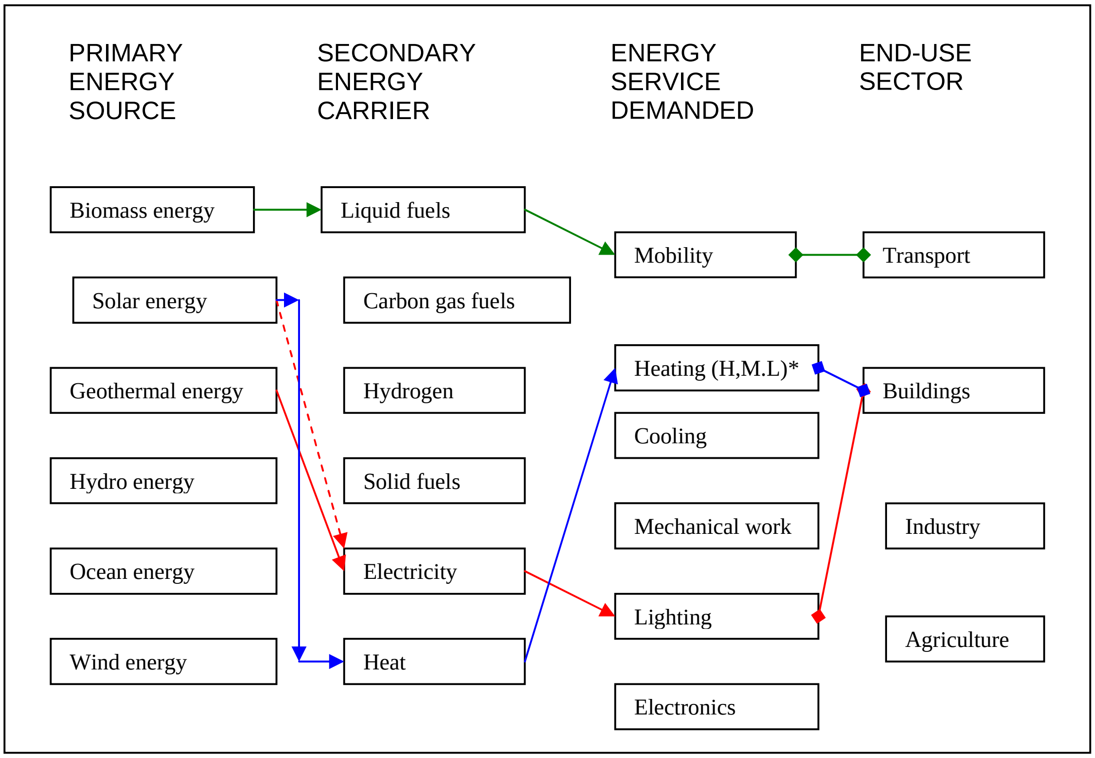
1.3.1 Energy pathways from source to end use

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. Here energy is transformed again by appropriate technologies to provide the service demanded. Renewable energy sources can serve as a primary energy supply.

Analysis of energy flows is described using four different organizing principles: primary energy, secondary energy carriers, energy services and economic sector. Figure 1.9 shows several simplified energy flow pathways of renewable energy from source to end use linking these four parts. Energy transport and storage are often needed to provide a stable energy service to the consumer, making the energy pathway more complicated. These aspects are not shown in the figure. It should be noted that renewable energy can be transformed to appropriate forms of energy to meet the energy services demanded. Selection of the pathway can be made using various criteria such as availability of energy sources, environmental burden, capital cost, life cycle analysis (LCA), matching supply to demand, and other factors, some of which may be regionally specific.

This diagram can be used as an organizing tool for conducting a life cycle assessment of specific energy options to meet alternative energy service needs in different end use sectors. One can identify where energy transformation losses occur and where do environmental impacts occur. Similarly, the LCA 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 or 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 and Mills, 2005).

Figure 1.9. The relationship among primary renewable energy source, Secondary energy carrier, energy service demand and End-use sectors. Some energy pathways are shown from renewable energy source to end-use sector. * H, M, L refer to high, medium and low temperature heat.



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 can be attributed to one of the four end-use sectors shown (in this example, buildings). The diagram indicates the range of sources, carriers, services and sectors examined in this report. Arrows indicate a few of the possible pathways; many others are possible but for simplicity are not shown here. The term 'carbon gas fuels' refers to methane, biogas, producer gas, etc, as distinct from pure hydrogen. A given energy service can be met by alternative primary and secondary sources with very different climate and other environmental implications.

1.3.2 Importance of energy end-use efficiency

As discussed in sec.1.1.4, energy efficiency plays a synergistic role with renewables. Because of the relatively low energy density of renewables such as solar energy, it may only be feasible to supply electricity from solar PVs for efficient lighting, or to meet thermal comfort needs if the demand is sufficiently low. End use efficiency has been especially important in meeting energy service needs by renewable energy in developing countries for cost reasons.

It is important to realize that renewable energy need not replace fossil fuel energy on an Exajoule for Exajoule basis. If one measures energy service delivery rather than primary energy, there is a substantial drop in primary energy needs when renewable electric generation replaces inefficient thermal electric conversion systems. One recent study suggests that if all thermal electric systems in the United States were replaced, the demand for primary energy would decrease by 31% for electricity production in 2030 (Jacobson and Delucchi, 2009; Jacobson, 2009).

1.3.2.1 Rebound Effect

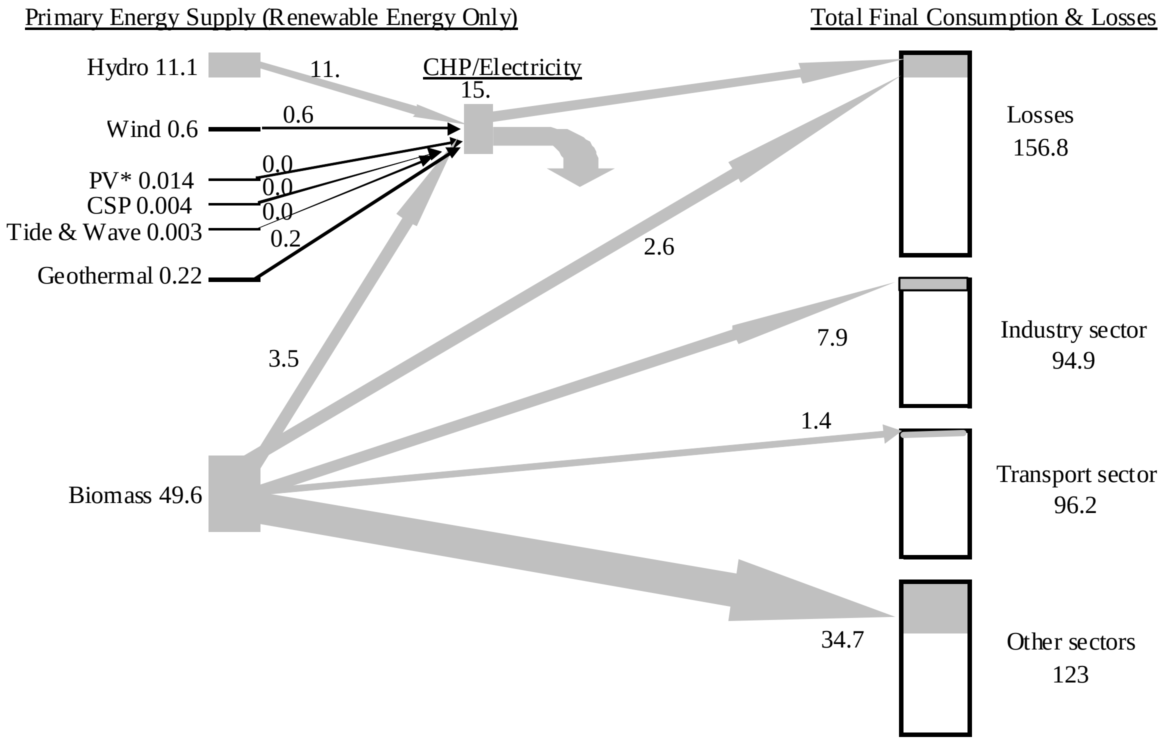
The rebound effect is defined as the failure to achieve full energy savings because the lower cost of providing an energy service with less energy may increase the use of that service. For example, as drivers switch to more efficient vehicles, they may drive more miles because fuel cost is less per mile. Such rebound may partially or, in rare cases, fully negate the expected reduction in GHG emissions when older less efficient devices are replaced. One advantage of shifting to renewable energy is that even if one's energy consumption increases while utilizing the renewable technology, there is no increase in GHG emissions (Sorrell, 2008).

1.3.3 Current status of renewable energy

1.3.3.1 Global energy flows from primary renewable energy

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 [2007, IPCC AR4 WG3]. Figure 1.10, shown here, reflects primary renewable energy only, utilizing the data for 2007 [IEA 2009b]. For that year, the share of renewable energy to total primary energy supply is 13%, about 16% of total final energy consumption. Renewable energy here includes combustible renewables and waste as well as those more commonly included: wind, hydropower, geothermal energy, solar energy, etc. Figure1.10 summarizes global energy fluxes.

Figure 1.10. Global energy flows (EJ in 2007) from primary renewable energy through carriers to end-uses and losses drawn with IEA data



Source: IEA 2009b.

Transport sector includes international aviation and international marine bunkers. Other sectors include agriculture, commercial & public services, residential and non-specified other sectors.

1.3.3.2 Share of renewable energy and its growth rate

Biomass and hydropower are the largest contributors to the sum total of all primary renewable energy at 81% and 18%, respectively. Renewable sources other than biomass and hydro account for less than 1% of the primary energy supply.

Approximate technology shares of 2008 investment were wind power (42 percent), solar PV (32 percent), biofuels (13 percent), biomass and geothermal power and heat (6 percent), solar hot water (6 percent), and small hydropower (5 percent). An additional $40–45 billion was invested in large hydropower, which contributes the largest share (86%) (Ren21, 2009a). Between 2003 and 2008, solar installations grew at an average annual rate of 56%, Biomass and wind at 25% and hydro by 4%. 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. Germany in 2008 produced 15% of its electricity and 10% of its total energy from renewable sources (Sawin and Moomaw, 2009 and references therein). Table 1.3 summarizes the share of renewable energy in world electricity generation.

Table 1.3. Renewable energy share of world electricity production

	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: REN21, 2009a.

1.3.3.3 Contribution of renewable energy to end users

Biomass is utilized primarily in the buildings sector, particularly for heating, where “Buildings” include residential, commercial, public service and agricultural. The contribution of renewable energy to the industry sector is the second largest, after Buildings, with the transport sector consuming only small amounts of energy from renewable sources. While the total amount of renewable energy consumed in each sector is small, there exist many possible applications. The following applications are examples of various applications for each sector at present and in the future:

Buildings sector:

- hot water supply, heating for air conditioning and for cooking, cooling, geothermal heat pump, lighting

Agriculture sector:

- irrigation, greenhouse heating, agricultural drying, aquaculture pond heating, gaseous (biomethane) and liquid (ethanil and biodiesel) fuelsgasiquid and gaseous fuels for machinery and onsite electricity [TSU: sentence unclear]

Industry sector:

- process heat supply, air conditioning, lighting

Transport sector:

- bio-fuels, electricity for Electric Vehicle, hydrogen for Fuel Cell Vehicle

1.3.4 Energy system management

Energy is useful only if available when and where it is wanted. To link the supply and demand, we have to carry energy to the end-users through grids (e.g. hot water, gas pipe, vehicle transportation, and networked electricity) (Twidel and Weir, 2006). Since the end-use demand varies with time on scales of months, days and even seconds, energy storage is also required.

An AC electric power grid is the most convenient and prevailing energy network to transport and distribute energy to the end-users as electricity. Although electric power transported with the grid is generated mainly by centralized power stations such as nuclear, fossil-fired, large hydro and geothermal, the capacity of grid-connected distributed renewable energy sources has recently been increasing rapidly (REN21, 2009b).

The output from wind and solar power is variable, although if it correlates with peak load the value of the electricity produced is higher (for example, solar energy is available at peak hours in California, Japan and Southern Europe). The electric power grid has to be operated to keep the quality of electricity: almost constant voltage and frequency and no failure in secure electricity supply. The rising share of the variable energy sources in electricity generation provides additional costs associated with the integration of these technologies into the power-supply system, including those associated with necessary back-up capacity and operation, and grid access (IEA, 2009b).

Energy storage is without doubt most important key technology for the future energy systems. R&D is under way on various kinds of electric power storage facilities with different storage duration time and capacity: various batteries, compressed air energy storage (CAES), superconducting magnetic energy storage (SMES), etc (Kondoh et al., 2000). Producing hydrogen as an energy carrier from renewable electricity systems can be another form of storage.

Future energy systems would be sort of integrated networks of electric grid, gas (hydrogen) pipeline and hot- and cold-water supply systems. Sophisticated control of the energy system is required in near future to maximize mitigation potential (or to connect as much renewable energy as possible to the energy network) without deteriorating the quality of energy supply as mentioned above. Key technologies to realize such controls are IT, weather and demand prediction, demand response, power electronic devices, and controllable power sources as well as energy storage (Tsuji et al, 2009). Controlling demand-side equipments using "smart-meter" has been proposed (Brown, 2008).

1.3.5 Current status of renewable energy as function of development

1.3.5.1 Rural-urban and developed – developing countries

Access to electricity in developed countries is high and is still increasing but 1.4 billion people in developing countries don't enjoy electricity supply. Without more energy supply, people can't get energy services for activities such as electronics and mobility. That said, in some developing countries (Martinot et al., 2002 in Johansson, 2004), various kinds of renewable energy have been introduced to meet the energy service demands as shown in 1.3.5 [TSU: i.e. in this section?].

Figure 1.11 shows the energy consumption per capita for various countries (IEA data). These can be classified into three categories based upon annual per capita energy use: (1) about 8 toe per capita: USA, Canada, (2) about 4 toe per capita: Japan, Korea, Germany and other European countries (3) less than 2 toe per capita: most developing countries. It would appear that developing countries (less than 2 toe per capita), will need more energy and will emit more carbon dioxide unless more efficient and lower emitting technologies provide the desired energy services.

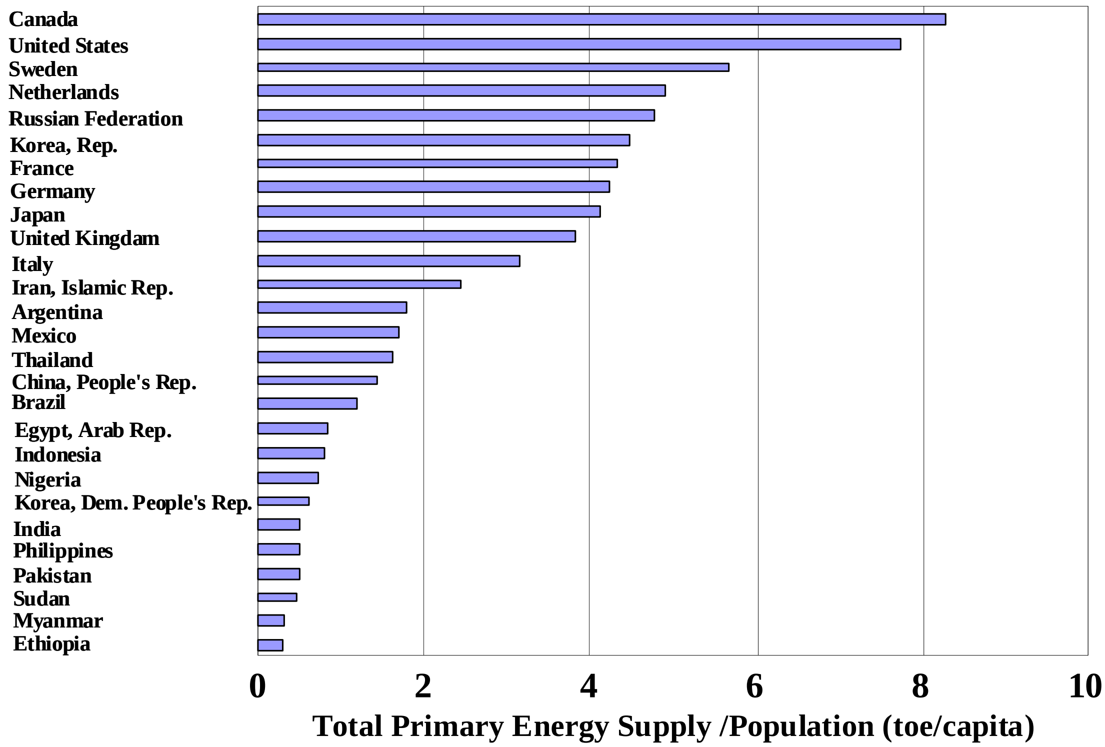


Figure 1.11. Total primary energy supply per population in various countries: 8 toe/capita for USA and Canada, 4 toe/capita for Japan, Korea, Germany, and other European countries, << 2 toe/capita most developing countries (IEA, 2009c).

Biomass is a major source of energy in developing countries. Actually, the percentage of biomass in total primary energy supply is very high in Africa (49%), Asia (25%) and Latin America (18%), whereas that in OECD countries is 3% in 2001 (IEA, 2003 in Karekezi, 2004). In part of Africa, it reaches 90% where it is used for cooking and heating. Table 1.4 shows 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 carbon black, which contributes to global warming. Finding improved energy sources in developing countries would improve health, enhance productivity and lower climate forcing.

Table 1.4. Energy consumption of households in urban and rural areas of China. Non-commercial energy includes combustible renewables such as methane, rice straw, and firewood (National Bureau of Statistics of China).

	Energy consumption GJ/y per capita	Electricity consumption kWh/y per capita
Urban	7.52	3.05
Rural	3.57	1.49
Rural (including non-commercial energy)	14.08	

In urban areas or mega-cities, population density is very high and many energy-consuming activities exist creating demand for high peak power and reliability. Renewable energy supplies for these regions must therefore be capable of responding to the very large demands.

While blackouts are common in many cities in developing countries, they also occur in developed countries as well. These urban centres have become totally reliant on electricity, and cannot function without it. Introduction of very large amount of variable renewable energy supply to the power grids requires energy networks referred to as "Smart grids" to maintain a consistent and reliable supply of electricity. Integration technology of various renewable and distributed energy sources will become more and more important because they can supply electricity at lower cost and with lower carbon dioxide emissions.

Heat pump systems have been penetrating into the market in advanced countries along with the usual renewable technologies such as PV and wind. Heat pump technology captures the thermal energy of air, soil, or river water. The Eco-Cute system of power electric companies of Japan is a hot water supply system based on heat pump technology. Its penetration has been accelerated by electric rate structure, which offers cheap off-peak nighttime electricity. Heat pump technology is being increasingly adopted in North America and in Europe, too. Such modern systems are still too expensive for most residents of developing countries at the moment.

1.3.5.2 Leading countries of renewable energy utilization

Although renewable energy is more evenly distributed than fossil fuels, there are countries or regions rich in specific renewable energy 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 seventy percent of energy is supplied by hydropower and geothermal energy in Iceland. 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 hydro-power electricity to the total electricity: 65% and 60 %, respectively. Brazil is famous for bio-ethanol production from sugarcane and Malaysia is known for its biodiesel from palm oil, however, the latter is produced at the expense of large carbon emissions associated with deforestation. Sun-belt areas such as desert and the Mediterranean littoral are abundant in solar energy. Many developing countries are located in these areas. Renewable energy is mostly utilized in a distributed manner, but its export from the countries rich in resources will become important as well in the future.

In China, strong needs for solar cooker 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 could become the leading global producer. 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 it has become a major international turbine manufacturer.

1.3.5.3 Unmet demands for energy services

Renewable energy, largely based on off grid energy systems can contribute to poverty alleviation and assist addressing MDGs. This can be achieved through provision of modern energy services to meet unmet demand for cooking, lighting and other small electric needs, process motive power, water pumping, heating and cooking in developing countries with relatively low access to electricity. Sub-Sahara Africa (SSA) in particular can benefit from provision of such energy services in view of its relatively low rural electrification rate of less than 10% compared to North Africa 86%, South Asia 32.0%, China and East Asia (82.0%), and Latin America (60%) (IEA, 2004). Provision of improved energy services for cooking for households, currently dependent on traditional biomass, is being realised through use of improved biomass stoves and biogas from households scale bio digesters and, to some extent, solar cookers.

Improved biomass stoves save 10% to 50% of biomass consumption for the same cooking services and can dramatically improve indoor air pollution, as well as reduce GHGs emissions (Clancy 2003). Improved biomass stoves have been produced commercially to the largest extent in China and India, where governments have promoted their use, and Kenya in Africa, where a large commercial market has been developed. Equally, tremendous progress has been made in India, China, and Nepal towards use of biogas from household scale bio-digesters for cooking (Ren21, 2007). Energy services for lighting, small electric needs (street lighting, telecoms, hand tools, and vaccine storage) and process motive power for small-scale industry is currently being met by an array off grid renewable energy technologies. These technologies include micro/pico hydro, biogas from households scale bio digesters, small gasification systems, village scale mini grids/hybrid system and solar PV. Small scale thermal biomass gasification is a growing commercial technology in developing countries notably China and India.

Electricity generation from solar PV, wind or biomass, often in hybrid combinations including batteries and/or supplementary diesel generators, is slowly providing an alternative to traditional energy supply based on diesel or biomass, mostly in Asia. In addition, solar PV and wind power for water pumping (both irrigation and drinking water) are gaining widespread acceptance (Ren 21, 2007)

1.3.6 Climbing the energy ladder

Renewable energy is available everywhere but its energy density is usually low but appropriate for use in the area where it is obtained. Renewable electricity seems more suitable for distributed applications where there is a grid or in remote or rural areas off the grid.

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) renewable energy 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. Solar PV will hopefully follow the wind energy. The potential of these modern renewable energy 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 bio fuel production. Solar water heating is an established technology that can be manufactured in the developing countries. It should be noted that Spain and USA have recently been developing concentrated solar thermal power plants. In regions with strong direct insulation such as deserts, they can produce electricity with higher conversion efficiency than typical solar PV systems. Most of the developing countries are located in hot regions and are therefore promising for the application of this technology.

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.

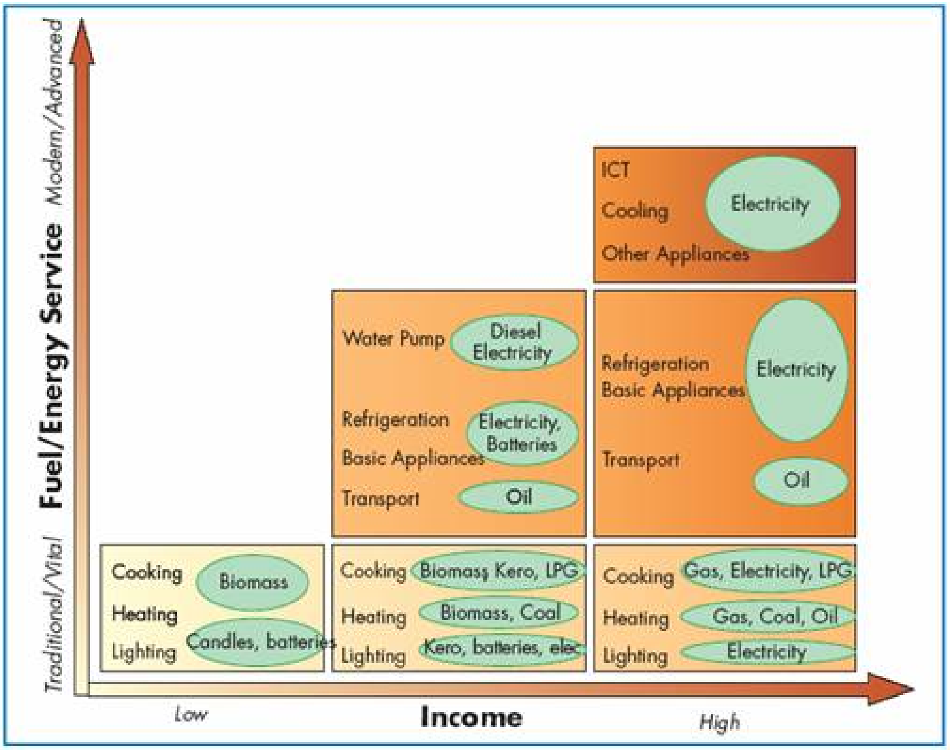


Figure 1.12. Energy Ladder: Household Fuel Transition Source: IEA Analysis, World Energy Outlook 2002.

As per capita incomes increase, the transition to commercial energy sources, which include natural gas, petroleum products and electricity, does not simply represent a substitution of more convenient and expensive fuels for cheaper traditional fuels. 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 and film [TSU: colloquial], which opens rural residents to new information that can instil the idea of change and the potential for self - improvement. Modern liquid fuels permit modern modes of transportation that cut the cost, both monetary and in time, of travel to nearby towns where, again, individuals are exposed to different ways of doing things and different views. Faster and cheaper transportation can increase the reliability of supply of modern fuels, reducing the need to maintain supplies of firewood as a back up and facilitating movements up the energy ladder. Of interest in the energy ladder transition is the need to use some aspects of renewable energy.

Table 1.5 summarizes the progress that has been made in introducing renewable energy 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 renewable energy.

Table 1.5. Progress on Energy ladder and of grid renewable energy 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.

1.3.7 Present status and future potential for developing countries to utilize renewable energy

1.3.7.1 Meeting demands of developing countries through renewable energy leapfrogging

The preceding section 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. India's advancement in harnessing biomass gasification technology to solve part of its energy is an example of renewable energy leapfrogging. Power levels from 5 kWe to 1 MWe have been field tested and standardized in Africa (Brew-Hammond, 2008).

Malaysia and Indonesia are becoming formidable world players in biodiesel industry. These countries have been able to turn their primary goods/raw materials into finished and semi-finished biofuel products mainly for export in the EU and USA and generating income and employment. The achievements of Brazil through the PROALCOHOL programme in becoming a world-acclaimed consumer and exporter of ethanol thereby generating income within the country.

However, technological development cannot alone contribute to improved energy access in developing countries. Innovative policies, including financing, are required. Provision of affordable financial services for rural areas has been shown to be a key component of achieving sustainable market for energy services. For example, the UNDP project "expanding access to modern energy services-replicating scaling up and mainstreaming at a local level" demonstrated how appropriate financing mechanism contributed to increased access in three case studies in (Kenya, Nepal, Dominican Republic) (UNDP 2006). This mechanism included establishing channels for enabling access to financial services for the suppliers, consumers, and/or institutions that support them.

Another success story for provision of sustainable energy finance is the UNEP's Rural Energy Enterprise Development (REED) initiative (Usher, 2003). The REED initiative focused on enterprise development and seed financing for clean energy entrepreneurs in Brazil, China and five countries in Africa. A total of US$ 7 million was committed to REED programmes in these countries. REED invests in small and mid size enterprises (SMEs) that deal in clean energy products and services, the sector generally considered too risky to attract conventional sources of financing.

1.3.7.2 Scenarios for renewable energy deployment in the future

There are numerous energy supply and demand scenarios that are referred to in Chapter 10. One of the striking aspects of these scenarios is the wide range of the renewable energy share of the supply. More recent scenarios tend to provide larger contributions from renewable energy and project lower costs than do earlier ones (IEA, McKinsey, Stern).

In 2008, investment in renewable electric supply exceeded that for coal and natural gas for the first time. Much of this investment was in the United States, China and Europe (UNEP, 2009; REN 21, 2009). This event, which is part of a recent trend, suggests the possibility that renewable energy can play an increasing role over the coming decades. New policies in the United States, China and the EU are supporting this effort, and one country, Germany has set a goal of 100% renewable energy by 2050.

There are however very early estimates by Lovins that suggested the possibility of very large penetration of renewable energy accompanied by significant reductions in end use demand. His 1975 estimate for total energy supply in the United States for 2000 of approximately 100 EJ was substantially lower than official government estimates of 150 EJ, but was within 5% of the actual energy use in 2000. However, a larger share of this amount came from efficiency gains than from renewables (Lovins, 1975). His "soft path" scenario has been based upon an examination of current innovations and his more recent analysis projects the potential for very large penetration of renewable energy in a distributed energy system (Lovins, 2008).

Methodologies differ in developing scenarios, and there are no generally agreed upon strategies for determining either costs or for assessing the rate of introduction, the role or rate of introduction of policies or the level of public acceptance. For example scenarios predicting large-scale adoption of nuclear power have consistently overestimated the levels actually achieved. Bottom up scenarios usually find lower costs for renewable and energy efficiency, while top down, macroeconomic models usually predict higher prices. It appears that it is not fruitful to simply project current trends with the current technology and fuel mix, and substitute renewable energy sources for fossil fuels. It seems that a useful approach is to identify alternative futures and then to determine what prices, policies and other factors would be needed to achieve those goals.

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 renewables. The major investments in recent years suggest that this trend may continue.

1.4 Barriers and issues

Almost everywhere in the world, one can find a renewable energy resource of one kind or other – e.g., solar radiation, blowing 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 (as described in chapters 2 to 7 of this report). Why then is renewable energy (RE) not in universal use?

Firstly, there are barriers. A barrier was 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' (Metz et al., 2007: glossary). 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 (R&D).

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.

In this section, we briefly consider in a general way 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. Some barriers are particularly pertinent to a specific technology; they are 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. 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.

Some of these barriers are directly to do with energy prices, and what 'externalities' they do or do not yet take into account. They are examples of the 'market failures' that dominate today's energy markets. Others (e.g., the institutional or informational barriers) would remain barriers to RE even in the economist's dream world of 'perfect markets'. [TSU: language]

1.4.1 Informational barriers

1.4.1.1 Deficient data about natural resources

Renewable Energy is widely distributed (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 would be 30% higher on top of a local hill than in the valley a few hundred metres away. 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.

1.4.1.2 Skilled human resources (capacity)

To develop renewable energy 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. In particular, the dispersed nature of RE implies that each user community requires someone to have basic technical training to deal with routine maintenance. This is particularly important, for example, for village-level solar energy in developing countries. Developing the "software" to operate and maintain the renewable energy "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 upon which he or she is depending.

1.4.1.3 Public and institutional awareness

The oil price peaks of 1973, 1989 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 the more 'obvious' forms such as 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 Social Reserch Centre, 2008) indicate strong public support for greater use of RE (and for action 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.

It is also the case that, to be fully successful, a program to implement renewable energy technologies requires that there be awareness and support from not only the public, but the government, utilities and industries. In only a few countries has there been a major effort to educate all parts of society about the nature of renewable energy relative to traditional fossil fuels.

1.4.2 Socio-cultural issues

1.4.2.1 Social acceptance

A certain cachet has begun to attach to having solar energy systems on one's roof, as a mark of the owner's environmental responsibility. On the other hand, many wind farms have had to battle the 'not in my backyard' (NIMBY) attitude before they could be established. Rich owners of holiday homes in remote areas in particular have objected to their view being 'spoilt'. (The same people would probably object even more vehemently to having a nuclear power station or large coal plant built nearby!) [TSU: language]. See chapters 7 and 11 of this report for more discussion of how such local planning issues impact the uptake of RE.

1.4.2.2 Land use

Farmers on whose land such 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. 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 will insist on being paid for the use of their land for (e.g.) a mini-hydro system of which they are the sole beneficiaries. Unintended consequences, such as displacement of rain forests to grow crops for biofuels must also be avoided.

1.4.3 Technical and structural barriers

1.4.3.1 Resource issues

RE draws on natural environmental flows of energy, most of which by their nature are variable and almost always of lower energy intensity [W per m^3] than the petrol consumption of a motor car or the core of a nuclear reactor (Twidell &Weir 2006). Both these characteristics of the flows imply that different engineering techniques are needed to harness them cost-effectively from those used with fossil or nuclear energy. In particular, to manage energy supply systems for variable supply as well as variable demand requires a systems approach, which may involve 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 dotting electric heaters around the building (See Chapter 3 of this report).

1.4.3.2 Existing infrastructure and energy market regulation

The dispersed, relatively low energy-density, nature of most forms of RE implies that the most effective way to use them may be though dispersed 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. Even when a planned RE application is of a centralized nature, such as the proposed solar concentrating power system in North Africa intended to supply southern Europe, the energy source is usually nowhere near existing supply systems, so that (expensive) new 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. Most of them therefore assume that systems are of high power density and/or high voltage, and are therefore 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). However, such regulations were 'liberalised' in several countries in the 1990s, to allow 'independent power producers' to operate, although often such producers are still required to be of a big enough scale to exclude many proposed RE projects (See chapters 8 and 11 of this report).

1.4.3.3 Intellectual property issues

Technological development of RE has been rapid in recent years, particularly in photovoltaics and wind power. Many of these new developments are protected by patents. 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. In particular, developing countries fear that the technology transfer referred to in the UN Framework Convention on Climate Change will come not as untied aid but on commercial terms, heavily restricted by intellectual property rights that are too costly for them to acquire.

1.4.4 Economic barriers

Chapter 10 of this report includes a detailed discussion of the current and projected costs of RE systems. Here we merely highlight a few pertinent general features of the economics of RE.

1.4.4.1 Cost issues

Twidell &Weir (2006) point to some key questions that affect an assessment of the economic costs and benefits of an energy system:

(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 (sec. 1.4.2.1). 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 vagaries of fossil energy prices - compare the oil price which has varied over the past decade from $11 to 145 USD (2005) per barrel. Such variation makes it very difficult to assess, at the outset of a project, what will be its levelized cost of energy production and hence (for a private investor) its profitability. 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.

1.4.4.2 Availability of capital and financial risk

As just noted, the initial capital cost comprises most of the economic cost of an RE system. The financial viability of an RE system therefore strongly depends on the availability of capital and its cost (interest rates). While the predictability of such costs is an advantage of RE systems, sometimes bankers are reluctant to lend for even sound business propositions (e.g., in the financial crisis of 2008-09).

In the case of developing biofuels for aviation, neither the potential bio jet refiners nor the airlines fully understand 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. The problem was that the ethanol and bio diesel markets had collapsed resulting in project sponsors and their lenders loosing most of their investments. Alternative energy lenders were focused on solar and wind projects that served the electric generating markets, where there are guaranteed revenue streams that ensured the project-generated profits for the participants. Using the electric market as a model, if the airlines want to have sources of alternative fuel, they would have to provide a guaranteed market for the aviation products, which were Green Jet and Green Diesel, or 80% of a hypothetical refineries output. (That left only 20% being subject to market sources.) In addition, the airlines would have to enter into a cost plus arrangement with the refinery because no lender would take the pricing risk for the Green Jet and Green Diesel.

During discussions with banks and with the DOE and USDA, it was found that there were no private lending sources that would lend even with these government guarantees, and that there was only one government entity that might take debt risk on a non-experimental alternative fuel for aviation project. That was the US Department of Agriculture. The Department of Energy provides grant money and the DOD will pay the full cost for “Experimental” projects, but no agency will guarantee alternative energy loans for aviation. (There was no certified fuel until September 2009 and no bank or government will guarantee a loan to produce something that might never get certified – newly certified fuels ease this somewhat.)

If any financings get done, it will be due to the willingness of the airline industry to take bio fuel risks. However, no one will know for certain what is possible until some deals are done. The airlines apparent willingness to assume real risk by signing long term off take agreements that are not tied to spot market prices is a major step forward. This willingness is as important as government guarantees, perhaps more important.

1.4.4.3 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, not least because of their military connections. Only in times of ‘energy crisis’ has there been appreciable spending on RE technologies. (IEA statistics) Tax write-offs for private spending have been similarly biased towards non-renewable energy sources (e.g. in favour of oil exploration or new coal-burning systems) (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 Institutional barriers

1.4.5.1 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 (see Section 1.5.5) [TSU: section 1.4.3.2]. 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 most forms of RE.

In this situation, policy change to the laws and regulations governing energy supply is needed to allow decentralized RE concerns to operate at all, let alone to compete on a fair basis.

Energy businesses are among the largest in any country, industrialised or developing. They have billions of dollars tied up in the existing infrastructure. Many executives of these large concerns belittle the potential contribution of RE to the national energy mix and have the economic clout to lobby – often successfully – against any moves that might threaten their entrenched position, e.g., by adding effective competition from RE. Hamilton (2007) graphically describes such efforts in Australia.

1.4.5.2 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 already access to spare parts requires new infrastructure to be set up.

Because the cost of such systems is largely up-front (see Section 1.5.5) [TSU: section 1.4.4.1], 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 riddled 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 (Wade et al, 2005).

1.4.6 Opportunities and Issues

Some form of renewable energy is available in most parts of the world, and has the advantage of being delivered to the site of use for free. However, the cost of the technology to convert the "free: fuel often places these sources out of economic reach when compared to fossil fuels. In part this is because the environmental and health benefits of RE is seldom calculated into the price, and the health and environmental damages from fossil fuels are seldom assessed. There are also many non-economic barriers (See Section 1.5 and Chapter 11). [TSU: section 1.4]

Research and Development is underfunded globally (UNEP, 2008). Despite this shortfall, there have been significant breakthroughs in solar PV and battery storage technology in recent years by the private sector. As the scale and experience with wind technologies have increased, the cost and reliability of these technologies have improved significantly. Because many renewable technologies are unfamiliar to utility and government decision makers, there needs to be technology transfer from countries that have adopted them to those (especially developing ones) that have not. With the introduction of the new technologies must come the training and capacity building that is essential to operate, maintain and utilize these sources of energy.

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

In situations where one wishes to introduce public change, policy sets the framework, the conditions and often the impetus under which such change can occur. If the advancement of renewable energy in the context of climate change is seen as desirable or necessary, then action on behalf of policy and decision makers will be required. Such policies cover every aspect of the progress of renewable energy 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 development, 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 concessions 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 European feed-in-tariffs has propelled them into the lead in manufacturing at a profit, renewable energy technologies.

1.5.1 Policies for development of technologies

One always faces the question of who should cover the costs associated with the research and development (R&D) of new technologies; 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 renewable energy 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, 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 (Fisher, et al., 2007, Section 3.4.2).

Market barriers exist that prevent the development and penetration of novel renewable energy 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 renewable energy to have qualities and values related to their cleanliness and renewability, the current market attributes no value as such to these characteristics.

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 or to ameliorate the risks faced by R&D products in the market.

1.5.2 Policies to move technologies to commercialization

The importance of technology development and deployment should not be underestimated. Bossetti, 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). Edmonds et al. (2004) consider advanced technology development to be far more important as a driver of emission reductions than carbon taxes. 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. 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.

The failure of many worthy technologies to move from the research and development to commercialization is often the most difficult stage, and has been referred to as the "valley of death" for new products. Attempts to move to renewable technology into mainstream markets following the oil price shocks failed at the time 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 Deployment of policies (supply push vs. demand pull)

The task of policy and decision makers with respect to the market can have a variety of approaches: 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 Research and Development, 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 research and development attempt to create new products through market push. 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. 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. The United States has relied mostly on government R&D subsidies for renewable energy 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.

The use of Renewable Portfolio Standards (RPS) has been moderately successful in some states in the United States. 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 likely soon to become the largest producer of PV technology. Having dropped its domestic incentives for PV technology, Japan has fallen 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. So many governments resort to levelling the playing field by granting similar subsidies to renewable energy technologies.

1.5.4 Integrate policies into sectors

Since all forms of renewable energy capture and production involve spatial considerations, policies need to consider land use, employment, transportation, agricultural and other sector specific issues.

The major focus for renewable energy is the electric power sector where we see a 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.

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. 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 developing 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.

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 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 (e.g., reduction in Criteria Air Contaminants, GHG emissions reduction). Current 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 recent 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 et al, 2004; Tobias et al, 2007)

It is also critical to consider the potential of RE to reduce emissions from a life cycle perspective. The fundamental reason that biofuels present the opportunity for lower GHG emissions is that biomass feedstocks absorb CO_2 for growth during photosynthesis in relatively short time scales (in a sense petroleum is a "renewable source – but its CO_2 "absorption" occurred over very long time scales. In general, the growth of biomass feedstocks could offset some, if not all, of the combustion CO_2 emissions, resulting in reduced life cycle GHG emissions. However, direct and indirect land-use changes are important aspects that must be evaluated when considering biofuels. Such changes can include deforestation, conversion of grasslands to agricultural production, or diversion of agricultural production to fuel production. These may result in considerable GHG emissions, and can potentially overwhelm the gains from CO_2 absorption. An illustrative life cycle analyses, featuring expanded boundaries, for aviation is shown in Figure 1.13. The use of different approaches to life cycle analyses can lead to substantially different results. Ultimately, the best one might achieve is to quantify uncertainties and provide policy makers with a range of possible outcomes. Clearly, there are many complexities and global guidance will be needed to ensure a robust accounting of the benefits and negative externalities of RE.

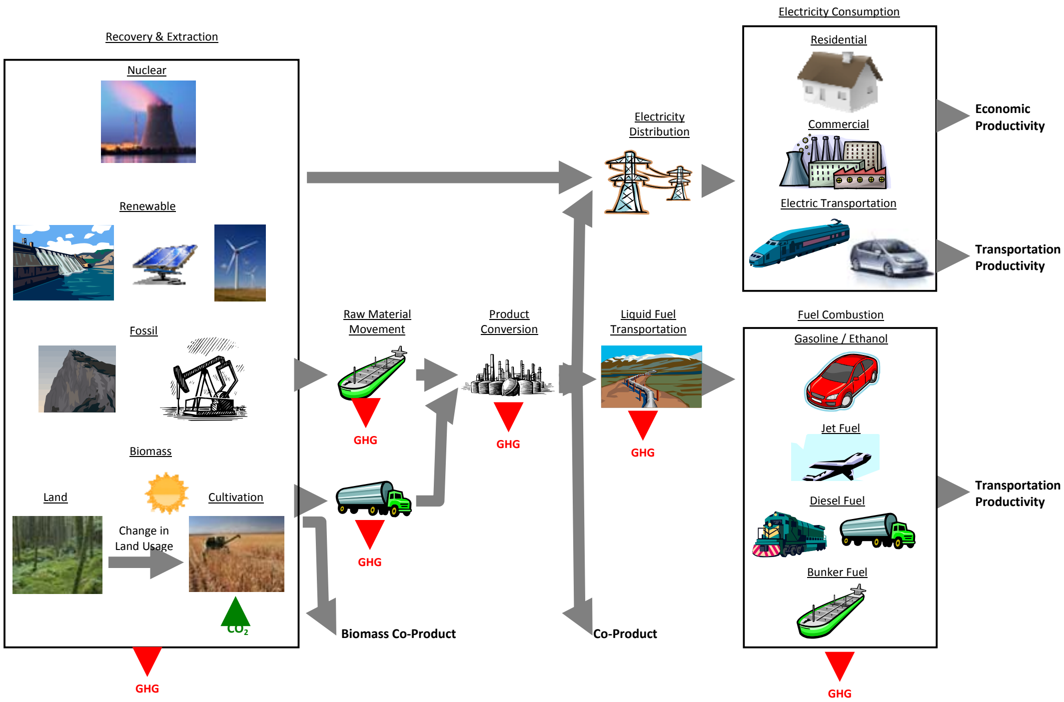


Figure 1.13. Illustrative system for energy production and use illustrating the role of RE along with other production options. A systemic approach is needed to conduct life cycle analysis. [TSU: Source?]

1.5.6 Options are available if policies are aligned with goals

An examination of alternative policies to encourage adoption of renewable energy 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 renewable energy, it has been more effective than renewable portfolio standards (Carpenter, 2009). For example, Germany has moved from having essentially no renewable energy in 1989 to being a leading user and producer of wind and solar power (Sawin and Moomaw, 2009), and the government recently announced a goal to become 100% renewably powered by 2050 (Bundesministerium, 2009). According to David Wortmann, Director of Renewable Energy 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 renewable energy supply into grid system

All renewable energy forms must function within the current system (although many may in fact be stand alone when communities or demand is isolated from the energy system). Institutional or operational barriers may prevent the advent of renewable energy into the system. Utilities in many parts of the world are also focused on all aspects of the energy system and may form monopolies where a broader market representation may in fact be available and be allowed to exist. 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. Europe and the United States have had to deal with interconnection standards, net metering, issues of variability of power output, discriminatory practices against distributed energy sources of all kinds, and a failure to recognize the benefits to clean air and other environmental quality measures. Where these issues have been addressed the penetration of renewable energy has been greatest.

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Chapter 2

Bioenergy

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COMMENTS ON TEXT BY TSU TO REVIEWER

Yellow highlighted – original chapter text to which comments are referenced

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Chapter 02 has been allocated a total of 102 pages in the SRREN. The actual chapter length (excluding references & cover page) is 107 pages: a total of 5 pages over target.

Expert reviewers are kindly asked to indicate where the Chapter could be shortened in terms of text and/or figures and tables.

In addition, all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005. For conversion tables see http://www.ipcc-wg3.de/internal/srren/fod

Chapter 2: Bioenergy

CONTENTS

EXECUTIVE SUMMARY

Bioenergy today

Chapter 2 discusses biomass, a primary source of fiber, food, fodder and energy. Since the dawn of society 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 non-commercial and relates to charcoal, wood and manure used for cooking 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 9 EJ, and this share is growing.

Currently, modern bioenergy chains involve a wide range of feedstocks, 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 widely 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 bioenergy systems today, most notably sugar cane based ethanol production and heat and power generation from residual and waste biomass that can be deployed competitively. Depending on energy prices and specific market conditions, also smaller scale applications (for power heat and biofuels) can compete, such as jathropha oil production in rural settings.

Future potential

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.

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. The supply potential may then be 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 sugar cane based ethanol production). Biomass supplies may then remain limited to an estimated 100 EJ in 2050.

Impacts

Bioenergy production interacts in complex ways with society and the environment, including feedbacks among climate change, biomass production and land use. The impacts 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 how actual projects are designed and implemented. Many conflicts can also be avoided and synergies with better management of natural resources (e.g. soil carbon enhancement and restoration, water retention functions) and contributing to rural development are possible. Optimal use and performance of biomass production and use is regionally 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.

Future options and cost trends

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 carbon taxes of some 20-30 U$/tonne would be deployed (or when CCS would be deployed), biomass can also be competitive with coal based power generation.

There is clear evidence that technological learning and related cost reductions do occur with comparable progress ratio's as for 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.

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) as well as bio-CCS may become very attractive mitigation options on medium term. Algae may have a potential to produce liquid or gaseous fuels with minimal land-use, but their deployment is uncertain and may not be significant before 2030

GHG & Climate change impacts

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.

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.

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.

2.1 Introduction Current Pattern of Bioenergy Use and Trends

Biomass continues to be the world's major source of food, fodder and fibre as well as a renewable resource of hydrocarbons for use as a source of heat, electricity, liquid fuels and chemicals. Biomass 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 chemical and physical process, produce energy carriers in the form of solid fuels (chips, pellets, briquettes, logs), liquid fuels (methanol, ethanol, butanol, biodiesel), and gaseous fuels (synthesis gas, biogas, hydrogen). These fuels can then be used to produce mechanical power, electricity and heat as shown in Figure 2.1.1.

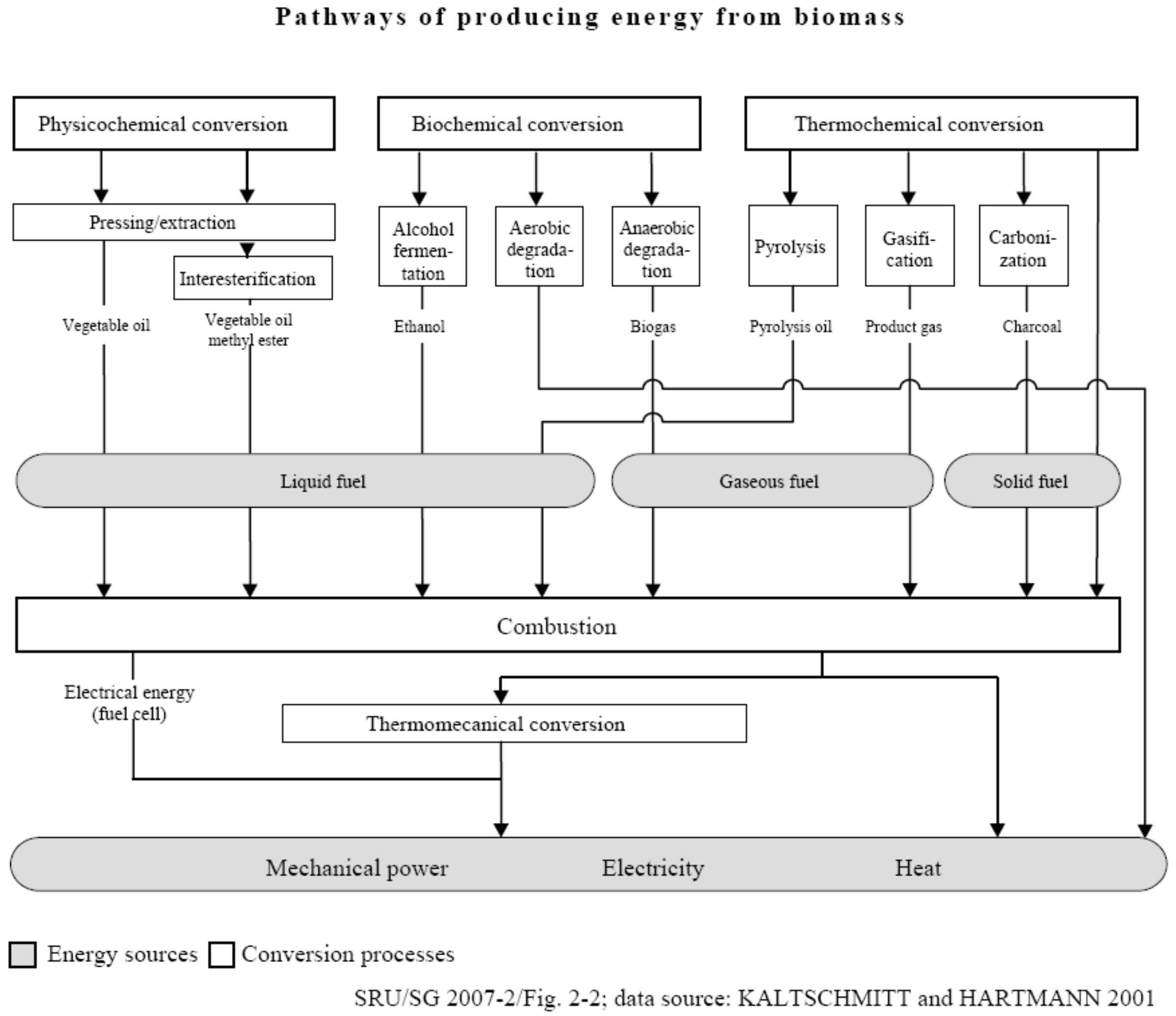


Figure 2.1.1: Pathways of producing energy from biomass TSU: improve readability of graph

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 CHP TSU: definition missing 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 or negatively impact local populations in terms of land tenure or reduced food security. In all these cases a life-cycle analysis must be conducted to assure that the net effect of bioenergy options is positive.

According to available IEA energy statistics, bioenergy provides about 10 percent of the world's current total primary energy supply (47.2 EJ of bioenergy out of a total of 479 EJ in 2005, i.e. 9.85 percent) (IEA-ETE, 2007a). Most of this is for use in the residential sector (for heating and cooking) and is produced locally. In 2005 bioenergy represented 78 percent of all global renewable energy produced. 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. 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 over 130 Mt of MSW TSU: definition missing 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).

Biomass can be used as a source of many forms of useful energy as is shown in Figure 2.1.1 but up to now 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 percent). 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 50% of TPES in the poorest 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), while bioenergy's contribution in Canada, France and Germany is around 450 PJ/yr.

Global bioenergy use has been steadily growing worldwide in absolute terms in the last 40 years, with large differences among countries (see Fig 2.1.2 for the case of woodfuels). The bioenergy share in India, China and Mexico is decreasing, mostly as traditional biomass is substituted by kerosene and 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.

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 in Germany, Italy and the United Kingdom.

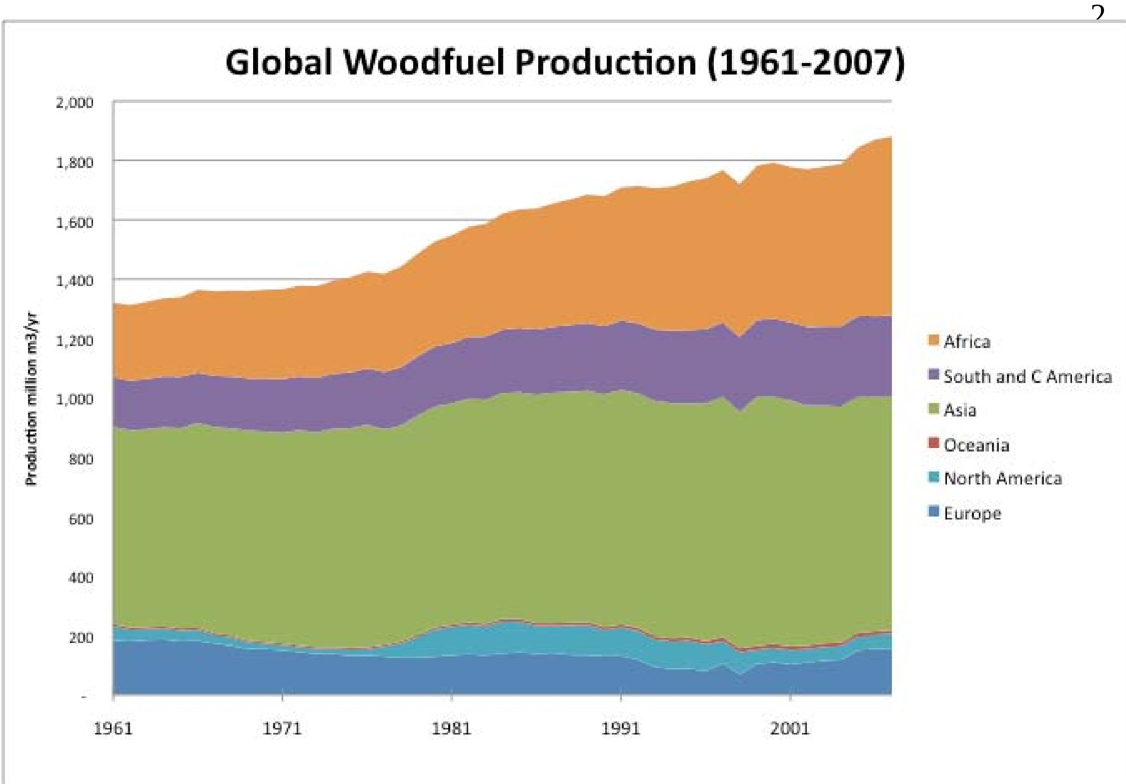


Figure 2.1.2. Global Fuelwood and Charcoal Production. Woody biomass is the main component of the solid biomass reported by IEA. According to the national statistics reported by FAO, in 2007 the total amount of wood used as fuelwood and for charcoal production reached 1,881 million m^3, 42% came from Asia, 32% from Africa, 15% from Latin America. The evolution of global fuelwood production in the period 1961-2007 is shown. World production increased from 1.3 billion m3/yr in1961 to 1.9 billion in 2007, which means an annual growth rate of 0.7%. It is interesting to note that outside of the periods with high oil prices (1977-82 and after 2004) the annual growth rates are smaller 0.3% in the period 1961-77 and 0.5% in the period 1984-2003. The bulk of fuelwood and charcoal demand is concentrated in developing countries, particularly within Africa and Asia. Their production has remained essentially constant in LA and Asia – with important differences among countries – while it has been growing significantly in Africa. Source: FAOSTAT, 2009.

While FAO statistics (Figure 2.1.2) 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 (FAO, 2005b (Mexico); FAO, 2006a (Slovenia), FAO. 2007 (Italy), FAO, 2009a in press (Argentina), FAO, 2008a (Mozambique)).

2.1.1 Previous IPCC Assessments

Bioenergy has not been examined in detail in previous IPCC reports. In the most recent assessment (AR4) 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 AR4 report (IPCC, 2007) are as follows: i) the global sustainable potential for bioenergy was estimated at 250 EJ/yr (with a wide range on both sides); ii) The mitigation potential for electricity generation reaches 1,220 $MtCO_2$-eq for the year 2030, a substantial fraction of it at cost lower than 20 US$/t$CO_2$ TSU: use SI units, i.e."t" not "tonne"!; iii) Within agriculture the report estimated an overall biomass supply for energy ranging from 22 EJ/yr in 2025 to more than 400 EJ/yr in 2050. From a top-down assessment estimate the economic mitigation potential of biomass energy supplied from agriculture to be 70–1260 MtCO_2-eq/yr at up to 20 US$/t CO_2-eq, and 560–2320 MtCO_2-eq/yr at up to 50 US$/t$CO_2$-eq. These potentials represent mitigation of 5–80% resp.20–90% of all other agricultural mitigation measures combined, at carbon prices of up to 20, and up to 50 US$/t$CO_2$-eq, respectively; iv) The energy potential for bioenergy coming from forest residues reaches 14-65 EJ/yr and the overall mitigation from the sector may reach 400 MtCO_2/yr up to 2030.

2.1.2 Structure of the chapter

Estimating the future mitigation potential of bioenergy presents unique analytical challenges in comparison to other renewable energy sources, given the multitude of existing and rapidly evolving bioenergy sources, complexities of physical, chemical, and biological conversion processes, variability in site specific environmental and socio-economic conditions and the many interlinkages between bioenergy and other land-based activities, such as food and fibre production, forest protection, and others, as well as particular political interests triggered by the rapid evolution in production and use of liquid biofuels.

In this chapter we seek to overcome these methodological and practical challenges by undertaking an integrated and comprehensive global review of the mitigation potential of bioenergy up to the year 2030. To reach this goal, we first examine the biomass resource potential, pointing out at the range of estimates from different sources as well as the opportunities and limitations from the potential competition for land, water and other resources. We then examine the main technology chains related to bioenergy production, from the feedstocks to the main end uses. Section 2.4 provides the global and regional status of market and industry development in bioenergy, while section 2.5 analyzes the environmental and socio-economic impacts of the current bioenergy systems. We pay particular attention to the recent developments in life-cycle analyses. Section 2.6 examines the emerging bioenergy technologies and integration systems. In section 2.7 we examine the cost trends for the major bioenergy systems and in section 2.8 we discuss the potential future deployment of bioenergy.

2.2 Resource Potential

2.2.1 Introduction

Different types of biomass can be used for energy:

- Primary residues from conventional food and fiber 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-flows and retail/ post consumer waste;
- various plants produced for energy purposes including conventional food/feed/industrial crops, new types of agricultural plants and forest plants grown under varying rotation length.

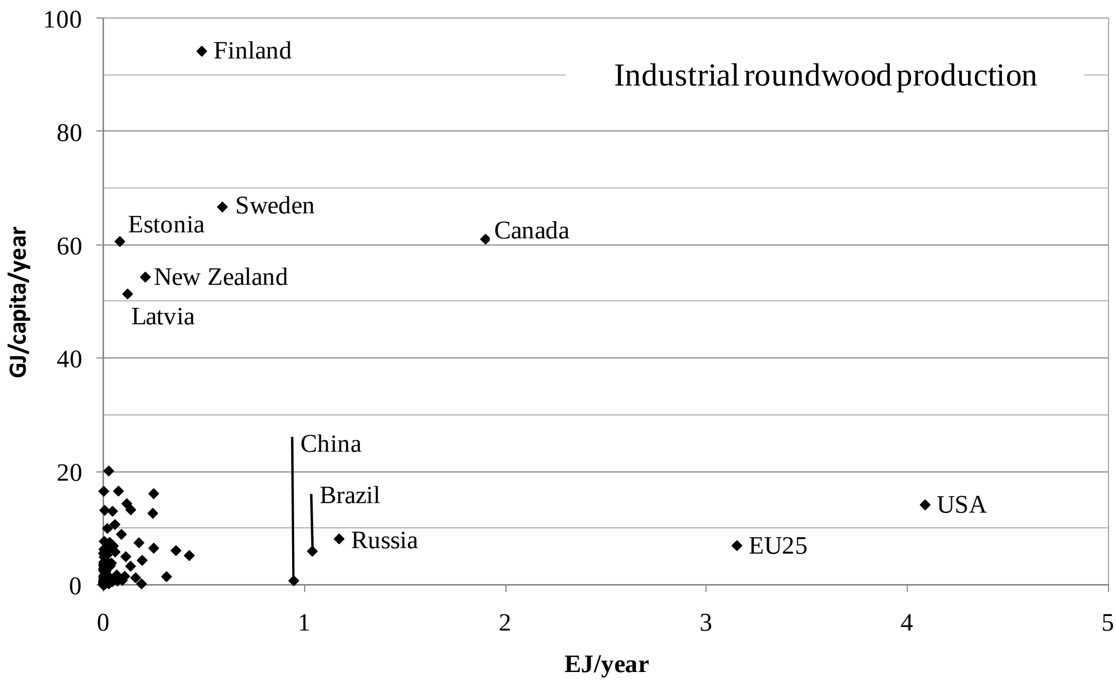
The quantification of current production of major crops and of industrial roundwood shown in Figure 2.2.1 offers a first perspective on the present human biomass production in relation to the size of the national and global energy systems. The present global industrial roundwood production amounts to 15-20 EJ (2-3 GJ/capita) of biomass per year and the global production of the major crops included in Figure 2.2.1 corresponds to about 60 EJ (10 GJ/capita) per year in total. For comparison, about 390 EJ (60 GJ/capita) of fossil fuels were commercially traded globally in 2005 (BP 2007).

The total biomass flows in agriculture and forestry – including also the flows considered to be potential bioenergy feedstocks – are substantially larger. Krausmann et al. (2008) estimate that residues make up 50-60% of the aboveground biomass on the world's cropland and that close to 40% of these residues are presently left on the fields after harvest. Wirsenius et al. (2004) estimate that the total global production of by-products and residues from the food and agriculture system (crop residues, manure, food industry residues, organic waste, etc.) amounted to about 140 EJ/yr in 1992/94. In forestry, felling losses are estimated to correspond to roughly one-third of the global wood removals, with substantially larger relative losses in tropical developing countries (Krausmann et al. 2008). In addition to this, large volumes of wood are cut during silvicultural thinning, which is an integrated part of forest management.

From this it can be concluded that:

- the present total global industrial forest biomass flow is much smaller than the present fossil fuel use. But a number of countries with large forest industries have significant per capita forest biomass flows and consequently have good prospects for making forest biomass an important part in the domestic energy supply (or export forest fuels to other countries);
- globally, agricultural biomass flows are larger than the forest sector flows and there are more countries than in the case of forestry that have a significant per capita production (e.g. above 20 GJ/capita/year). The agricultural biomass flows are rather limited compared to the energy system, but still in many countries residues could become a significant part of the energy supply.

This section focuses on the longer term biomass resource potential and how this has been estimated based on considering the Earth's biophysical resources 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. More near term potentials are treated in Section 2.3 that discusses implementation potentials for bioenergy. The different bioenergy production systems are described in more detail in Section 2.3 and 2.6.



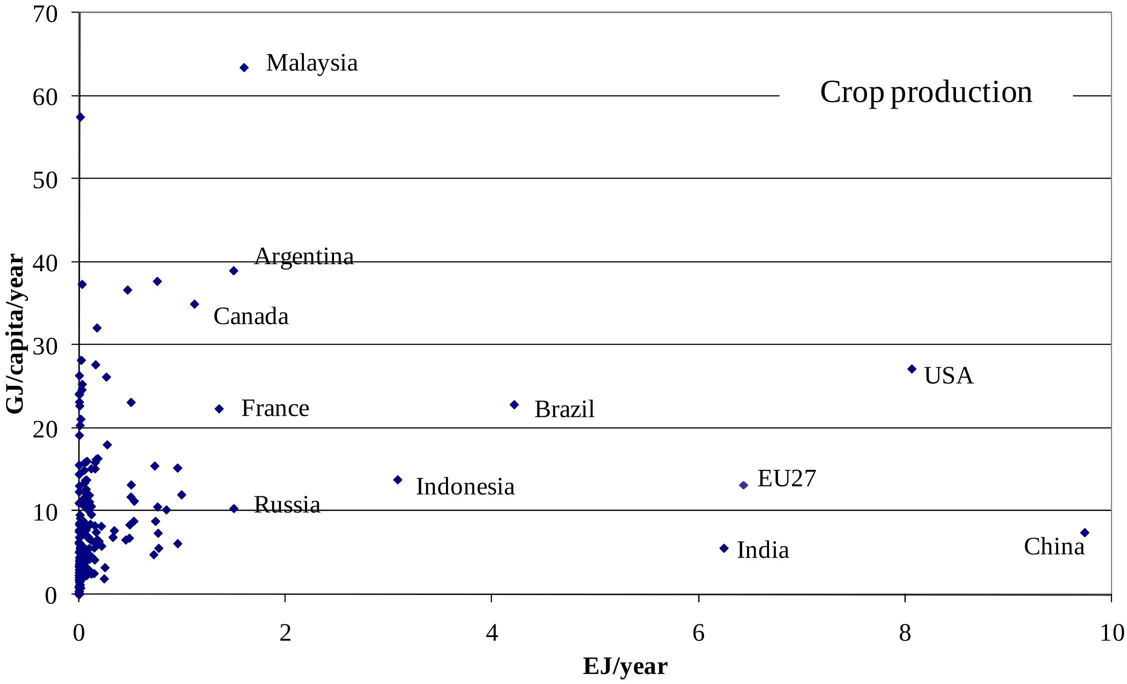


Figure 2.2.1. Production of major crop types (cereals, oil crops, sugar crops, roots & tubers and pulses) and industrial roundwood in the countries of the world: average for 2002-2006 (crops) and 2000-2003 (roundwood), converted to energy units. The figure shows the dominant crop and industrial wood producers in the world and the production per capita in different countries. Based on data provided by the UN Food and Agriculture Organization, FAO (FAOSTAT, 2008). Note that the two diagrams have different scales.

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 2.2.2). Socio-economic conditions also influence the bioenergy potential by defining how – and how much – biomass can be produced without causing unacceptable socio-economic impacts. Socio-economic restrictions vary around the world, change as society develops, and – once again – depends on how societies prioritize bioenergy in relation to specific more or less compatible socio-economic objectives (see also Section 2.5 and Section 2.8).

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 extensive TSU: did you mean "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.

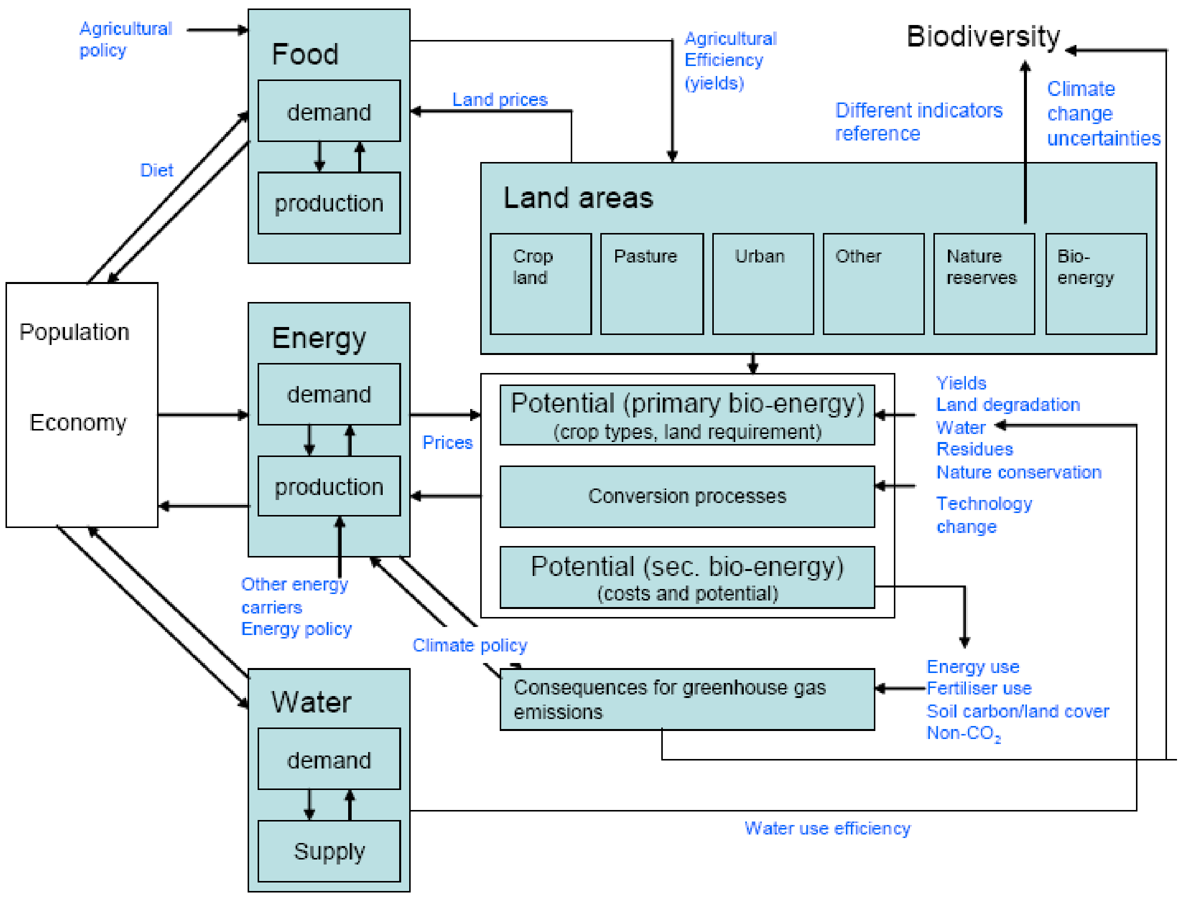


Figure 2.2.2. Overview of key relationships relevant to assessment of bioenergy potentials (Dornburg et al., 2008). Indirect land use issues and social issues are not displayed.

Studies quantifying the biomass resource potential have in various ways assessed the resource base while considering the influence of natural conditions (and how these can change in the future), socio-economic factors, the character and development of agriculture and forestry, and restrictions connected to nature conservation and soil/water/biodiversity preservation. A review of 17 available studies of future biomass availability carried out in 2002 revealed that no complete integrated assessment and scenario studies were available by then TSU suggests: “at that time” (Berndes et al., 2003). Since then, a number of studies have assessed the longer term (2050-2100) biomass supply potential for different regions and globally.

Most assessments of the biomass resource potential are based on a “food first” principle intending to ensure that the biomass resource potentials are quantified under the condition that global food requirements can be met (see e.g. WBGU, 2009). Assessments of the forest resource potential commonly employ a similar “fiber first” principle to ensure availability of resources for the production of conventional forest products such as sawnwood and paper.

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 fiber production. They quantify how much bioenergy that could be produced at a certain future year based on using resources not required for meeting food/fiber 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 fiber production.

Studies using integrated energy/industry/land use cover models (Johansson and Azar, 2007; Leemans et al., 1996; Strengers et al., 2004; Müller et al., 2007; Van Vuuren et al., 2007; Melillo et al., 2009; Wise et al., 2009; Melillo et al., 2009; Lotze-Campen 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 is another source of 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.

2.2.2 Assessments of the biomass resource potential

Theoretical/physical/technical biomass resource potentials correspond to biomass production potentials that are limited only by the technology used and the natural conditions. 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/fiber 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 socio-economic factors as a rule limits the assessed potential to lower levels.

Table 2.2.1 shows ranges in the assessed biomass 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 biomass supply potential, and on selected additional studies not included in these reviews (Field et al., 2008; Smeets and Faaij, 2007; Fischer and Schrattenholzer , 2001; Van Vuuren et al., 2009; Wirsenius et al., 2009). Diverging conclusions regarding the future biomass availability for energy can be explained by studies differing in scope, e.g., some studies are limited to assessing only selected biomass categories. But a major reason is that 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; biodiversity and nature conservation requirements set restrictions 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 decisions on tradeoffs that have to be made, e.g. with respect to the amount of acceptable additional biodiversity loss or acceptable intensification pressure in food production.

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.

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). For comparison, current global primary energy consumption is about 500 EJ per year and the present biomass use for energy is about 50 EJ per year.

Biomass category	Comment	Global biomass resource potential year 2050 (EJ/yr)
Energy crop production on surplus agricultural land	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 use due 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
Energy crop 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. 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
Residues from agriculture	By-flows 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
Forest residues	By-flows 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). Unexploited forest growth represents an additional resource. Forest growth on lands estimated as available for wood extraction that is not required for production of conventional forest products such as sawnwood and paper. Zero potential TSU: according to number in right column, zero potential is no possible indicates that studies report that demand from other sectors than the energy sector can become larger than the estimated forest supply capacity	30 – 150
Unexploited forest growth	Forest growth on lands estimated as available for wood extraction that is not required for production of conventional forest products such as sawnwood and paper. 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 – 100
Dung	Animal manure	5 – 50
Organic wastes	Biomass associated with materials use, e.g. waste wood (producers), municipal solid waste	5 – >50
Total		<50 – >1000

2.2.2.1 The contribution from residues, processing by-flows and waste

Retail/post consumer waste and primary residues/processing by-flows 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 size of these biomass resources are ultimately determined by the demand for conventional agriculture and forestry products, and as was indicated by Figure 2.2.1 the present biomass flows in agriculture and forestry are rather limited compared to the global energy system (although these flows are clearly significant in some countries).

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). 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 fiber board production in the forest sector.

In addition to the forest biomass flows that are linked to industrial roundwood production and processing into conventional forest products, unexploited forest growth is considered in some studies. This biomass resource is quantified based on estimates of biomass increment in forests 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 restrictions.

2.2.2.2 The contribution from energy plantations

From Table 2.2.1 it is clear that substantial supplies from energy plantations are required for reaching very high future bioenergy supply. Land availability (and suitability) for the production of dedicated energy crops, and the biomass yields that can be obtained on the available lands, are consequently two critical determinants of the biomass resource potential. Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimating the contribution from energy 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 (Fischer et al., 2008).

Figure 2.2.3 – representing one example (Fischer et al. 2009) – shows the modeled global land suitability for first generation biofuel feedstocks (sugarcane, maize, cassava, rapeseed, soybean, palm oil, jatropha). In this case a suitability index has been used in order to represent both yield potentials and suitability extent (see Caption to Figure 2.2.3). 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 that 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 – agriculture 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 is assessed suitable for soybean. About 580 and 470 Mha are assessed suitable for maize and jatropha while less than 50 Mha is 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 with high carbon content into oil palm plantations would negatively impact biodiversity and also lead to large CO_2 emissions that can dramatically reduce the climate benefit of substituting fossil diesel with biodiesel from the palm oil produced (see Section 2.5).

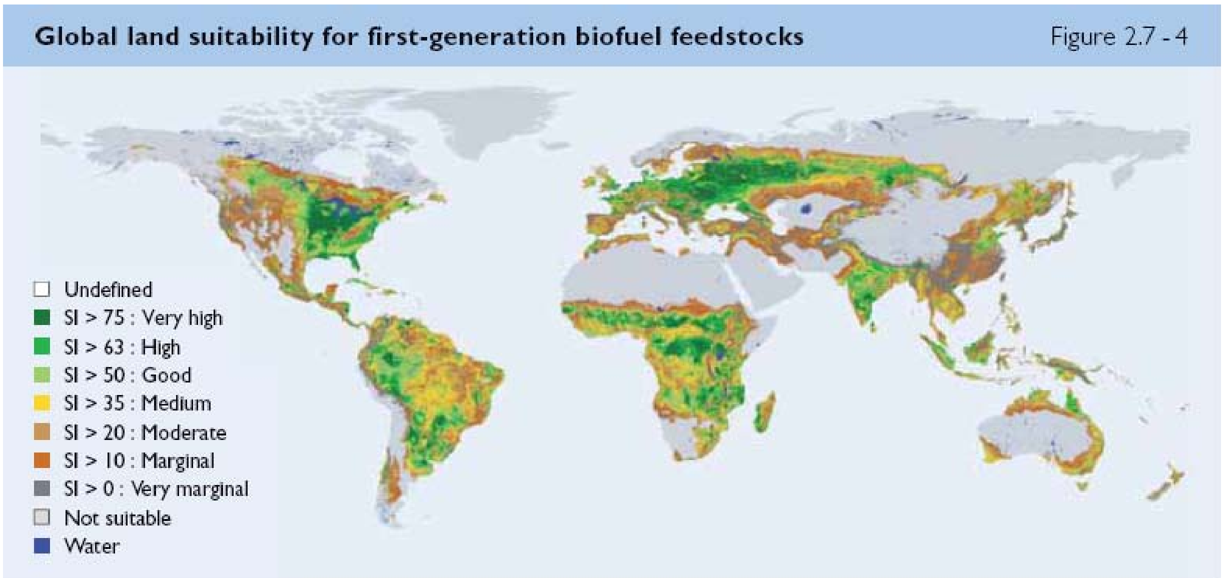


Figure 2.2.3. Suitability of land for production of selected agricultural crops that can be used as biofuel feedstocks. The suitability index SI used reflects the spatial suitability of each pixel and is calculated as SI=VS*0.9+S*0.7+MS*0.5+mS*0.3, where VS, S, MS, and mS correspond to yield levels at 80-100%, 60-80%, 40-60% and 20-40% of modelled maximum, respectively. Source: Fischer et al. 2009.

Supply potentials for energy crops can be calculated based on assessed land availability and corresponding yield levels. Table 2.2.2 shows the example of rain-fed lignocellulosic crops on unprotected grassland and woodland. In this case, lands with low productivity has been excluded and a rough land balance was made based on subtracting land estimated to be required for livestock feeding (Fischer et al. 2009). Note that Table 2.2.2 represents 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 population, diets, climate, etc. and quantifications of future biomass resource potentials need to consider how such parameters change over time.

Table 2.2.2. Potential bionergy supply from rain-fed lignocellulosic crops on unprotected grassland and woodland where land requirements for livestock feeding have been considered. Calculated based on Fischer et al. (2009). TSU: all units in table if not otherwise stated are ha.

	Total grass- & woodland	**Of which**		**Balance available for bioenergy**	**Bioenergy 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) and Smeets et al. (2007) (from where Figure 2.2.3 is taken) are illustrative of the importance of energy crops for reaching higher global biomass resource potentials, and also of how different determining parameters are highly influential on the resource potential. Based on varying assumptions for critical aspects (e.g., population growth, level of improvements in agronomic technology, water supply and efficiency in use (rain-fed/irrigated), productivity of animal production system) Smeets et al. (2007) show that 0.7-3.5 billion hectares of surplus agricultural land – mainly pastures and with large areas in Latin America and sub-Saharan Africa – could potentially become available for bioenergy by 2050. If the suitable part of this land was used for lignocellulosic crops the total technical biomass resource potential – including also residues and forestry growth not required in the forest industry – would be above 1500 EJ (Figure 2.2.4).

Also pointing to the potential of pasture land conversion to bioenergy, Wirsenius et al. (2010) analyse the potential for land-minimized growth of world food supply through (i) faster growth in feed-to-food efficiency in animal food production; (ii) decreased food wastage; and (iii) dietary changes in favor of vegetable food and less land-demanding meat. They show that faster-yet-feasible livestock productivity growth combined with substitution of pork and/or poultry for 20% of ruminant meat can reduce land requirements by about 700 million hectares compared to a projection of global agriculture development up to 2030 presented by the Food and Agriculture Organization of the United Nations, FAO (Bruins, 2003).

In an analysis (WBGU, 2009) where current and near-future agricultural land is reserved for food and fibre production, thereby assuming mid-range future yield intensification, and where unmanaged lands are excluded from biomass production if carbon compensation from land conversion to plantation is slow (large standing biomass or carbon sink), the land is degraded, a wetland or environmentally protected, or where it is rich in biodiversity, global bioenergy potential from dedicated biomass plantations is estimated to vary between 34 and 120 EJ depending on the scenario (severity of the rules applied).

In a much less optimistic scenario for bioenergy – where agricultural productivity would remain at its current levels, population growth would continue at high rates and (biomass) trade and technology exchange would be severely limited – Smeets (2007) show that no land would be available for energy crops and the biomass resource potential be about 50 EJ consisting of municipal solid waste and some agricultural and forestry residues. Similarly, assuming a scenario of high population growth, high food demands and extensive agricultural production systems Wolf et al. (2003) arrive at zero potential for bioenergy.

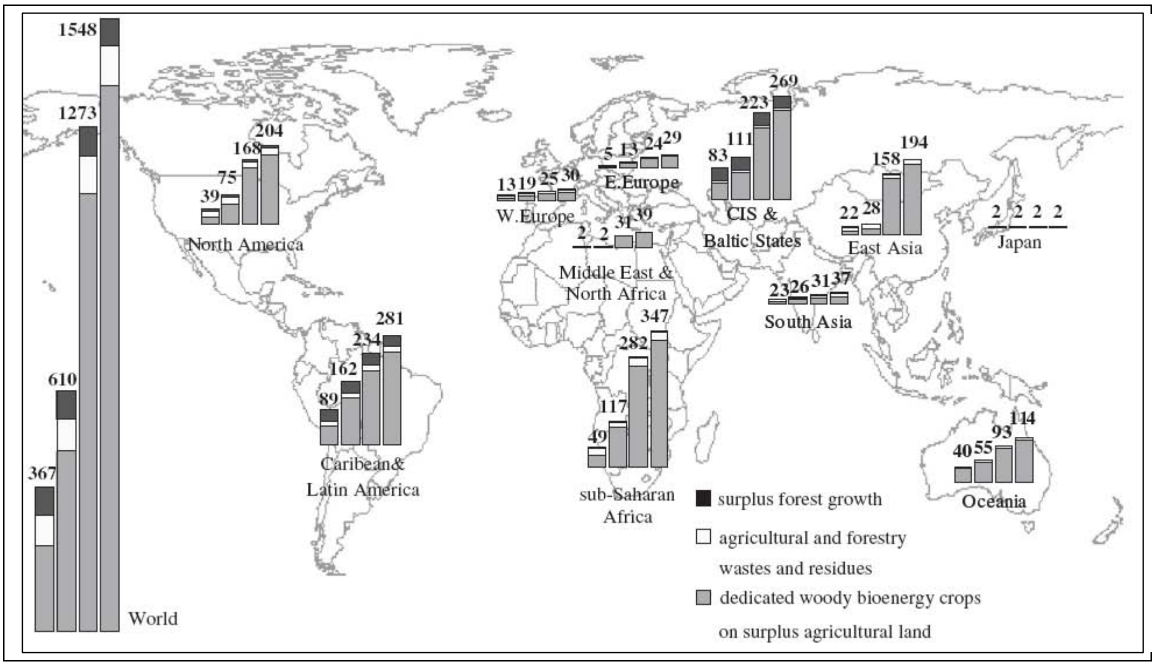


Figure 2.2.4. Illustration of the impact of different scenarios for agricultural productivity improvement on total technical bioenergy production potential in 2050, all other assumptions remaining equal (Smeets et al. 2007). All numbers in EJ.

2.2.3 Economic considerations in biomass resource assessments

Besides using restrictions based on minimum yield thresholds, assessments of the potential of energy plantations can include economic thresholds that exclude biomass resources judged as being too expensive to mobilize. For instance, land areas that are assessed as suitable for some types of bioenergy plantations can still be excluded when the estimated biomass production cost is considered too high. Alternatively, the potential of energy crops can be quantified based on combining land availability, yield levels and production costs to obtain crop- 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 – ranging from feasibility studies of supplying individual bioenergy plants to describing the future global cost-supply curve. Figure 2.2.5 shows examples of global cost-supply curves for energy crops. A number of studies use this approach at different scales (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.

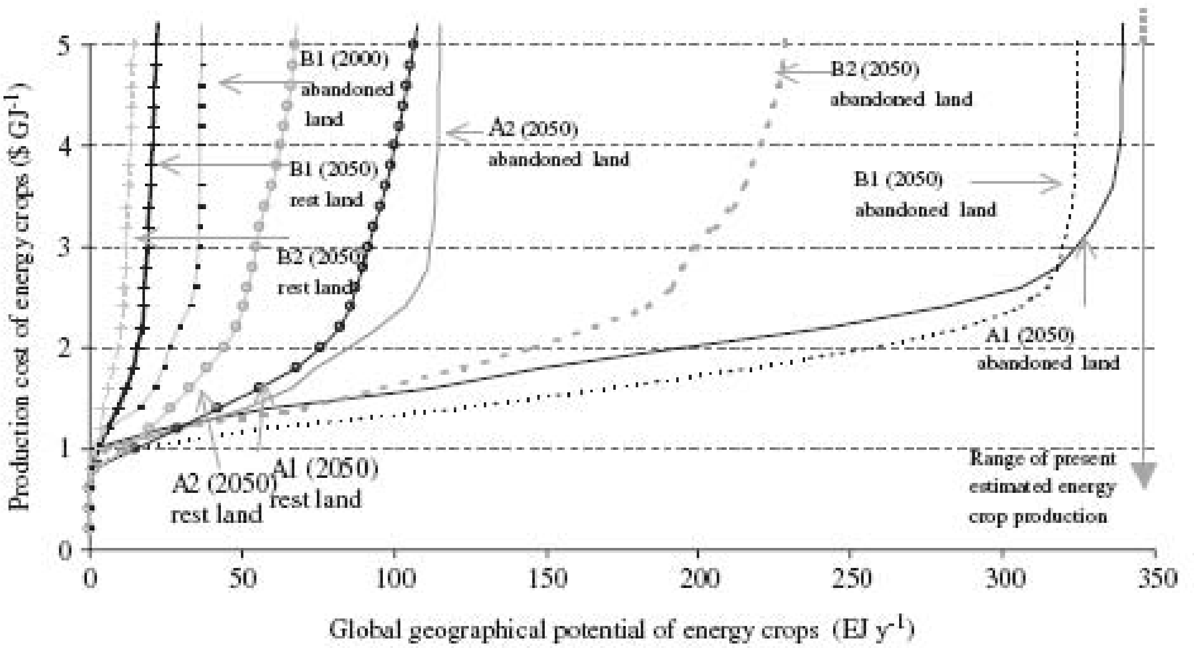


Figure 2.2.5. Global average cost-supply curve for the production of energy crops on the two land categories "abandoned land" (agriculture land not required for food) and "rest land" (TSU: add definition here), year 2050. The curves are generated based on IMAGE 2.2 modeling of four SRES scenarios (IMAGETeam 2001). The cost-supply curve at abandoned agriculture land year 2000 (SRES B1 scenario) is also shown. Source: Hoogwijk et al. 2008.

The 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 modelling can provide information about implementation potentials in relation to a specific energy system context and possible climate and energy policy targets. This is further discussed in Section 2.7.

2.2.4 Constraints on biomass resource potentials

As described briefly above, many studies that quantify the biomass resource potential consider a range of constraints 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 constraints are briefly discussed in relation to how they have been considered in studies assessing the biomass resource potentials.

2.2.4.1 Constraints on residue extraction rates

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 can be recirculated to forests to recycle nutrients taken from the forest and to 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). In agriculture, 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). When ploughed under or left on the field/forest, primary residues may recycle valuable nutrients to the soil and help prevent erosion. Prevention of soil organic matter depletion and nutrient depletion are of importance to maintain site productivity for future crops. Overexploitation of harvest residues is one important cause to soil degradation in many places of the world.

However, 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).

There are also large uncertainties linked to the possible future development of important determining factors. 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 at harvest 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 intensification 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 – is not 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 identical 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 energy crops (indirectly by determining the land requirements in the food sector) and the yield levels obtained for these crops (Lotze-Campen et al., 2009, provides an example). High assessed potentials for energy plantations rely on very efficient agricultural systems and optimal land use allocation beyond national borders, and the use of high-yielding bioenergy plantations on available lands. A notable example, Smeets et al. (2007) report a high-end bioenergy potential on surplus agricultural land at 1272 EJ/yr. However, as the authors also stress, this corresponds to a technical potential requiring productivity increases in agriculture that appear unrealistically high when comparing with other scenario studies of agriculture development (see, e.g., Koning 2008, IAASTF 2009, Alexandratos 2009).

Increasing yields on existing agricultural land is commonly 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), Bruins, 2009 . Theoretical limits still appears to leave scope for further increasing the genetic yield potential (Fischer et al. 2009). But there can be limitations and negative aspects of further intensification of the use of cropland aiming at farm yield increases; high crop yields depend on large inputs of nutrients, fresh water, and pesticides, and contribute to negative ecosystem effects, such as eutrophication (Donner and Kucharik, 2008; see also Section 2.5).

Some observations indicate that it can be a challenge to maintain yield growth in several main producer countries, while other observations indicate that rates of gain obtained from breeding have increased in recent years and that yields may increase faster again as newer hybrids are adopted more widely (Edgerton 2009). Many infrastructural, institutional and technical constraints can reduce farm yields and prevent closing the gap between genetic yield potentials and farm yields for major crops. Even maintaining current yield potentials may prove to be difficult, as there are signs of intensification-induced declines of the yield potentials over time, related to subtle and complex forms of soil degradation (Cassman, 1999; Pingali and Heisey, 1999). Large areas of croplands and grazing land experience degradation and productivity loss as a consequence of improper land use (Fischer et al. 2002).

Biomass resource potential assessments that rely on established biophysical datasets and modelling tools run less risk of assuming developments towards biophysically unrealistic productivity levels. But databases still needs improvements (Sanchez et al. 2009) and assessment studies' modeling of agronomic advancement has a less solid basis leading to that the derived productivity growth rates could still prove to be too optimistic. Limits on intensification – connected to the effects of nutrient and chemical leaching causing eutrophication, and also to the risks that high-yielding alien species grown for bioenergy spread to surrounding natural ecosystems – are seldom treated explicitly as a constraint on intensification in biomass resource assessments but rather noted as a risk with the proposition that proper land management practice is critical for avoiding negative effects.

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. 2009, Edgerton 2009, Fischer et al. 2002).

2.2.4.3 Water related constraints

Water related constraints primarily influence the prospects for bioenergy plantations, including both intensification possibilities and the prospects for expansion of bioenergy plantations (Berndes 2008, Rost et al. 2009). To the extent that bioenergy is based on the utilization of residues and biomass processing by-products within the food and forestry sectors, water use would not increase significantly due to increasing bioenergy. The water that is used to produce the food and conventional forest products is the same water as that which will also produce the residues and by-products potentially available for bioenergy.

The impact of bioenergy plantations on water availability and use depends on site-specific conditions and prior land use/vegetation cover. To the extent that plantation establishment leads to higher site productivity and biomass accumulation it can be expected that the evapotranspiration increases, which can lead to falling groundwater levels and reduced downstream water availability in regions where water is scarce (Jackson et al. 2005, Zomer 2006). Impacts are further discussed in Section 2.5.

Water constraints are explicitly considered in some – but far from all – studies of the biomass resource potential. In studies that use biophysical datasets and modelling, water limitations can constrain the modelled land productivity to levels considered too low for meeting suitability criteria for bioenergy plantations. However, assumptions about productivity growth in agriculture may implicitly presume irrigation development that could lead to challenges in relation to regional water availability and use.

Illustrative of how water scarcity might constrain biomass resource potentials, Van Vuuren (2009) overlaid a water scarcity map for 2050 (Döll et al. 2003) and found that about 17% of the assessed bioenergy potential was in severe water-scarce areas and an additional 6% was in areas of modest water scarcity.

Studies that have investigated the link between large scale bioenergy supply and water have made impact assessments of a specified future bioenergy supply rather than assessed biomass resource potentials as determined by water availability (see, e.g., Berndes 2002, De Fraiture et al. 2008, De Fraiture and Berndes 2009). Thus, they add an important dimension but they do not give information about how much biomass that can be produced for energy within limits set by availability and competing use of water.

2.2.4.4 Biodiversity constraints on agriculture land expansion

Besides influencing possible residue extraction in agriculture and forestry, biodiversity can limit biomass resource potentials in many ways.

As noted above, biodiversity limits on intensification – connected to the effects of nutrient and chemical leaching, which can lead to changes in species composition in the surrounding ecosystems, and also to the risks that alien species grown for bioenergy spread to surrounding natural ecosystems – are not treated explicitly as a constraint on productivity growth. But some studies indirectly consider these constraints on productivity implicitly by assuming a certain expansion of alternative agriculture production that yields lower than conventional agriculture and therefore requires more land for food production (Fischer et al. 2009, EEA, 2007). Van Vuuren et al. (2009) illustrate the sensitivity to yield assumptions and show that yield increases for food crops in general have a more substantial impact on bioenergy potentials than yield increase for bioenergy crops specifically.

The common way of considering biodiversity requirements as a constraint is by including requirements on land reservation for biodiversity protection (e.g. WBGU, 2009). 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.

Clearly, biodiversity impacts still may arise in the real world. 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 modelling have better prospects for analysing these risks. They are further discussed in Section 2.2.6 below. WBGU (2009) show that differences in the assumed severity of biodiversity protection between scenarios have a larger impact on bioenergy potential than either irrigation or climate change.

2.2.5 Summary conclusions on biomass resource assessments

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:

- Biomass use for energy can already today be strongly increased over current levels based on increased use of forestry and agricultural residues
- The short to medium 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.
- 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 – also due to that the cultivation of conventional crops would lead to large soil carbon emissions (further discussed in Section 2.5.2).
- 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 modelling capacity have not succeeded in providing narrow distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various parameters are on the potential. Some of the most important parameters are inherently uncertain and will continue to make long term biomass supply potentials unclear. However, the insights from the resource assessments can improve the prospects for bioenergy by pointing out the areas where development is most crucial. This is further discussed in Section 2.2.6 below where we also propose areas for further research.

2.2.6 Uncertainties and requirements for further research

There are several important but uncertain aspects that make assessments of future potentials for bioenergy plantations challenging but also important.

2.2.6.1 Water

Since many studies of the biomass resource potential have pointed out that plantation establishment on abandoned agricultural land and sparsely vegetated degraded land is one major option, the water use dimension of expanding bioenergy needs to be carefully investigated.

The impact of energy plantations on changes in hydrology needs to be researched in order to advance our understanding of how the changes in water and land management will affect downstream users and ecosystems. Such impacts can be both negative and positive. For example, local water harvesting and run-off collection upstream may reduce erosion and sedimentation loads in downstream rivers, while building resilience in the upstream farming communities. Also, a number of crops that are suitable for bioenergy production are drought tolerant and relatively water efficient crops that are grown under multi-year rotations. These crops provide an option to improve water productivity in agriculture and help alleviate competition for water as well as pressure on other land-use systems (Berndes 2008). They also offer a possibility to diversify land use and livelihood strategies and protect fragile environments.

Assessments of biomass resource potentials should preferably include the possibility of introducing bioenergy plantations into the agricultural landscape so as to improve water use efficiency. Rost et al. (2009) show how low-tech measures may alleviate water stress limitations to agricultural production.

2.2.6.2 Climate change impact on land use productivity and availability of land

The possible consequences of climate change for agriculture are not firmly established but indicate net global negative impact, where damages will be disproportionately concentrated in developing countries that will lose in agriculture production potential while developed countries might gain (Fischer et al. 2002, Cline 2007, Fischer 2009,).

Climate change is likely to change rainfall patterns while water transpiration and evaporation will be enhanced by increasing temperatures. Semi-arid and arid areas are particularly likely to be confronted with reduced water availability and problems in many river basins may be expected to increase. Generally, negative effects of climate change will outweigh the benefits for freshwater systems, thereby adversely influencing water availability in many regions and hence irrigation potentials.

Clearly, future assessments of biomass resource potentials need to reflect the most recent understanding of climate change impacts – including up-to-date databases. They should also reflect the understanding of how introduction of energy crop as a strategy for adaptation to climate change.

2.2.6.3 Plant breeding and genetic modification of crops

Advances in plant breeding and genetic modification of crops not only raises the genetic yield potential but also adapts crops 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). It can also reduce water requirements in irrigated systems.

Dedicated energy crops have not been subject to the same breeding efforts as the major food crops. Selection of suitable crop 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 crops, and traditional plant breeding, selection and hybridization techniques are slow, particularly in woody crops but also in grasses. New biotechnological routes to produce both non-genetically modified (non-GM) and GM plants are possible. GM energy crop 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. As a result, non-GM biotechnologies may remain particularly attractive. On the other hand, GMO food crops have already been widely accepted in many non-EU countries. One challenge will be to make advances in plant breeding become available for farmers in developing countries.

2.2.6.4 Intensified forest management

The prospects for intensifying conventional long-rotation forestry to increase total biomass output is not investigated in global/regional studies so far, but national level studies point to significant possibilities and also trade-offs to be managed.

2.2.6.5 New types of integrated land use systems

Assessments of biomass resource potentials have been done without sufficiently considering possibilities of new innovative agronomic practice involving integrated bioenergy/food/feed production. Integration can be realized at the feedstock production level – e.g., double-cropping systems (Heggenstaller 2008) and different types of agroforestry systems – and 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)

Much attention has been directed to the possible negative consequences of land use change, such as biodiversity losses, greenhouse gas emissions and degradation of soils and water bodies, referring to well-documented effects of forest conversion and cropland expansion to uncultivated areas. However, most impact studies concern conventional food/feed crops and TSU suggests: whereas studies of environmental effects of lignocellulosic crops are less common (Dimitrou et al. 2009). Also, the production of biomass for energy can generate additional benefits. In agriculture, biomass can be cultivated in so-called multifunctional plantations that – through well chosen localization, design, management, and system integration – offer extra environmental services (including soil carbon increase and improved soil quality) that, in turn, create added value for the systems (Berndes et al. 2008) .

Many such plantations provide water related services, such as vegetation filters for the treatment of nutrient bearing water such as wastewater from households (Börjesson and Berndes 2006), collected runoff water from farmlands and leachate from landfills. Plantations can also be located in the landscape and managed for capturing the nutrients in passing runoff water. Sewage sludge from treatment plants can also be used as fertilizer in vegetation filters. Plantations can be located and managed for limiting wind and water erosion. For example perennial grasses are used by the US Conservation Reserve Programme to minimize soil erosion. Besides the onsite benefits of reduced soil losses, there are also offsite benefits such as reduced sediment load in reservoirs, rivers and irrigation channels. Plantations can also reduce shallow land slides and local ‘flash floods’.

Comprehensive assessments of the biomass resource potential linked to multifunctional bioenergy systems exists on national level (see, e.g., Berndes and Börjesson 2007) and for specific applications (e.g., Berndes et al. 2004), where plantation establishment for reclamation of degraded land is among the more diverse and numerous. Solid assessments require detailed comprehensive data making global comprehensive assessments based on uniform methodology challenging. However, an increased number of local/national assessments can give important information for implementation of strategies to capture the environmental benefits of expanding multifunctional biomass plantations.

2.2.6.6 Availability of degraded land

Future biomass potentials are co-determined also by whether degraded lands - of which productive capacity has declined temporarily or permanently - can be used for biomass production. At this moment the potential of the large area of degraded soils – classified as light and moderately degraded and covering about 10% of the total land area – to contribute to the production of biomass has not yet clearly assessed. Two possible drawbacks are the main reason: firstly the large efforts and long time period required for the reclamation of degraded land and secondly the low productivity levels of these soils. Analysis has been shown that using severely degraded land could increase biomass potentials from energy crops by about 30-45%. However, using severely degraded land for annual crop production might require large investments and many attempts for reclaiming degraded land for food production have failed.

2.2.6.7 Complementary methodological approaches

Studies using integrated energy/industry/land use/cover models produce a more dynamic description of the biomass resource potential, showing bioenergy development where bioenergy production and use is a modeling result rather than an input parameter. In such studies, land allocation to bioenergy as well as land/food/fiber prices give insights into the competitiveness of bioenergy in relation to other competing energy technologies, and in relation to other competing land uses. The outcome is among other things dependent on assumed policies influencing the demand for and competitiveness of bioenergy as well as other energy technologies.

In contrast to conventional assessments of biomass resource potentials where normative restrictions (e.g., with reference to food sector impacts and biodiversity considerations) limits the resource potential, this type of studies have the character of impact assessments and can show consequences of expanding bioenergy to scales beyond those defined by normative restrictions. Thus, instead of quantifying biomass resource potentials based on considering a range of sustainability constraints they provide an important basis for discussions of trade-offs between bioenergy supply and various socio-economic and/or environmental objectives.

An example of such studies, Melillo et al. (2009) developed two scenarios to analyse the environmental consequences of an aggressive global cellulosic biofuels program over the first half of the 21st century. They found that both could contribute substantially to future global-scale energy needs, but with significant unintended environmental consequences, either due to the clearing of large areas of natural forest, or due to the intensification of agricultural operations worldwide. Also, numerous biodiversity hotspots suffer from serious habitat loss. This further discussed in Section 2.5).

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 and near-term technologies used in the various steps of these chains, and details the major systems which are currently deployed, while future technologies are presented in section 2.6.

2.3.1 Feedstock

2.3.1.1 Feedstock production or recovery

Feedstock types may be classified into 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 production from dedicated plants includes the provision of seeds or seedlings, stand establishment and harvest, soil tillage, and various rates of irrigation, fertilizer and pesticide inputs. The latter depend on crop requirements, target yields, and local pedo-climatic conditions, and determine the intensity in the use of production factors (inputs, machinery, labor or land), which may vary across world regions for a similar species (Table 2.3.1). Within a given region, similar yield levels may be reached through a variety of cropping systems and production intensities. Strategies such as integrated pest management or organic farming may alleviate the need of synthetic inputs for a given output of biomass. Such distinction is beyond the scope of this section, but is a major avenue to improve the sustainability of biomass supply.

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. Some of this is converted into charcoal. 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 (Nabuurs et al., 2007). The management of planted forests involves silvicultural techniques similarly to those of cropping systems, from stand establishment to tree fellings. The use of synthetic fertilizers is considerably less intensive than on agricultural species.

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 road transport to the bioenergy unit or an intermediate storage. It may be preconditioned and densified to make storage, transport and handling easier (section 2.3.2.).

Primary residues from agriculture consist of plant materials that remain on the farm after removal of the main crop produce, and include straw, stalks or leaves. They may be collected upon crop harvest. Primary residues from forest may be available from additional stemwood fellings or as residues (branches, stumps) from thinning salvage after natural disturbances, thinnings or final fellings. Typical values of residue recoverability are between 25 and 50 % of the logging residues and between 33 and 80% of processing residues (Nabuurs et al., 2007).

Secondary residues are by-products of post-harvest processing of crops, namely, cleaning, threshing, sawing, sieving, crushing, etc., and can be in the form of husk, dust, bagasse, cobs or straw, along with post-consumer recovered wood products having served their purpose e.g., pallets, construction wood, or furniture (Steierer et al., 2007). Examples include groundnut shells, rice husk, sugar cane bagasse or corn cobs (Dhingra, Mande, Kishore, et al.1996). They are stored and collected at the processing site. Although modes and volume of production of agricultural residues 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 (Hall et al. 1993).

A number of important factors have to be addressed when considering the use of residues for energy. First, there are many other alternative uses, for example, as animal feed, soil erosion control, animal bedding, and or fertilizers (manure). Second, they are seasonally available and their availability is difficult to predict. Availability is also conditioned by the amount of residue deemed essential for maintaining soil organic matter, which depends on pedo-climatic conditions and cultural practices (Wilhem et al., 2004), soil erosion control, efficiency in harvesting, and losses (Iyer et al., 2002). Although the availability of residues upon harvest makes collection easy for small-scale utilization, it creates storage problems if residues have to be saved for use during other months of the year, especially due to their low bulk density.

Organic waste utilizable for energy purposes includes animal residues such as cattle dung; poultry litter; MSW (municipal solid waste), including food and vegetable market waste, tree trimmings and lawn cuts; and industrial organic waste from food-processing industries, pulp and paper mills (black liquor). Sewage sludge from domestic and industrial water treatment plants is also a source of biomass for energy. Organic waste is usually stored on the production site in a tank or heap, prior to collection and transportation to the bioenergy unit in liquid or solid form. Organic waste contains many degradable organic materials and nutrients, and may be returned to soils as manure after conversion to energy. The organic waste that is buried into landfills is also a source of biomass, since it is digested by micro-organisms and evolved into biogas (landfill gas).

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 for first-generation liquid biofuels (ethanol and bio-diesel), which only use a fraction of their total above-ground biomass, the rest being processed in the form of animal feed or lignocellulosic residues. Nevertheless, it is worthwhile to recognize that sugar cane bagasse and even sugar cane straw are being used as a source of bioelectricity 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, while 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). In addition, with the current status of technology lignocellulose can only provide heat and power whereas the harvest products of oil, sugar and starch crops may be readily converted to liquid biofuels and bioelectricity. 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 will scale with the demand of energy feedstock (Bureau et al., 2009). Cost-supply curves are needed to account for these effects in the economics of large-scale deployment scenarios.

Residues and waste streams are a coveted resource since their apparent costs only include collection, pre-conditioning and transport (Table 2.3.2). However, 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% (EEA, 2006). Nutrient exports should also be compensated for, possibly by recycling residual ash, stillage or digestate from the bioenergy conversion process.

2.3.1.2 Interactions with the agriculture, food & forest sectors

Energy feedstock production may compete with the food, feed, and fibre and forest sectors either directly for land or for a particular 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 (see section 2.2). From a technology standpoint and at a local scale, synergistic effects may also emerge between these competing usages. Agroforestry makes 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. Intercropping and mixed cropping are also interesting options to maximize the output of biomass per unit area farmed (WWI, 2006). 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 (Openshaw, 2000; Semere and Slater, 2007). Perennial species such as switchgrass offer other benefits in terms of building and maintaining soil organic matter and improving soil structure (Paustian et al., 2006). Annual energy crops may be used as break crops in rotations involving cereals, to decrease the pressure of specific pathogens. Mixed cropping systems (e.g. a combination of legume and cereal crops, or a high diversity of grass species) 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). 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). The latter authors reviewed small-scale bioenergy projects in developing countries and concluded that they did not affect (and possibly improve) local staple food security, under those conditions.

Table 2.3.1. Typical characteristics of the production technologies for dedicated species and their primary residues.

Feedstock type	Region	Yield (GJ/ha) / fraction	Management			Co-products	Costs USD/GJ	Refs.
			N/P/K use	Water needs	Pesticides			
OIL CROPS		Oil						
Oilseed rape	Europe	42	+++	+	+++	Rape cake, straw	7.2	1,2
Soybean	N America Brazil	25 18,21	++ ++	+ +	+++ +++	Soy cake, straw	11.7	3,12
Palm oil	Asia Brazil	135-200 169	++ ++	+ +	+++ +++	Palm fronds, fruit bunches, press fibers	12.6	3
Jatropha	India Africa	21 45	+ +	+ +	+ +	Seed cake (toxic), wood, shells	2.9	3,4,5, 10,11
STARCH CROPS		As ethanol						
Wheat	Europe	54-58	+++	++	+++	Straw, DDGS	5.2	3
Maize	N America	72-79	+++	+++	+++	Corn stover, DDGS	10.9	3
Cassava	World	43	++	+	++	DDGS		3
SUGAR CROPS		As ethanol						
Sugar cane	Brazil India	116-149 95-112	++	+	+++	Bagasse, straw	1.0-2.0	3,20 3
Sugar beet	Europe	116-158	++	++	+++	Molasses, pulp	5.2	3,13
Sorghum (sweet)	Africa China	105-160	+++	+	++	Bagasse	12.8	3
LIGNOCELLULOSIC CROPS								
Micanthus	Europe	190-280	+/++	++	+		4.8-16	6,8
Switchgrass	Europe N America	120-225 103-150	++ ++	+ +	+ +		2.4-3.2 4.4	10,14
Short rotation Eucalyptus	S Europe S America	180 250	+ +	++ +	+ +	Tree bark	2.9-4 2.7	2,19
S.rotation Willow	Europe	140					4.4	3,7
Fuelwood (chopped) Fuelwood (from native forests)	Europe C America	110 80-150				Forest residues Forest residues, whole trees and branches	3.4-13.6 2-4	17
PRIMARY RESIDUES								
Wheat straw	Europe USA	60 7	+				1.9	2 14
Sugar cane straw	Brazil	90-126	+					21
Corn stover	N America India	15-155 22-30	+ +				0.9	9,14 21
Sorghum stover	World	85	+					9
Forest residues	Europe World	2-15					1-7.7	17

References: 1: EEA, 2006; 2: JRC, 2007; 3: Bessou et al., 2009; 4: Ndong et al., 2009; 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, pers. com., 2009; 17: Karjalainen et al., 2004; 18: Nabuurs et al., 2007; 19: Scolforo, 2008; 20: Folha, 2005; 21: Guille, 2007.

Table 2.3.2: Typical characteristics of the production technologies for selected secondary residues and waste stream). Same references as Table 2.3.1.

Feedstock type	Region	Energy content	Cost USD/GJ	Ref.
Charcoal	Worldwide	29 GJ/odt	2	
Sugar cane bagasse	Brazil	15.5 GJ/odt	1.6-7.6	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	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

2.3.2 Logistics and supply chains

2.3.2.1 Preconditioning of biomass

Most non-woody biomass is available in loose form and has low bulk densities, which causes problems of handling, transportation and storage. Shredded biomass residues may be densified by briquetting or pelletizing, typically in screw or piston presses that compress and extrude the biomass (FAO, 2009c). The application of high pressure increases the temperature and lignin present in the biomass partially liquefies and acts as a binder. 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.

Briquettes are larger than pellets and are produced by compression and extrusion, with various compaction rates (Erikson and Prior, 1990). 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). There are indications that most of these obstacles are being overcome in efforts to protect the Virunga National Park in the Democratic Republic of Congo, a global biodiversity hotspot, by replacing illegal charcoal production by briquettes in the surrounding densely populated areas on the open market.

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. Pelletizing generally requires conditioning of biomass material by mixing with a binder or by raising its temperature through direct addition of steam or both (BEC, 2009). Wood pellet are easy to handle and burning is easy; shape and characteristics of fuel 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. The handling of both chips and pellets is amenable to automation. Bark and wood are usually chipped separately because they have different properties. Depending on end use, chips may be produced on-site, or the wood may be transported to the chipper. For example in Durban, South Africa the chipper is located at the port and debarked logs are transported to the port by road and rail. The chips are pumped directly onto ships for export, in this case to Japan. 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. It has been in use in India and China since times immemorial. In many African countries charcoal is produced 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 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). In Africa, frequently illegal charcoal production is seen as a primary threat to remaining wildlife habitats.

2.3.2.2 Logistics

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). They are complicated by certain characteristics of the feedstocks, including high moisture content, low density, and seasonal availability patterns, necessitating specific handling, drying and voluminous storage. They may involve several intermediate steps between the supplier and the end-user and encompass wide geographical areas. A generic value chain showing elements and stakeholders is given on Table 2.3.3.

Table 2.3.3. A generic value chain showing elements and stakeholders (based on GTZ, 2008).

Production ⇨	Harvesting/ charcoal making ⇨	Transport ⇨	Wholesale ⇨	Retail ⇨	End use
Wood Producer	*Charcoal producer*	*Transporter*	*Wholesaler*	*Retailer*	*End user*

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.

2.3.3 Conversion technologies

Different end use applications of biomass involve various conversion processes, which can be classified according to Table 2.3.4.

Table 2.3.4: Main routes for converting biomass to a range of possible end-uses.

Process	Type of Feedstock	Conversion Technology	End use
Thermo chemical conversion	Lignocellulosic crops, wood , primary and secondary residues	Combustion Pyrolysis Gasification Liquefaction Cogeneration	Cooking/heating/electricity/ cogeneration
Chemical	Oil crops, waste	Acid Hydrolysis/ Transesterification	Electricity /liquid biofuels
Biochemical	Starch, sugar, lignocellulosic crops, wood, residues, organic waste	Anaerobic digestion Ethanol Fermentation	Cooking/heating/ power /liquid biofuels in vehicles

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. About 2.4 billion people in developing countries use firewood in inefficient traditional open fire cook stoves in poorly ventilated kitchens leading to major health problems in women and children (see section 2.5). Major efforts have been launched in the past decade on the development of more efficient and reliable cookstoves.

Grate combustion is the most commonly-used technology for small-scale industrial processes and heating systems. Combustion applications of fluidised bed technology were commercially developed in the 1970’s, with the advantages of more flexibility for fuels, and lower emissions of sulphur, nitrogen oxides and unburned components (Fargernäs et al., 2006). The technology for generating electricity from biomass is similar to the conventional coal-based power generation. The biomass is burnt in boilers to generate steam, which drives a turbo alternator for generation of electricity. The equipment required for these projects comprises mainly of boilers, turbines, and grid inter-phasing systems. Recent innovations include the use of air-cooled condensers to reduce consumptive use of water.

Charcoal as described earlier is produced through a process known as carbonization, which comprises three distinct phases: drying, pyrolysis and cooling. These may considerably overlap when the charcoal is made in large kilns. Selection of the charcoal making technology is based on:

the investment costs, duration of carbonization, yield and labour intensiveness. The Missouri kiln is widely used in developed countries (Massengale, 1985). Unlike the earth mounted traditional charcoal kiln, they consist of permanent structures made up of brick or concrete construction that can be used for several batches with minor maintenance.

Cogeneration is the process of using a single fuel to produce more than one form of energy in sequence. In normal electricity generation plants, up to 70% of heat in steam is rejected to the atmosphere. In cogeneration mode, however, this heat is not wasted and is instead used to meet process heating requirement. The overall efficiency of fuel utilization can thus be increased to 60% or even higher (over 90%) in some cases (Williams et al., 2009). The sugar industry across the world has traditionally used bagasse-based cogeneration for achieving self-sufficiency in steam and electricity as well as economy in operations. Technologies available for high-temperature/high-pressure steam generation using bagasse as a fuel make it possible for sugar mills to operate at higher levels of energy efficiency and generate more electricity than what they require. Similarly black liquor, an organic waste produced in paper and pulp industry is being burnt efficiently in boilers for producing energy that is used back as process heat (Faaij, 2006).

Biomass Gasification is the thermo-chemical conversion of solid biomass into a combustible gas mixture (synthesis gas, a mixture of CO and H_2) through a partial combustion route with air supply restricted to less than that theoretically required for full combustion. Synthesis gas can be used as a fuel in place of diesel in suitably designed/adopted internal combustion (IC) engines coupled with generators for electricity generation. It can replace conventional forms of energy such as oil in many heating applications in industry. The gasification process renders use of biomass relatively clean and acceptable in environmental terms. 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). Fuel is loaded into the reactor from the top, and is subjected to drying and pyrolysis as it moves down Air is injected into the reactor in the oxidation zone, and through the partial combustion of pyrolysis products and solid biomass, the temperature rises to 1100 °C, helping in breaking down heavier hydrocarbons and tars. As these products move downwards, they enter the reduction zone where synthesis gas is formed by the action of carbon dioxide and water vapour on red-hot charcoal. The hot and dirty gas is passed through a system of coolers, cleaners, and filters before it is sent to engines or turbines. It can also be upgraded to a liquid fuel using a catalyst (with e.g. the Fischer-Tropsch process) to produce a range synthetic liquid biofuels (synfuels). Biomass gasifier stoves are also being used in many rural industries for heating and drying (Yokoyama and Matsumura, 2008).

Biomass Liquefaction is the process of conversion of biomass materials to liquid fuels. This can be done by thermal and biochemical methods. Among the most common method in use is destructive distillation of wood to form charcoal and methanol. Destructive distillation was used in the past for generating methyl alcohol, which is used as a solvent and in many other applications.

2.3.3.2 Chemical Processes

Transesterification is the process where the alcohols reacts 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; WWI, 2006). The production of this fuel referred to as bio-diesel 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. Bio-diesel can also be made by hydrodeoxygenation of vegetable oil through processes which are currently already deployed (IEA Bioenergy, 2009), which is especially interesting for oils with low saturation such as palm oil.

2.3.3.3 Biochemical Processes

Fermentation of sugars by appropriate yeasts produces 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 continuous processes, the latter becoming widespread and being much more efficient since yeasts can be recycles. 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).

Ethanol is viewed as a promising alternative to gasoline throughout much of the world. It is widely used in cars and buses in Brazil (WWI, 2006). Technological developments, improvements in feedstock and better management practices induced with adequate environment control have turned Brazil into a global benchmark in production of ethanol from sugarcane. In India, sugar cane molasses is the feedstock for ethanol production. India is one of the developing countries where ethanol is being used as a five percent ethanol-gasoline blend. Corn ethanol is popular in U.S.A where it is used as a blend with gasoline. However, it is considered less efficient than other types of ethanol (e.g., sugar cane) because only the grain is used and many petroleum-based products are used in its production. In Europe, most of the ethanol is refined to ethyl tertiary butyl ether (ETBE) in oil refineries before blending (WWI, 2006).

Anaerobic digestion involves the breakdown of organic matter in biomass such as animal dung, human excreta, leafy plant materials, and urban solid and liquid wastes by micro-organisms in the absence of oxygen to produce biogas, a mixture of methane (50-60%) and carbon dioxide with traces of hydrogen sulphide. 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 (IEA Bioenergy, 2009). 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. In recent years biogas systems have become an attractive option for decentralized rural development as it produces a cheap fuel and good quality, rich manure (Faaij, 2006). Many developing countries like India and China are making use of this technology extensively in rural areas. In Germany large size biogas plants have been set up for digesting grains, food waste to produce green power that can bring more returns to the farmers (Faaij, 2006).

2.3.4 Bioenergy Systems and Chains: Description of existing state of the art systems

Table 2.3.5 shows the most relevant bioenergy systems and chains in commercial and demonstration status (marked in the last column as NA TSU: please indicate what NA is abbreviation of) at global level presently. For each end-use biofuel there is information about the feedstock being used the technology required in the processing stage, the end-use sector, the country or region, the production cost, the market potential and the deployment potential. Some other information is also described in the column “Comments”. Liquid biofuels are mainly used in the transport sector and 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). It is relevant to note that conversion efficiency (from feedstock to end-use product) is modest, from a little over 50% to around 10%. Note that this efficiency is measured with respect to the feedstock listed, which usually is a fraction of total biomass grown. Thus, space for better use of the feedstock and, mainly the total biomass produced, is remarkable. Solid biomass, mostly used for heat, power and heat&power has usually lower 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. It is important to note that some of the bioenergy systems are under demonstration for small scale application due cost barriers imposed by economy 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).

Table 2.3.6 describes the characteristics of the existing state of the art of some bioenergy systems. The table lists the major end-use, the technical process on which its operation is based, the fuel efficiency, and capital cost. Some brief explanations are added in the column “Comments”. It is important that all these systems are being used commercially but some of them are cost competitive for the particular activity listed in the row “Type of use”.

Table 2.3.5. Table summarizing the state of the art of the main chains for production of end use biofuels**.**

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Production Cost by 2006 (EU$/GJ)	Market potential +low/+++ high	Present deployment +low/+++high	References
Ethanol	Transport	Fermentation	Sugar cane syrup	Brazil	Eff. = 0.38 only ethanol production; Mill size, advanced power generation and optimised energy efficiency and distillation can reduce costs further in the longer term/surplus electricity, 50kWh/t of sugar cane	8 to 12*	+++	+++	*IEA Bioenergy: ExCo,2007
		Fermentation	Molasses	India					
				Colombia					
				Thailand					
				Brazil	Mill size, advanced power generation and optimised energy efficiency and distillation can reduce costs further in the longer term/surplus electricity, 50kWh/t of sugar cane	8 to 12*	+++	+++	
	Transport	Fermentation	Corn grain	USA	Eff. = 0.56 wet milling and 0.55 dry milling *	25**	++	+++	*UK DFT, 2009; **Hamelinck, 2004; *** Tao, Aden, 2009;****Bain, 2007
				USA	Dry mill only	16***-17****			
				China	Price includes subsidy	4.5RMB/kgEtOH			
	Transport	Fermentation	Sugar beet	EU	Eff. = 0.12 *	20 to30**	+	+	*UK DFT, 2009;**IEA Bioenergy: ExCo,2007
	Transport	Fermentation	Wheat	EU	Eff. = 0.53 to 0.59* ** ***	29***	+	+	*Reith, 2002;**IEA, 2002;***UK DFT, 2009
	Transport	Fermentation	Cassava	Thailand			+	+	
	Transport	Hydrolysis/Fermentation	Lignocellulosic	USA	Eff. = 0.47 for wood and 0.40 for straw; includes integrated electricity production of unprocessed components*	12 to 17** 14-16*** (TC-BC) 10-13****(TC-BC) 17.6 (BC)*****	+++	NA	*Reith, 2002;**IEA Bioenergy: ExCo,2007; *** Tao, Ling, 2009;;****Bain, 2007;*****NRC, 2009
			corn stover***	USA	TC=thermochemical; BC=biochemical				

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Production Cost by 2006 (EU$/GJ)	Market potential +low/+++ high	Present deployment +low/+++high	References
				OECD		18 to 39*	+++	NA	*Sims et al., 2008
Liquids from biomass	Transport	Fischer-Tropsh	Lignocellulosic	USA	Via biomass gasification and subsequent syngas processing	12 to 17*	+++	NA	*Sims et al., 2008
						21**			** NRC, 2009
				OECD		18 to 39*	+++	NA	*Sims et al., 2008
Biodiesel	Transport	Transesterification	Rape seed	Germany	Eff. = 29%. For the total system it is assumed that surpluses of straw are used for power production*	25 to 40**	+++	++	*CSIRO, 2000; **IEA Bioenergy: ExCo,2007
				France					
	Transport	Transesterification	Soya	Brazil		24 to 34*	+++	+	*Agrolink, 2009
				USA		18**			**Tao, Aden, 2009
	Transport	Transesterification	Oil palm	Indonesia			+++	++	
	Transport	Transesterification	Jatropha	Tanzania	Large uncertain in yield/lack of data: assuming seed yields of 2.5 and 1 t/ha/yr in semi arid and arid regions can be obtained. With oil content of seeds of 34% and oil extraction of 90%, oil yields ranges from 0.8 to 0.3 t/ha/yr in these regions*	5.5*	+++	NA	*Wicke et al., 2009
	Transport	Transesterification	Vegetable oil	109 countries	Based in total lipids exported costs was evaluated for 109 countries. Neglects few countries with high production cost*	5.52 to 23.8*	+++	++	*Johnston and Holloway, 2007
	Transport	Transesterification	Microalgae	USA Experiment	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. Assuming biomass contains 30% oil by weight, cost of biomass for providing a liter of oil would be $1.40 and $1.81, respectively. Oil recovered from the lower-cost biomass produced in photobioreactors costs $2.80/L.*. **Productivity =2.5 g/sqm/day; ***Productivity=10 g/aqm/day	80 or more* 140-180** 40-60***	+++	NA	*Chisti, 2007 *** Pienkos, Darzins, 2009
Renewable diesel	Transport	Hydrogenation	Soya	USA	LC Energy required 9.3 MJ/l assuming electricity efficiency conversion of 40%*	16**	+++	NA	*USEPA, 2008
									**Bain, 2007

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Production Cost by 2006 (EU$/GJ)	Market potential +low/+++ high	Present deployment +low/+++high	References
	Transport	Hydrogenation	Yellow grease	USA	LC Energy required 3.3 MJ/l assuming electricity efficiency conversion of 40%*	10**	+++	NA	*USEPA, 2008 **See note 2
	Transport	Hydrogenation	Rape seed	OECD		16*	+++	NA	*Hamelinck, 2004
Methanol	Transport	Gasification/Synthesis	Lignocellulosic	USA/EU	Combined fuel and power production possible	10 to 15*	+++	NA	*IEA Bioenergy: ExCo,2007
Butanol	Transport	Fermentation	Sugar/starch	USA		17.5*	+++	NA	* Tao, Aden, 2009
Liquid biofuels in general	Transport	Hydrolysis& Fermentation	Energy crops	EU	Price value calculated for the year 2000	12 to 16 *	+++	+++	*Hoogwijk, 2004
Hydrocarbons fuels (gasoline, diesel and jet fuel)	Transport	Biological synthesis from sugars or catalytic upgrading	Sugar, starch, or lignocellulosic	U.S. (and elsewhere)	Ongoing R&D with small pilots; insufficient public data for technoeconomic evaluation; dozens of companies developing intellectual property and starting commercialization*		+++	NA	NSF, 2008; DOE, 2009; Tang, Zhao, 2009; Biofuel Digest, 2008
briquettes	Electricity	Drying/Mechanical compression	Wood residues	EU/USA/ Canada	Large and continuously increasing co-combustion market	5.0*	+++	++	*Riegelhaupt et al., 2009
wood pellets	Heat	Drying/Mechanical compression	Wood residues	EU/USA/ Canada	Large and continuously increasing residential market	5.3*	+++	++	*Riegelhaupt et al., 2009
bagasse pellets	Heat	Drying/Mechanical compression	Sugar cane	Brazil	Large potential availability. No commercial use	3.1*	+++	NA	*Riegelhaupt et al., 2009
Solid biofuel	Electricity/Heat	Direct combustion	Forestry	EU		4*	+++	++	*Hoogwijk, 2004
	Heat (residential)	Pyrolysis	Wood	Developing countries	Use wood in large pieces or whole tree trunks. It is difficult to dry such large pieces before carbonising and the yield overall is lower but wood preparation costs are negligible*	2.1**	+++	+	*FAO, 2009; **Riegelhaupt et al., 2009
	Heat (industry)	Pyrolysis	Wood	Worldwide	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*	2.1**	+++	+	*FAO, 2009; **Riegelhaupt et al., 2009

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Production Cost by 2006 (EU$/GJ)	Market potential +low/+++ high	Present deployment +low/+++high	References
Fuelwood (small scale)	Heat (residential)	combustion	Fuelwood, biomass residues	Worldwide	Traditional devices are inefficient and generate indoor pollution. Improved cookstoves are available that reduce fuel use (up to 60%) and cut 70% indoor pollution	2.5*			See Note 1)
							´+++	+	
	Heat (small industries)	Combustion		Worldwide	Existing industries have low efficiency kilns that are also high polluting. Improved kilns are available that cut consumption in 50-60%	2.5*	´++	+	
Biomass gases									
(small scale)	Power & heat	Gasification	Wood residue	Worldwide	eff., 17%, India	2.5-3.5Rs/kWh	++	+	
		Gas engine	Agro residues		eff., 20%, Japan; Assumptions: 1) Biomass cost $3/GJ; Discount rate 10%; 2) Heat value $5/GJ.	7.5*			
									*IEA Energy, 2007
(large scale)	Power & heat	Gasification	Wood residue	Worldwide	IGCC; Assumptions: 1) Biomass cost $3/GJ; 2) Discount rate 10%	7 to 9*	+++	NA	
		Gas turbine	Agro residues						*IEA Energy, 2007
(large scale)	Synthetic diesel	Gasification	Wood residue	Worldwide		22	+++	NA	*Hamelinck, 2004
		Synthesis	Agro residues			21**			**NRC, 2009
Biogas									
Household biogas	Cooking, heat	Digestion	Manure	Worldwide	byproduct: liquid fertilizer		++	+	
			Human wastes		payback time	1-2 years			
Biogas (big scale)	Electricity	Digestion plus gas engine/ steam turbine	MSW	Worldwide	byproduct: liquid fertilizer		+++	+	
			Agro residues		eff., 15-20%				
			Industry waste		Widely applied for homogeneous wet organic waste streams and waste water*				*IEA Bioenergy: ExCo,2007
Biogas (medium scale)	transportation	Digestion plus gas clean up and compression	manures	US	By product credit not considered for fertilizers	14*	++	+	*Krich et al., 2005 Sustainable **Transportation Solutions, 2006
				UK	Developmental stage	13**			

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Production Cost by 2006 (EU$/GJ)	Market potential +low/+++ high	Present deployment +low/+++high	References
Biogas (small scale) includes landfill	Cooking, heat, electricity				Widely applied and, in general, part of waste treatment policies of many countries*		++	++	*IEA Bioenergy: ExCo,2007
					eff. 10-15%*				*IEA Bioenergy: ExCo,2007
Co-firing	Electricit y	Combustion	MSW	Worldwide	eff., ~40%				
			Wood residue		Assumptions: 1) Biomass cost $3/GJ; 2) Discount rate 10%; 3) eff. 35-40%	0.05 US$/kWh*			*IEA Energy, 2007
Biomass pyrolysis	Fuel	Pyrolysis	Wood residue	OECD	Demonstration stage*		++(+)	NA	*Bauen et al., 2004
			Agro residues	USA	Commercial for specialty, demo for fuels	5.5**			**Bain, 2007
Biomass for direct combustion	Power & heat	Combustion	Wood	Worldwide	Processes are in demonstration for small-scale applications between 10 kW and 1 MWe. Steam turbine based systems 1-10 MWe are widely deployed throughout the world. Efficiency of conversion to electricity in the range of 30-35%*	Ect5-15 /kWh. High costs small scale power gen. with high-quality feedstock. Low costs for large-scale (i.e., >100 MWth) state-of-art* ** ***	+++	+	*IEA Bioenergy: ExCo,2007
			Wood residues						*Egsgaard et al., 2009, **IEA Bioenergy: ExCo,2007, ***IEA Energy, 2007
			Briquettes						

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Production Cost by 2006 (EU$/GJ)	Market potential +low/+++ high	Present deployment +low/+++high	References
			Bagasse		Concentration of chloride and potassium salts. Straw contains a lot of these salts, which can cause corrosion and slagging problems. The need to make power plants from corrosion-resistant materials has increased the cost of energy from straw, at least in Denmark*	state-the-art combustion (wood, grasses) and co-combustion**	+++	NA	*Risø Energy, 2009
			Straw						
									**Egsgaard et al., 2009
	Power	Combustion	Several solid biomass	USA	Cost of electricity delivered to consumer in EU/GWh. Cost off biomass EU$ 2/GJ	19.8*	+++	++	*Electricity from Renewable, 2009
Hydrogen	Transpor t	Gasification/Syn gas processing	Several solid biomass	USA/EU	Combined fuel and power production possible	9 to 12*	+++	NA	*Hoogwijk, 2004
						10**			**Bain, 2007
Note 1) Costs are extremely variable (from 0 monetary costs when fuelwood is collected to 8 GJ or more when fuelwood is scarce)									
Note 2) http://www.eia.doe.gov/oiaf/analysispaper/biodiesel/pdf/tbl5.pdf corrected									

Table 2.3.6: Main characteristics of the existing state of the art Bioenergy Systems

Type	**Major end-use**	**Process**	**Type of use**	**Characteristics**	**Cost $US_{2005}$$**
Improved Cookstoves	Cooking	Combustion/ Gasification	Domestic/ Commercial	Fuel Efficiency 15-40%. New stoves with optimized combustion chambers and cookstoves that gasify fuelwood are being disseminated at large scale. Stoves may be massive, with chimney and multiple pans, or small and light-weight without a flue and single pot. Newest models serve also as water heaters for bath and produce electricity using the themo-electric effect.	5-100 US$/device
Gasifiers	Cooking /Power generation	Partial combustion of woody biomass, agro residues to generate producer gas	Community /Commercial	$CO + H_2$ low calorific producer gas can be used for thermal energy 80% and electrical energy 60% applications	0.5-0.8 million US$ / MW thermal 0.5- 0.8 million US$ / MW electrical
Steam Boilers	Heat	Cogeneration	Power for captive and grid requirements	High pressure boilers	0.5- 0.8 million US$ / MW electrical
BiogasPlant s	Cooking /Power generation /Lighting	Anaerobic Digestion /Biomethanation	Individual households /Commercial for decentralise d power generation	Digestor with an inlet and outlet and a unit for storage of Gas Can digest organic waste through the biological route to produce gas and manure Efficiency is 20%	200 US$ per M^3
Biodiesel/ Ethanol plants	Power Generation /Transport ation	SVO or transesterificatio n	Commercial and for grid interactive and decentralize d power production	Expellers, Transesterification plants	1 US$ per liter

2.4 Global and Regional Status of Market and Industry Development

2.4.1 Introduction

The status and development of biomass market are reviewed considering technologies, activities and products that are used regionally and in geographically widespread applications through international markets.

For local markets it is worth noting that the use of bioenergy technologies provides a simple, local and renewable solution for energy related to cooking, heating and lighting mainly in rural areas. However widespread, dissemination of these technologies may be limited by the purchasing power of the people and availability, as well as access to the biomass resource used. Lack of education, awareness and motivation are among the prime factors that obstruct regional penetration of such technologies. The extent to which they have currently penetrated into or are in use in rural areas and the limitations faced are described in the first part of this section.

For non-local biomass market barriers cover a larger area of issues and we will discuss them in section 2.5

2.4.2 Biogas Technology

Biogas systems are functional under a wide range of climatic conditions. Nonetheless, widespread acceptance and dissemination of biogas technology has not yet materialized in many countries.

A number of psychological, social, institutional, legal and economical factors present barriers that impair the development of energy from biogas.

Legal and Financial Barriers:

- lack of proper legal standards determining explicitly the programme and policy;
- insufficient economic mechanisms, in particular fiscal, to facilitate achieving the desirable profits related to the investment costs, installations and equipments;
- relatively high costs of technologies and of labour (e.g. geological investigations).

Information Barriers:

- lack of easily available information on projects feasible for technical applications;
- lack of easily accessible information on procedures for projects implementation and realisation, standard costs, economic, social and ecological benefits;
- lack of information on installations producers, suppliers and contractors
- lack of information on the certainty of the design and construction of scale anaerobic digestion systems
- limited application of knowledge gained from the operation of existing plants in the design of new plants
- lack of familiarity with biogas investments in the financial community

A number of countries have initiated biogas programmes - 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). Results have been mixed, especially in the early stages (TSU: empty bracket – reference missing?). Quality control and management problems have resulted in a large number of failures. Biogas experience in Africa has been on a far smaller scale and has been often disappointing at the household level (TSU: empty bracket – reference missing?). 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 with slurry has been more of an obstacle than expected. Possibilities are better where farming is done with more actively managed livestock and where dung supply is abundant - as in rearing feedlot-based livestock. (Hedon Household Network, 2006)

Experience of NGOs that are members of the Integrated Sustainable Energy and Ecological Development Association (INSEDA) for the last more than 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. Developing such partnerships would lead to establishing a global data base, measurement of GHGs, as well as closer follow-up and monitoring that ensures the longer term sustainability of such programmes. In order to realize the full potential, treating biogas programmes as an important tool for empowering rural population in general and rural women in particular, appropriate changes in funding and policy support for such programmes is required (VODO, 2001).

In order to promote dissemination of biogas technology at the grassroots communities four activities are important (Hedon Household Network, 2006):

Promotion. It should make potential users aware of the existing technology and raise interest in biogas. Awareness is the starting point for later investment decision, but does not necessarily lead to active interest (TSU: empty bracket – reference missing?).

Information and education. Potential users who are aware and have some interest in the technology need be able to obtain more information and properly evaluate the usefulness of implementation under their circumstances. The information activities should not be biased, should be available for all members of the households, need to be decentralized and could include farmers' seminars, orientation workshops, but also individual contacts between potential users and extension workers or service providers (TSU: empty bracket – reference missing?).

Personal persuasion by a credible personal contact is required to solidify the interest of potential users of the technology. Persuasion to illiterate and semi-literate people requires more time than with educated population.

Implementation is an individual or intra-family matter. The period between awareness and decision for adoption varies and depends on a number of factors including the economic and socio/cultural situation of the potential user. Economical and socio/cultural constraints influence the ultimate potential.

2.4.3 Improved Cookstove Technology

Reasons for success or failure of Improved Cookstoves Programs have been outlined in Table 2.4.1 below:

Table 2.4.1

Reasons for success	Reasons for Failure
Program targets region where traditional fuel and stove are purchased or fuel is hard to collect. People cook in environments where smoke causes health problems and is annoying. Market surveys are undertaken to assess potential market for improved stoves. Stoves are designed according to consumer preferences, including testing under actual use. Stoves are designed with assistance from local artisans. Local or scrap materials are used in production of the stove, making it relatively inexpensive. The production of the stove by artisans or manufacturers is not subsidized. Stove or critical components are mass-produced.	Program targets region where traditional fuel or stove are not purchased or fuel is easy to collect. People cook in the open, and smoke is not really a problem. Outside experts determine that improved stoves are required. Stove is designed as a technical package in the laboratory, ignoring customers' preferences Local artisans are told or even contracted to build stoves according to specifications. Imported materials are used in the production of the stove, making it expensive. The production of the stove by artisans or manufacturers is subsidized.

Similar to traditional stove.	Critical stove components are custom built.
The stove is easy to light and accepts different sized wood.	Dissimilar to traditional stove.
Power output of stove can be adjusted.	The stove is difficult to light and requires the use of small pieces of wood.
The government assists only in dissemination, technical advice, and quality control.	Power output cannot be easily controlled.
The stove saves fuel, time, and effort.	The government is involved in production.
	The stove does not live up to promised economy or convenience under real cooking conditions.
Donor or government support extended over at least 5 years and designed to build local institutions and develop local expertise.	Major achievements expected in less than 3 years, all analysis, planning, and management done by outsiders.
Monitoring and evaluation criteria and responsibilities chosen during planning stages according to specific goals of project.	Monitoring and evaluation needs are not planned and budgeted, or criteria are taken uncritically from other projects or not explicitly addressed.
Consumer payback of 1 to 3 months.	Consumer payback of more than 1 year

The World Bank and the Shell Foundation, and ARTI an NGO based in Pune have developed strategies to promote improved biomass based fuels and improved cooking devices through commercialisation mode. A programme, acceptable to all the stake-holders has been chalked out and no direct subsidy would be given either to the improved fuels nor to any of the cooking devices, but financial assistance would be made available for propaganda, users' training, manufacturers' training, market research, market development and promotion. (Arti Pune artiindia.org, quoted in Muller, 2007) TSU: If this is a direct quote, please mark it as one. Ideally rephrase/shorten it. . In the eastern Democratic Republic of Congo, stoves using briquette fuel manufactured from biomass wastes are being disseminated into urban as well as rural populations through a coordinated programme that is economically stabilised through NGO funding. The aim is to decrease unsustainable charcoal use that is causing illegal deforestation in biologically diverse national parks, particularly in Virunga National Park. The programme is transitioning from the NGO-guaranteed start-up phase to economic viability on the open market in competition with traditional charcoal (Virunga National Park, www.gorilla.cd).

2.4.4 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). These resources were matched to a range of energy needs that included cooking, mobility, productive uses and electricity for lighting and communication. 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 insulation is an option

- Longer term planning and regulation plays a crucial role for the success of small-scale bioenergy projects.
- Flexibility and diversity can also producer risk TSU: did you mean "produce risks" or "increases produces' risks"?
- Collaboration in the market chain is key at start up
- Long local market chains spread out the benefits
- Moving bioenergy resources up the energy ladder adds value
- 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

2.4.5 Overview of existing policies relevant for bioenergy

2.4.5.1 Global Bioenergy Partnership (GBEP) Overview

The purpose of the Global Bioenergy Partnership is to provide a mechanism for partners to organize, coordinate and implement targeted international research, development, demonstration and commercial activities related to production, delivery, conversion and use of biomass for energy, with a particular focus on developing countries. GBEP also provides a forum for implementing effective policy frameworks, identifying ways and means to support investments, and removing barriers to collaborative project development and implementation. The partnership builds in the three strategic pillars of energy security, food security and sustainable development, which demonstrates the interlinkage between these topics. It will undertake the GBEP Report (GBEP, 2007), which provides a platform for future GBEP's work towards the sustainable development of bioenergy, facilitate the sustainable development of bioenergy and collaboration on bioenergy field projects, and formulate a harmonized methodological framework on GHG emission reduction measurement from the use of biofuels for transportation and for the use of solid biomass while raising awareness and facilitating information exchange on bioenergy.

2.4.5.2 Policies that might promote bioenergy in the U.S. Research, development and demonstration

TSU: Not clear why U.S. is taken as example here. Either state reason for this ("representatice", "forerunner") or replace section with overview including/compare with other industrialized countries.

In developed countries such as the United States, there is a continued need for technology development to address issues such as contamination, improving efficiencies and reducing costs. There is also a need for more research on growing energy crops cheaply and with minimum of environmental impact.

Tax Credits

The last Energy Policy Act to be passed by Congress was in 1992 (Energy Policy Act, 1992). Section 45 of the Energy Policy Act of 1992 offers a 1.5 cent per kWh tax credit to wind power and "closed-loop biomass", which means only energy crops purchase the required biomass. Such a tax credit can be extended to include many more forms of biomass, which are cheaper than energy crops. The credit does not have to be restricted to biomass for power plants—it can include biomass for small industrial boilers and district energy operations. The tax credit allows bioenergy operators to compete with other industries that use biomass, so that a consistent, high quality supply of biomass is possible.

The US congress has been working on updating the Energy Policy Act for 2005 (Energy Policy Act, 2005) to include new incentives and support for the biomass industry. The proposed act as approved by the US senate June 28, 2005 would set an 8 billion gallon TSU: please use SI units renewable portfolio standard for ethanol by 2012 and supply $18 billion in tax breaks over the next 10 years.

Also, the National Security and Bioenergy Investment Act of 2005 would "expand research and development of biomass energy and biobased products, establish the position of Assistant Secretary of Agriculture for Energy and Biobased Products at the U.S. Department of Agriculture, and provide incentives to businesses producing biofuels." [1]

Finally, accelerated depreciation and investment tax credits can help catalyze new biomass CHP projects by making near-term economics more attractive to financiers.

Renewable fuels standard

The renewable fuels standard requires an increasing percentage of transportation fuel sold in the United States be biofuels. The policy features a credit trading system to allow refiners, blenders, and retailers to buy and sell credits from each other to meet their goals.

Renewable portfolio standard (RPS)

Biomass power plants can be included in renewable portfolio standards, which require a certain percentage of power within a state or the entire U.S. to come from renewables. The RPS also features a credit trading system similar to the renewable fuels standard. (Federal Bill, 2005)

2.4.5.3 Biofuel policies in selected Asian countries

In Asia, India has pioneered policies implementation in the renewable energy sector. The work started in 1974 with the establishment of the Fuel Policy Committee, proceeds with the creation of the Department of Non-conventional Energy Sources in 1982, creation of the Ministry of Non-conventional Energy Sources in 1992, and provided institutional and economic support to renewable through the Electricity Act (2003), National Electricity Policy (2005) and the National Tariff Policy (2006), which clearly set preferences and economic advantages to them (Singh, 2007).

Several others Asian countries have declared major policy initiatives so as to substitute petroleum products with a view to cut consumption reduce pollution and also avail CDM benefits (see Table 2.4.2). Some of these are tabulated below:

Table 2.4.2 Major Policy Initiatives in Asian Countries

Country	Blending rate	Major feedstocks	Strategy / Goal / Economic measures
India	E5	Jatropha, Sugarcane	Indian Biofuel National Strategy, 2008 / 20% biodiesel and bioethanol by 2017 / 11.2 mil ha of jatropha planted and matured by 2012 for the target blend of 20% / fixed prices for purchase by marketing companies.
China	E10	Corn, Cassava	Biofuel share 15% of transportation energy by 2020; incentives, subsidies and tax exemption for production
Malaysia	5%	Palm	National Biofuel Policy, 2006 / B5; Diesel : plans to subsidize prices for blended diesel
Indonesia	BDF : 10%		E5 Palm, Jatropha National Energy Program, B20 and E15 in 2025; Diesel : subsidies (at same level as fossil fuel)
Thailand	5%	Palm, Cassava	Biodiesel Development and Promotion Strategy Enforce national wide B2 in April, 2008 / B5 in 2011 / B10 in 2012; Ethanol : price incentives through tax exemptions
Philippines	BDF : 1%	Coconut	Biofuel Strategy 2006 / BDF mixing rate 1%, 2% by 2009 / Ethanol : 5% by 2009, 10% by 2011; tax exemption and priority in financing
Japan	E3, B5	Sugar, Waste oil	Plan to replace 500 ML / year of transport petrol with liquid biofuels by 2010; subsidies for production

Source: Romero J & Elder M, 2009

2.4.6 Barriers & Opportunities (institutional, regulatory issues, social, technological, economic/financial, etc.)

Bio-energy continues to play a significant share in global energy consumption. Bio-energy has often been associated with poor environment and health hazards but these attributes are not inherent to bio-energy but the consequence of under development, cultural factors and economic settings. Application of modern biomass systems supported by sustainable international trade could facilitate changes in biomass based employment in developing countries and contribute to their overall development. However, a fair trade concept and complete sustainability are still a big challenge. There are many issues which need to be resolved before biomass can take to the global markets. Some of the issues have been listed below.

2.4.6.1 Domestic production vs. import/export

Because biomass use is particularly favoured because of the desired effect of lowering GHG emissions, resources and chains should be favoured (and perhaps certified) that maximize GHG mitigation. This implies minimisation of energy inputs, but also optimization of the use of biomass, e.g., including comparison between indigenous use versus export. While many developing countries have a low energy consumption compared to developed countries, their energy demand is increasing rapidly. Hence there is need to assess the need within a country and its export.

2.4.6.2 Solving sustainability issues: International classification and certification of biomass

Certification of biomass may be one way to prevent negative environmental and social side-effects. By setting up minimum social and ecological standards, and tracing biomass from production to end-use, sustainability of biomass production can be ensured. In an exploratory study it has been shown that such social and environmental standards do not necessarily result in high additional costs (Smeets et al., 2005). However, when implementing a certification scheme for sustainable bio-energy, several other issues have to be dealt with. Firstly, criteria and indicators need to be designed/adopted according to the requirements of a region. Also, compliance with the criteria has to be controllable in practice, without incurring high additional costs. Second is avoidance of leakage effects (e.g. indirect land use emissions – see Section 2.5). Whether an independent international certification body for sustainable biomass is feasible should be investigated. Any certification scheme should on the one hand be thorough, comprehensive and reliable, but on the other also not become a barrier to markets in itself.

2.4.6.3 Setting up technical biomass standards

By setting up internationally accepted quality standards for specific biomass streams (e.g., Comité Européen de Normalisation, biofuel standards), biomass end users may have a higher confidence in using different biomass streams.

2.4.6.4 Lowering of trade barriers

Biofuels could help industrialized countries to promote reduction of carbon emissions but in some cases – as is the case of ethanol export to the US and the EU – exporting countries face trade barriers. Most of these barriers are established on the basis of technical reasons, but the aim can also be understood as a way to protect local producers whose production costs are much higher than those in developing countries. The solution pointed out by some analysts TSU: give reference here is to liberalize environmental goods and services (EGS) and to include biofuels as EGS. Building up structural international statistics (volumes and prices) on bio-energy trade is desirable, but has not been done so far.

2.4.6.5 Building up long-term sustainable international bio-energy trade

To achieve both growing markets and long-term sustainable biomass trade, a pragmatic approach is needed. It is desirable to focus first on routes with low barriers. A compromise should be found between developing certification efforts and ensuring sustainability of bio-energy and developing the market. While not all biomass types may fulfill the entire set of sustainability criteria initially, the emphasis should be on the continuous improvement of sustainability. For such an approach, public information dissemination and support is crucial (Lewandowski and Faaij, 2006). Sustainability may best be addressed by a sound certification framework, supported by international bodies. This is particularly relevant for markets that are highly dependent on consumer opinion, as is currently the case in Western Europe. It is even more important for the developing countries and rural regions to be aware of the opportunities and limitations for modern bio-energy in an international setting and to become involved in debate and collaboration for achieving sustainable development where it is most needed. The future vision for global bio-energy trade is that it develops over time into a real "commodity market". It is clear that on a global scale and over the longer term, large potential biomass production capacity can be found in developing countries and regions such as Latin America, Sub-Saharan Africa and Eastern Europe.

2.4.7 Emerging international bio-energy markets: Developments and perspectives

2.4.7.1 Trends and drivers

Trade flows are taking place between neighboring regions or countries, but trade is increasing also over long distances. Examples are export of ethanol from Brazil to Japan, the EU and the USA, palm kernel shells from Malaysia to the Netherlands, and wood pellets from Canada to Sweden. This is happening despite the greater bulk and lower calorific value of most biomass raw material. These trade flows offer multiple benefits for both exporting and importing countries but driving forces and rationales behind the development of trade in bio-energy are diverse. They can be structured as described below. (See also Hamelink et al., 2005a; Hamelink et al., 2005b; Junginger et al., 2005) In most cases the following factors appear in combination.

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.

2. *Market pull*. Import to the Netherlands is facilitated by the very suitable structure of the leading big utilities. This makes efficient transport and handling possible and leads to low fuel costs compared to those available to users in other countries where the conditions are less favourable.

3. *Utilizing the established logistics of existing trade.* Most of the bio-energy 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 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 has increased the strength of the driving forces and triggered an expansion of bio-energy 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. It seems obvious that institutions fostering general and free markets, e.g., CO_2 taxes on fossil fuels are more successful than specific and time-restricted support measures.

5. *Entrepreneurs and innovators.* In countries such as Austria and Sweden, individual entrepreneurs and innovators have had a leading role in the development of bio-energy trade. This has led to a more diversified pattern compared to that in, e.g., Finland, where bioenergy is handled by mature industries, especially within the forestry sector.

6. *Unexpected opportunities.* Storms, forest fires, insect attacks, etc., may lead to short-term imbalances in the supply. Technical failures and other reasons for shutdown cause disturbance in

the user and in distribution systems. Such short-term opportunities have often led to new trade patterns, some of which may remain even when the conditions return to normal. For example, last year's TSU: give year hurricanes in the eastern part of the USA led to a short-term trade in wood chips to Europe. For market parties such as utilities, companies providing transport fuels, and parties involved in biomass production and supply (such as forestry companies), good understanding, clear criteria and identification of promising possibilities and areas are of key interest. Investments in infrastructure and conversion capacity rely on minimization of risks of supply disruptions (in terms of volume, quality and price).

2.4.7.2 Barriers

On the basis of literature review and interviews, a number of potential barrier categories have been identified. Junginger et al. (2008) have listed the main barriers as follows

Economic barriers

Competition with fossil fuel on a direct production cost basis. High prices of bioenergy products cause a constraint on the supply side.

Due to the size, often small, of bio-energy markets and the fact that biomass by-products are a relatively new commodity in many countries, markets can be immature and unstable. This makes it difficult to sign long term, large-volume contracts, as doing so is seen as too risky. Also, with no harmonised support policy (e.g., on an EU level), new national incentives (and associated demand for bio-energy) may distort the market and shift supply to other countries within a short time-frame.

Technical barriers

Different types of biomass possess different physical and chemical properties making it difficult and expensive to transport and often unsuitable for direct use, say for co-firing with coal or natural gas power plants. Power producers are generally reluctant to experiment with new biomass streams, e.g., bagasse or rice husk.. While technology is available to deal with the fuels, it may take several years or even decades before the old capacity is replaced.

Logistical barriers

There is a lack of technically mature pre-treatment technologies for compacting biomass at low cost to facilitate transportation, although this is fortunately improving. Densification technology has improved significantly recently, e.g., for pellets, although this technology is only suitable for certain biomass types. In the case of the import of liquid biofuels (e.g., ethanol, vegetable oils, bio-diesel), this is not an issue, as the energy density of these biofuels is relatively high.

Various studies have shown that long-distance international transport by ship is feasible in terms of energy use and transportation costs (see below) but availability of suitable vessels and meteorological conditions (e.g., winter time in Scandinavia and Russia) need be considered.

Local transportation by truck (in both biomass exporting and importing countries) may be a high cost factor, which can influence the overall energy balance and total biomass costs. For example, in Brazil, new sugar cane plantations are being considered in the Centre- West, but the cost of transport and lack of infrastructure can be a serious constraint. Harbour and terminal suitability to handle large biomass streams can also hinder the import and export of biomass from and to certain regions.

International trade barriers

A lack of clear technical specifications for biomass (see above) and specific biomass import regulations. This can be a major hindrance to trading. For example, in the EU most residues that contain traces of starches are considered potential animal fodder and are thus subject to EU import levies. For example denaturised ethanol of 80 % concentration and above, the import levy is 102 Euro/m^3 (i.e., about 4.9 Euro/GJ) TSU: all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005. For conversion tables see http://www.ipcc-wg3.de/internal/srren/fod, representing substantial additional costs. It is important to bear in mind that some technical trade barriers can be, in fact, imposed to constrain imports and to protect local producers.

Transport tariffs. In recent years, general transport tariffs have increased quite significantly, e.g., transport for wood pellets to the Netherlands cost on average 1.75 Euro/GJ (on a total cost of 7-7.5 Euro) in 2004.

Possible contamination of imported biomass with pathogens or pests (e.g., insects, fungi) can be another important limiting factor in international trade. However, it is important to bear in mind that these limitations are not exclusive to bio-energy.

Land availability, deforestation and potential conflict with food production

Competition for land: while theoretically large areas of (abandoned/degraded) cropland are available for biomass cultivation, biomass production costs are generally higher due to lower yields and accessibility difficulties. Deforested areas may be easier as they may have more productive soil. Food security, i.e., production and access to food, would probably not be affected by large energy plantations if proper management and policies are put in place. However, in practice food availability is not the problem, but the lack of purchasing power of the poorer strata of the population.

In developed countries, a key issue is competition with fodder production. If there was a large increase in demand for energy, say of agricultural residues, scarcity of fodder products may occur, leading to a price increase.

Sustainability issues

Large-scale biomass-dedicated energy plantations also pose various ecological and environmental issues that cannot be ignored, including long-term monoculture sustainability, potential loss of biodiversity, soil erosion, freshwater use, nutrient leaching and pollution from chemicals. However, various studies have also shown that in general these problems are less serious when compared with similar plantations for food or fodder production.

Also linked to potential large-scale energy plantations are the social implications, e.g., the effect on the quality of employment (which may increase, or decrease, depending on the level of mechanization, local conditions, etc.), potential use of child labour, education and access to health care. However, such implications will reflect prevailing situations and would not necessarily be better or worse than for any other similar activity.

Methodological barriers – lack of clear international accounting rules

A lack of clear rules and standards for, e.g., allocation of GHG credits and the related issue of methodologies to be used to evaluate the avoided emissions, considering the fuel life-cycle (see also Schlamadinger et al., 2005).

Another issue is the indirect import of biomass for energy (processed biomass). Biomass trade can be considered a direct trade in fuel and indirect flow of raw materials that end up as fuels in energy production during or after the production process of the main product. For example, in Finland the biggest international biomass trade volume is indirect trade in round wood and wood chips. Round wood is used as raw material in timber or pulp production. Wood chips are raw material for pulp production. One of the waste products of the pulp and paper industry is black liquor, which is used for energy production.

Legal (national) barriers

Biomass for energy may be limited by international environmental laws. For example, in the Netherlands, four out of five major biomass power producers consider obtaining emission permits one of the major obstacles for further deployment of various biomass streams for electricity production. The main problem is that Dutch emission standards do not conform to EU emission standards. In several cases in 2003 and 2004, permits given by local authorities have been declared invalid by Dutch courts. TSU: reference missing

2.5 Environmental and Social Issues

Studies have over the past few years highlighted environmental and socio-economic issues associated with bioenergy, stressing both possible negative and positive effects. Negative effects relate to impacts already associated with the conventional agriculture and forestry systems (e.g., biodiversity losses, groundwater overexploitation and water contamination, eutrophication and soil degradation) and new types of impact specific for bioenergy including spread of alien invasive species, soil and vegetation degradation arising from overexploitation of forests and too intensive crop residue removal – and rising food commodity prices and displacement of farmers lacking legal land ownership due to increasing land use competition. Positive effects include 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 land slides 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 (JRC 2008, Farrell et al. 2006; Hill et al. 2006; Keeney and Muller 2006; Tilman et al. 2006; WWI 2006; Bringezu et al. 2007; Crutzen et al. 2007; Martinelli and Filoso 2007; Scharlemann and Laurence 2008; Donner and Kucharik 2008; Searchinger et al. 2008; Simpson et al. 2008; Gallagher 2008; Keeney 2009. Howarth 2009; The Royal Society 2008; Doornbosch and Steenblik 2007; von Blottnitz and Curran 2006; Rajagopal and Zilberman 2007; Rowe et al. 2008; Bird et al., 2010, Lattimore et al. 2009, Dimitriou et al. 2009, Andersson et al. 2002, Berndes et al. 2008).

In many instances, the analysis of the socio-economic and environmental implications of bioenergy has remained speculative, uncertain, and often controversial. Given the multitude of existing and rapidly evolving bioenergy sources, complexities of physical, chemical, and biological conversion processes, and variability in site specific environmental conditions, few universal conclusions can currently be drawn. Dominant factors determining merits and associated impacts are a function of the socio-economic and institutional situation where the feedstocks and bioenergy outputs are produced and utilized; types of lands used and feedstock type; the scale of bioenergy programs and production practice employed; conversion processes utilized including type of process energy used. It is also recognized that the rate of implementation matters (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).

2.5.1.1 Sustainability frameworks, standards and impact assessment tools

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; 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. International organizations and forums supporting the further development of sustainability criteria and methodological frameworks for assessing GHG mitigation benefits of bioenergy include IEA Bioenergy; Roundtable on Sustainable Biofuels (RSB); the G8 +5 Global Bioenergy Partnership (GBEP); International Bioenergy Platform at FAO (IBEP); OECD Roundtable on Sustainable Development; and also standardization organizations such as European Committee for Standardization (CEN) and the International Organization for Standardization (ISO).

Impact assessments (IAs) of bioenergy systems must be evaluated based on comparing with IAs for the energy systems they replace – usually these are fossil fuel based systems, but could also be based on other primary energy sources (Table 2.5.1). Methodologies for the assessments of environmental (Section 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 the socio-economic environment is difficult to quantify and is in general a very complex composite of numerous – directly or indirectly – interrelated factors where several are poorly understood. Further, social processes have feedbacks commonly difficult to clearly recognize and project with acceptable level of confidence. Environmental IAs may have the benefit of managing quantifiable impact categories to a higher degree but face challenges of uncertain quantification in many areas. Furthermore, the outcome of environmental IAs depends on choice of methodological approaches – 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	**Example 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 incl. psychological features	Family life styles; schools; hospitals; transportation; participation-alienation; stability-disruption; freedom of choice; involvement; frustrations; commitment; local/national pride-regret
Physical amenities incl. 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	health changes; medical standard
Cultural, religion, traditional belief	Values and value changes; taboos; heritage; religious and traditional rites
Technology	Hazards; emissions; congestion; safety
Political and legal	Authority and structure of decision making; administrative management; level and degree of involvement; resource allocation; local/minority interests; priorities; public policy

2.5.1.1.1 Environmental effects

Section 2.5.2 discusses mainly environmental impacts as reported from Life Cycle Assessments (LCA). The ISO 14040:2006 and 14044:2006 standards provide the principles, framework, requirements and guidelines for conducting an LCA study. LCA quantifies environmental effects in a more general manner than in relation to a specific bioenergy project. Basic methodology for the assessment of the effects of bioenergy systems compared to their substitutes corresponds to consequential LCA involving higher uncertainties than the conventional attributional LCA, and also auxiliary tools such as economic equilibrium or land-use models that might be needed to evaluate the consequences of bionenergy options. Complementary insights into the climate benefits can be obtained from energy system models – with or without linked land-use models – where the mitigation benefit is evaluated within 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 (see, 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 greenhouse gas balances of biomass and bioenergy systems has also been developed since the late 90s (Schlamadinger et al. 1997).

LCA results need to be further analyzed in the context of specific locations considering not only natural conditions but also industrial and institutional capacity. Water use is one such aspect: in some locations with scarce water availability production processes that consume large volumes of water can be problematic and in other locations with plenty of water this is less of an issue (Berndes 2002). Another example, effluent production, leads to very different impacts depending on how these effluents are managed on site. Technical solutions for managing effluents are available but may not be installed in regions with lax environmental regulations or limited law enforcement capacity. The major reduction in sugarcane ethanol plants' effluent discharge into rivers in Brazil is illustrative of the importance of institutions in determining the actual impacts of bioenergy projects (Peres et al., 2007).

Most assumptions and data used in LCA studies are so far primarily related to conditions and practices in Europe or USA, but studies are becoming available for other countries such as Brazil and China. Most studies have concerned biofuels for transport, especially those that are produced based on conventional food/feed crops. Prospective bioenergy options (e.g., lignocellulosic ethanol and options using the biomass gasification route) are less studied and their assessment via the LCA process involves projections of performance of developing technologies that can be at various stages of development and have greater uncertainties than commercial ones. Despite that studies commonly follow ISO standards a wide range of results has often been reported for the same fuel pathway, sometimes even when holding temporal and spatial considerations constant (Fava 2005). The ranges in results may, in some cases, be attributed to actual differences in the systems being modeled but are also due to differences in method interpretation, assumptions and data issues.

Key issues in bioenergy LCAs are system definition including the definition of both spatial and dynamic system boundary and the selection of allocation methods for energy and material flows over the system boundary. Disparities in the treatment of co-products have had major impacts on results of LCA studies and the handling of uncertainties and sensitivities related to the data for parameter sets used may have significant impact on the results (Kim and Dale 2002, Farrell et al. 2006, Larson 2006, von Blottnitz and Curran 2006, OECD 2008, Rowe et al. 2008, Börjesson 2009, Wang et al. 2009).

Many biofuel production processes produce several products and bioenergy systems can be part of biomass cascading cycles, where the biomass is first used for the production of biomaterials, while the co-products and biomaterial itself after its useful life are used for energy. This introduces significant data and methodological challenges, including also consideration of space and time aspects since the environmental effects can be distributed over several decades and occurs at different geographical locations (Mann and Spath 1997).

There are in addition gaps in scientific knowledge surrounding key variables, including N_2O emissions related to feedstock production (Ammann et al. 2007, Crutzen et al. 2008), non GHG-mediated climate impacts, and nutrient depletion and soil erosion due to too high rates of agricultural residue removal (Wilhem et al., 2007).

The influence of land use change (LUC) and associated biospheric carbon stock changes on the environmental (especially GHG) performance of bioenergy has received considerable attention recently (Fargione et al. 2008, Gibbs et al. 2008, Searchinger et al. 2008, Wise et al. 2009, Melillo et al. 2009), although has been subject to analyses for many years (DeLucchi 1991, Reinhardt 1991, Marland and Schlamadinger 1997, Schlamadinger et al. 2001). Marland's and Schlamadinger's (1997) and Schlamadinger's et al. (2001) studies clearly show the significance of LUC – and that the biospheric carbon stocks can both decrease and increase as a result of bioenergy initiatives – but further methodology development is needed to improve the confidence of quantifications made.

Also, empirical data on carbon flows linked to land use and LUC in different parts of the world is uncertain, the causal chains proposed to link specific bioenergy projects with specific land use changes taking place in distant locations – and being driven by a range of additional factors – are poorly understood. Critical aspects include the land use evolution as influenced by the combined food, feed, fiber and bioenergy demand, availability of new types of energy crops, new cropping patterns, and policies influencing the land use directly or indirectly, including possible instruments such as REDD. Additional uncertain factors influential on the outcomes include assumptions concerning drivers for technological development and productivity growth in agriculture (Gallagher 2008; Kim et al. 2009; Kløverpris et al. 2008a, b). Land use effects may also impact the earth system and climate via other processes: the emissions of black carbon aerosols due to the burning of biomass, and of precursors of tropospheric ozone (nitric oxide from soils and volatile organic compounds from plants), changes in surface albedo and in the water balance of soils and the hydrological fluxes. The magnitude and sign of these additional climatic forcings arising from bioenergy development has been little investigated yet, but it might be significant.

Finally, as noted above, bioenergy systems must be evaluated based on comparing their influence on impact categories with the influence of the energy systems they replace. The climate change mitigation benefit is determined by the net change in cumulative radiative forcing resulting from the replacement of another – commonly fossil – energy system. One difficulty experienced is that it has proven to be difficult to obtain comparable LCA data for the reference energy system replaced – ideally these LCA data should come from studies with consistent methodologies, scope, level of detail, and country representativeness. Reasons include:

- the impacts of bioenergy products are often characteristic of the agriculture sector and, by extension, are difficult to compare to other elements of the reference energy system i.e. oil and coal exploration, mining and refining, storage transportation and spills;
- there is an identified lack of updated LCA studies on fossil fuels assessing recent and emerging trends in extraction and use of oil, (microbial enhanced oil recovery, deep sea drilling, use of oil sands etc.) (see Fava 2005, von Blottnitz and Curran 2006 and OECD 2008); and,
- forward-looking analyses needs to consider that also the reference system can be changing

The reference energy system can also cause indirect emissions linked to LUC or other activities and these can be difficult to quantify. Examples include (i) surface mining of coal that destroys soils and eliminates existing vegetation leading to displacement or destruction of habitats and wildlife; (ii) oil and gas projects causing deforestation for access roads, drilling platforms, and pipelines; (iii) oil shale production where surface mining, processing and disposal requires extensive areas; (iv) oil sand production that requires removal of vegetation as well as the topsoil and subsurface layers atop the oil sands deposit. Indirect LUC can also arise from the easy access to previously remote primary forest provided by new roads and pipeline routes, causing increased logging, hunting, and deforestation from human settlement. A portion of military expenditures and associated GHG emissions are related to geopolitical considerations and energy security. Preliminary estimates for the case of U.S. military security associated with the acquisition of Middle Eastern petroleum indicate that this indirect source of emissions might be similar in size as the emissions usually linked to Middle Eastern petroleum (Liska and Perrin 2009).

2.5.1.1.2 Alternative indicators of net GHG effect of bioenergy

Different limiting resources may define the extent to which land management and biomass fuels can mitigate GHG emissions, and these require specific indicators (Table 2.5.2). Basic default in application of these measures is sustainable harvest of primary biomass. However, they do not explicitly value the temporal dimension of changes in biospheric carbon stocks: also sustainable biomass production systems can temporarily involve substantial decreases in biospheric carbon stocks, management of boreal forests being an illustrative example.

Ambitious climate targets such as the 2°C degree stabilization target which requires that global GHG emissions peak within a few decades, has lead the timing of net GHG emissions to become an important indicator for evaluation of bioenergy systems. In this context, upfront emissions arising from the conversion of land to bioenergy production has been subject to specific attention (e.g., Schlamadinger and Marland 1996, Fargione et al. 2008, Gibbs et al. 2008). A more complete LCA would deduct the carbon lost into the atmosphere due to land clearing and account for additional carbon added to a depleted soil over time with the bioenergy system. Near term performance needs to be balanced against long term performance (Section 2.5.2). Additional indicators such as cumulative radiative forcing have to a limited extent been used to describe the dynamic climate impacts of biomass and bioenergy (Kirkinen et al. 2009; O'Hare et al. 2009).

Table 2.5.2. Maximizing GHG emission reductions when biomass, demand for bioenergy, available land, or available funds for GHG mitigation are the limiting factor (Schlamadinger et al. 2005).

Case	Limitation	Relevant measure	Consequence
1	Available biomass (e.g. wastes)	GHG savings per tonne feedstock	▪ Favours most efficient use of biomass, even if at greater cost ▪ Allows external fossil inputs if they enhance biomass use efficiency ▪ Can compare between different outputs (electricity, heat, fuel) ▪ Ignores the variations in amount of biomass recovered when using different recovering systems (e.g., recovery of logging residues)
2	Demand for bio-energy (e.g. from policy targets for bio-energy or biofuels in terms of market share	GHG savings per unit output (electricity, heat, road-fuel)	▪ Favours biomass conversion processes with low GHG emissions, even if inefficient or costly ▪ Ignores the amount of biomass, land or money required ▪ Easy to distort ▪ Cannot compare between different outputs
3	Available land for biomass production	GHG savings by biomass production per ha of available land	▪ Biomass yield and conversion efficiency are paramount ▪ Greater GHG emissions from production (e.g., fertilizers) may be acceptable if that increases the biomass yield ▪ Costs not considered ▪ Can compare between different outputs (electricity, heat, fuel)
4	Available funds for GHG mitigation	GHG savings per €	▪ Will favour "close to economic" biomass options over more efficient but more expensive ones ▪ Can compare between different outputs (electricity, heat, fuel)

2.5.1.1.3 Socio-economic impacts

Analyzing the socio-economic impacts of bioenergy development is a daunting task, whether ex ante or ex post, since they depend on many exogenous factors and are affected by scale. The most commonly reported 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 current alternatives already on the market (fossil based), to judge the potential competitiveness. Possible externalities (environmental or societal) are seldom included in such cost/benefit analyses, since they are difficult to value (Costanza et al., 1997). However, policy instruments might already be in place to address these externalities, such as environmental regulations or emission-trading schemes. Bioenergy systems are most of the time 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 compensations 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, the negative externalities related to fossil energy pathways need to be assessed, with the above-mentioned difficulties in such valuation (Bickel and Friedrich, 2005).

Socio-economic impact studies are commonly used to evaluate the local, regional and/or national implications of implementing particular development decisions. Typically, these implications are measured in terms of economic indices, such as employment and financial gains, but in effect the analysis relates to a number of aspects, which include social, cultural, and environmental issues. A complication lies in the fact that these latter elements are not always tractable to quantitative analysis and, therefore, have been excluded from the majority of impact assessments in the past, even though at the local level they may be very significant. The varied nature of biomass and the many possible routes for converting the biomass resource to useful energy make this topic a complex subject, with many potential outcomes.

2.5.2 Environmental impacts

Production and use of bioenergy influences global warming through (i) emissions from the bioenergy chain including non-CO_2 GHG emissions and fossil CO_2 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 that e.g. reduce the snow cover albedo in the Arctic; and aerosol emissions associated with forests.

2.5.2.1 Climate change effects of modern bioenergy excluding the effects of land use change

The multitude of existing and 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 of large number of studies to produce generally valid quantification of the influence of bioenergy systems on climate. Review studies (e.g., IEA 2008, Menichetti and Otto 2009, Chum et al. submitted) reporting widely varying estimates of GHG emissions for biofuels are illustrative of this. Yet, some studies combining several LCA models and/or Monte Carlo analysis provide quantification with information about confidence for some bioenergy options (e.g., Soimakallio et al. 2009a, Hsu et al. submitted, Chum et al. submitted). Also, as showed in Section 2.5 maximization of GHG emission reductions is achieved differently depending on what factor is limiting for GHG mitigation (Table 2.5.2).

Biomass that substitutes for fossil fuels (especially coal) in heat and electricity generation (especially when replacing low efficiency fossil generation) in general provides larger and less costly GHG emissions reduction per unit of biomass than substituting biofuels for gasoline in transport (Figures 2.5.1) The major reasons for this are: (i) the lower conversion efficiency, compared to the fossil alternative, when biomass is processed into biofuels and used for transport; and (ii) the higher energy inputs in the production and conversion of biomass into biofuels for transport, especially when based on conventional arable crops.

Figure 2.5.1 shows net reductions in GHG emissions when biofuels replaces coal for power generation. Note that the low GHG reduction potential for the case of co-firing is due to that the share of biomass that can be co-fired currently is limited to typically 10%. On a per ton biomass basis, biomass co-firing with coal is among the best options for GHG reduction (also economically) since the biomass is converted at higher efficiency than in smaller dedicated biomass power plants ("Direct Fire" in Figure 2.5.1). The large size of the coal power plants also makes this option one of the more likely for combining biomass with CCS. The Landfil Gas option in Figure 2.5.1 is an example where systems definition is critical for the outcome; it looks much more attractive for the case where the alternative is that methane leaks into the atmosphere via uncontrolled anaerobic decomposition of landfill material, compared to the case where the methane collection technology is assumed to be installed and the alternative would be that the methane is used as vehicle fuel.

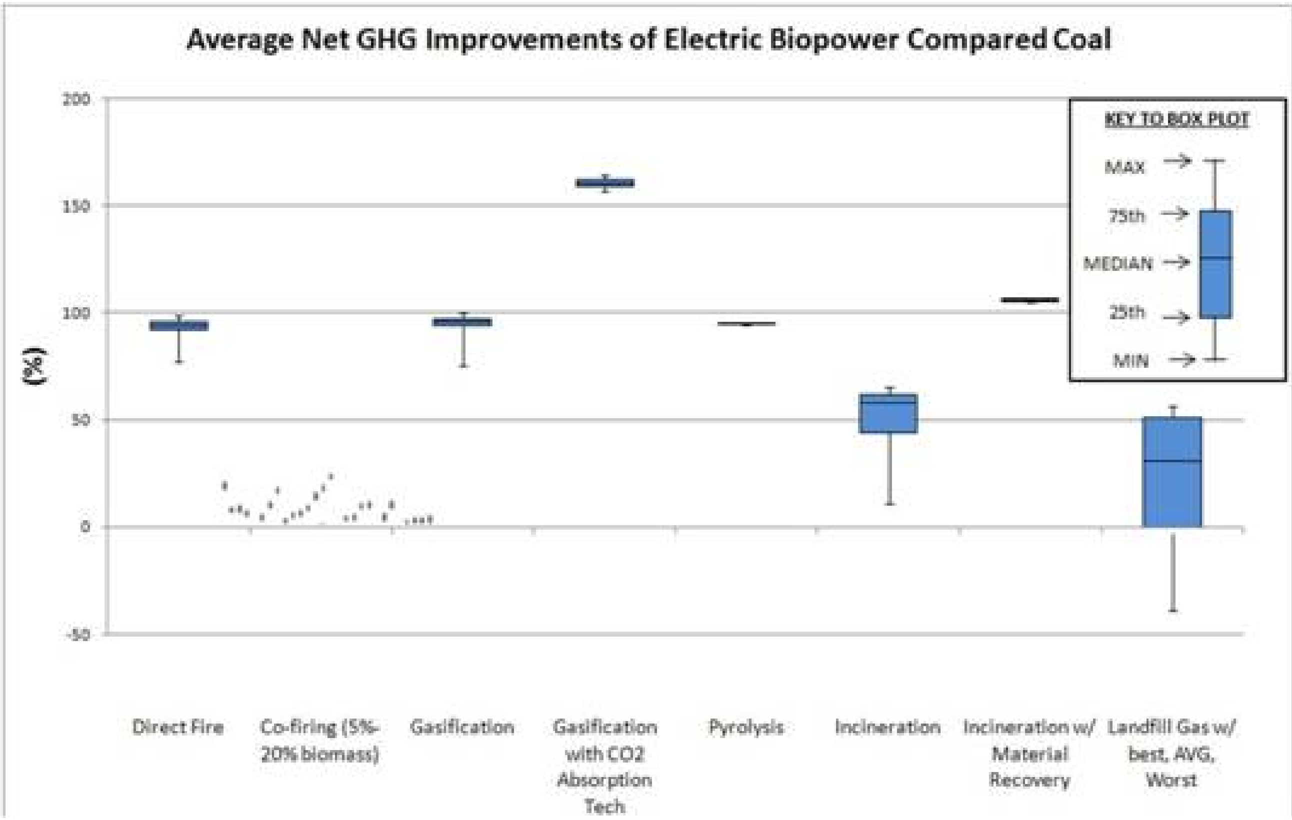


Figure 2.5.1. Net reductions in GHG emissions when biofuels replaces coal for power generation . Source: Warner and Heath, submitted TSU: readability needs improvement, align "reductions" in caption to "improvements" in graph for clarity.

Figure 2.5.2 shows the GHG emissions reduction, as a function of the net energy ratio, when ethanol from the two most common feedstocks maize and sugarcane replaces gasoline. A general tendency of increasing GHG reduction with increasing net energy ratio can be seen, but also that process fuel shifts can radically improve the GHG reduction with small improvements in net energy ratio. If coal is used in less efficient plants, the mitigation benefits might be completely lost, but if biomass (e.g., bagasse, straw, or wood chips) is used GHG emissions from the conversion can be very low. When evaluated using LCA such process fuel shifts can appear very attractive (Wang et al. 2007), but the marginal benefit of shifting to biomass depends on local economic circumstances and on how this biomass would otherwise be used. Also, the biofuel production can have relatively low emission reduction in proportion to the total volume of biomass consumed (feedstock + process fuel).

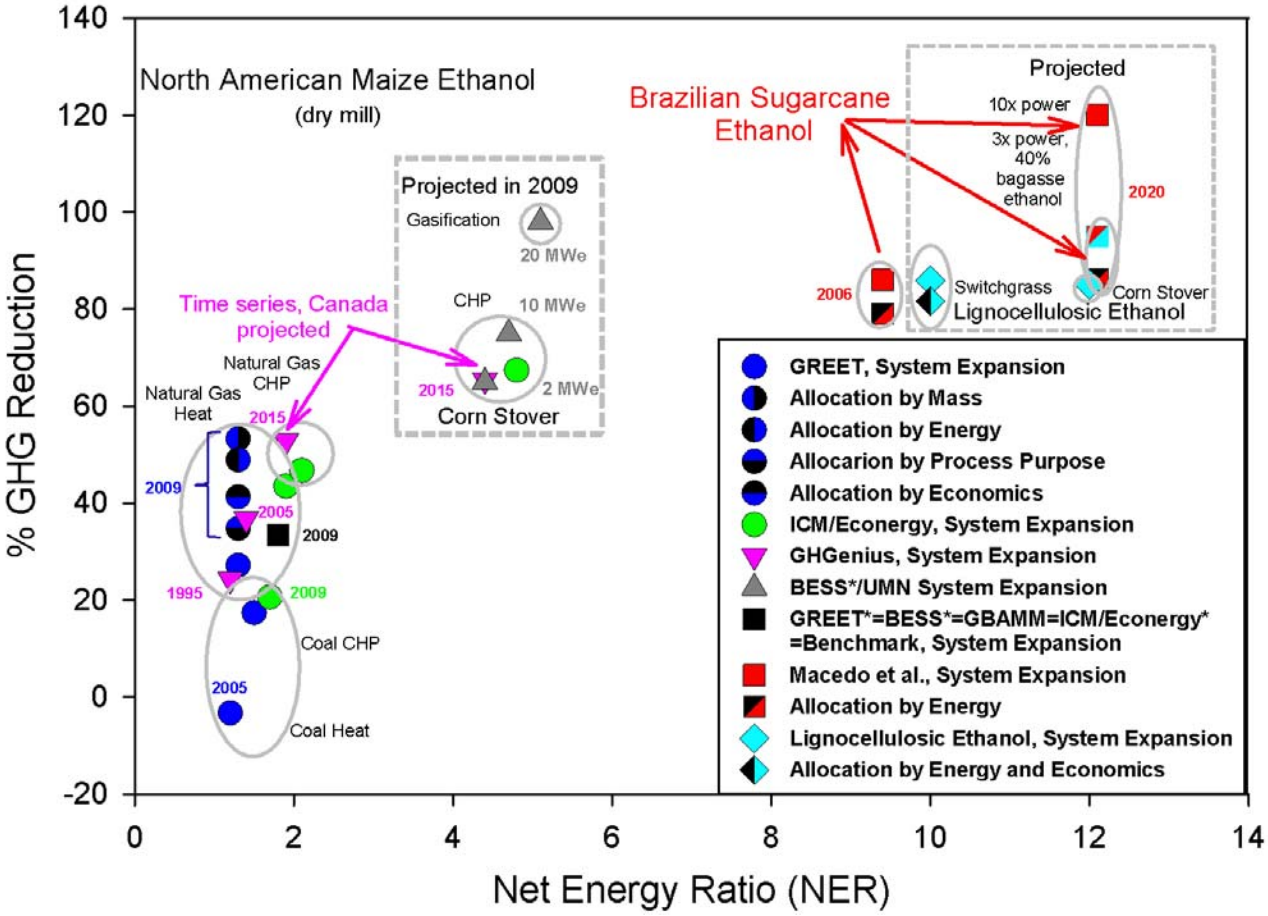


Figure 2.5.2. GHG reductions from gasoline emissions for ethanol production as a function of the net energy ratio (absent land use change) in Brazil,[a] Canada[b] and the U.S.[c] with specified co-product lifecycle assessment treatment and indicating methodological results' agreement for maize ethanold and projected values for lignocellulosic ethanol. TSU: (at least for TSU member editing this chapter:) figure not accessible, items in legend not enough explained.

[a] Red (■) points illustrate the Brazilian sugarcane ethanol industry average from mutual benchmarking (44 mills in 2006) and the 2020 projections for two scenarios of integrated biorefineries (cellulosic ethanol) or additional power production (Macedo et al. 2008). Hydrous ethanol is the product used in 2020 flex fuel vehicles in Brazil.

[b] Purple (▼) points show past and projected data for one dry grind Canadian mill (GHGenius version 3.13).

[c] Green (●) points at ~43% indicate modern maize ethanol production practices and efficient conversion that exists in the majority of natural gas mills in the U.S. Blue (●) points indicate primary energy (coal and natural gas) efficiency and process improvements with time for maize ethanol for the various process chains used in North America using GREET version 1.8c. Center dashed box gray (■), purple (▼), and green (●) points indicate biomass as a source of heat and power from various studies including projected integrated gasification combined cycle that coproduce electricity.

[d] Benchmark (■) point at 34% GHG reduction with net energy ratio of 1.4-1.6 results from three LCA models for natural gas-fired dry grind maize ethanol produced in the U.S. using the same input

data from the University of California, Berkeley, US, GREET-BESS Analysis Meta-Model, GBAMM-version 3. GREET= Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model version 1.8b; BESS= University of Nebraska, Lincoln, US, Biofuel Energy Systems Simulator version 2008.3.1; and ICM/Econergy is a commercial tool. Asterisk indicates meta-model conditions.

Sources: Chum et al. Submitted for publication and references therein; Macedo, I. C. and Seabra, J.E.A., 2008, Wang, M. et al., In press

The climate benefit of a given bioenergy systems can also vary significantly due to varying feedstock growing conditions and agronomic practices, conversion process configuration, differences in substitution effects of bioenergy and co-product use. As noted, methodologies for estimating nitrous oxide emissions from energy crops production are debated but it is clear that N2O emissions can have an important impact on the overall GHG balance of biofuels, though there are large uncertainties (Smeets, et al. 2008). The mitigation benefits can be significantly improved through minimization of nitrous oxide emissions by means of efficient fertilization strategies using nitrogen fertilizer produced in plants that have nitrous oxide gas cleaning.

2.5.2.2 Climate change effects of modern bioenergy including the effects of land use change

Conversion of natural ecosystems to biomass production systems (for food, fiber or fuel) and changes in land use (e.g., from food to fuel production) can lead to positive or negative changes in the biospheric carbon stocks. Establishment of bioenergy systems involves direct land use change (dLUC) but can also lead to indirect land use change (iLUC) if displacement of previous land use leads to LUC elsewhere. Biospheric carbon changes can also occur in the absence of LUC, such as when forest management is intensified – shorter rotations, forest residue removal, and fertilization – to increase biomass output, which at the same time can lead to smaller forest carbon stocks.

Conversion of dense forests into bioenergy plantations will likely lead to losses of biospheric carbon regardless of what type of bioenergy system becomes established. In worst case the CO_2 emissions can be much larger than the emissions displaced by bioenergy, one example being the palm oil plantations established on tropical peatlands (Hooijer et al. 2006) that in natural conditions have negligible CO_2 emissions and small methane emissions (Jauhiainen et al. 2005). Establishment of plantations requires drainage of the peatland, leading to rapid oxidation of the peat material causing annual CO_2 emissions between 70-100 Mg/ha (Hooijer et al. 2006).

In other situations, net effects of bioenergy-driven dLUC on biospheric carbon stocks varies: (i) if biofuel crops are grown on previous cropland land which has been taken out of production, soil carbon losses may be minimal; (ii) cultivating conventional crops such as cereals and oil seed crops on previous pastures or grasslands can lead to soil carbon losses, possibly mitigated under no-till management; (iii) similarly planting short or long rotation forestry on grasslands may result in soil carbon loss or gain, depending on the planting and management techniques used; (iv) if perennial grasses or short rotation woody crops are established on land with sparse vegetation and/or carbon depleted soils on degraded and marginal lands net gains of soil and aboveground carbon can be obtained. In this context, land application of bio-char produced via slow-pyrolysis offers an option where the carbon is sequestered in a more stable form and also improves the structure and fertility of soils (Laird et al. 2009).

IPCC provides default values that make it possible to consider effects of dLUC in LCA studies (IPCC 2006). Table 2.5.3 shows an example of biospheric carbon stock changes for specific cases of dLUC. However, it is preferable to use site specific data instead of general numbers for quantifying effects of dLUC in a specific case.

Table 2.5.3. Carbon stock changes for different land use changes (tC/ha). Based on (Bird et al. 2010)

To		Tropical			Temperate			Boreal	
From		Crop	Grass	Forest	Crop	Grass	Forest	Grass	Forest
Tropical	Crop		-11 to 22	35 to 351					
	Grass	-22 to -11		14 to 373					
	Forest	- 351 to - 35	-373 to -14						
Temperate	Crop					-11 to 25	34 to 730		
	Grass				-25 to 11		15 to 755		
	Forest				-730 to - 34	-755 to -15			
Boreal	Grass								11 to 138
	Forest							-138 to – 11	

Studies have shown that LUC emissions can substantially change the mitigation benefit of certain bioenergy projects. Recent studies have primarily concerned biofuels for transport (Fargione et al. 2008, JRC 2008, Gibbs et al. 2008, Searchinger et al. 2008, Wise et al. 2009, Melillo et al. 2009), but studies taking a broader view on bioenergy confirm the significance of LUC (e.g., Leemans 1996, Marland and Schlamadinger 1997, Pacca and Moreira, 2009). Figure 2.5.3 shows one example of recent quantifications of the cumulative GHG savings of expanded biofuel use for transport, including the impact of dLUC and iLUC. In this case, biofuels produced from cultivated lignocellulosic feedstocks contribute an increasing share of biofuel supply, which leads to improved cumulative GHG savings over time due to higher GHG savings from gasoline/diesel substitution and reduced LUC-GHG emissions. Figure 2.5.3 is illustrative of that LUC GHG emissions can impact net GHG savings especially on the near term while the relative importance LUC GHG emissions for cumulative net GHG savings decreases over time.

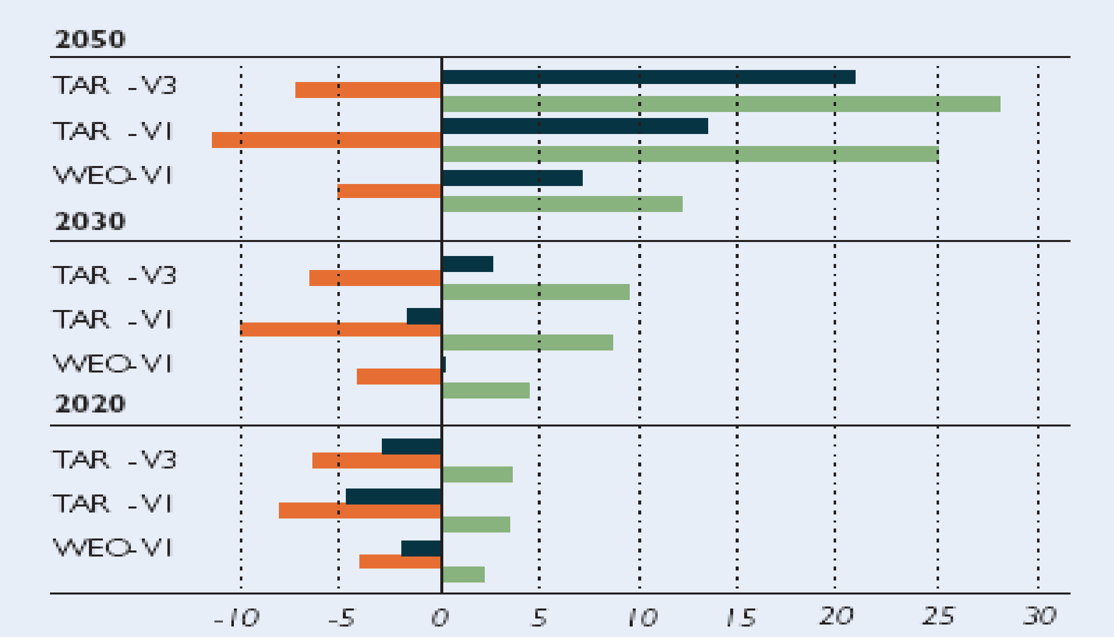


Figure 2.5.3. Cumulated net GHG savings of biofuel scenarios (Pg CO_2-eq). Green bars show the GHG savings from biofuel replacement of gasoline and diesel, orange bars show the GHG emissions caused by dLUC and iLUC, and blue bars show the net GHG balance. The share of biofuel use in total transport fuels is 3.5% in 2020 and rising to 6% in 2050. Percentage 2nd gen TSU: brief definition on biofuel generations should be given somewhere in text of total biofuels are (2020/2050): TAR-V3: 22/55; TAR-V1: 2/26; WEO-V1: 3/30. Source: Fischer et al. (2009) TSU: explanation of V1, V3 needed here

As discussed in Section 2.5.1, the quantifications of LUC effects reported so far involve a significant degree of uncertainty, especially for iLUC. The effects are complex and difficult to quantify in relation to a specific bioenergy project and the reference energy system substituted may also cause LUC. Cases much debated recent years include: (i) Brazilian sugarcane ethanol production (Sparovek et al. 2009; Zuurbier and van de Vooren 2008); (ii) Palm oil production (WWF 2007); (iii) biodiesel production from rape seed cultivated on the present cropland in Europe; (iv) the shift from soy to corn cultivation in response to increasing ethanol demand in the US, (Laurance 2007); (v) wheat based ethanol production in Europe.

Despite the substantial degree of uncertainty it can be concluded that if the expansion of biofuels production based on conventional food/feed crops results directly or indirectly in the loss of permanent grasslands and forests it is likely to have negative impacts on GHG emissions and for many biofuels it would take many years (decades to centuries) of production and use before a positive mitigation is reached. On the other hand, if biofuel and other relevant policies provide more stability and certainty in crop markets, promote improved land management, rural development and higher yields, and prevents far reaching deforestation for agriculture use (food/fiber/fuel), the LUC impacts could be substantially reduced or even contribute positively to GHG savings as bioenergy use expands.

2.5.2.3 Climate change effects of traditional bioenergy

The burning of biomass in open fires and stoves – commonly referred to as traditional bioenergy use – comprise the majority of global bioenergy uses at present. They are characterized by very low conversion efficiency compared, for instance, with their potential fossil fuel based competitors. Incomplete combustion of biomass also leads to significant emissions of short-lived GHGs such as carbon monoxide, methane and black carbon.

Consolidation of emission factors into broad fuel categories with traditional or improved stoves oversimplifies the wide range of fuel types, stove designs, cooking practices, and environmental conditions across the world. The vast majority of emission factor data comes from studies using controlled testing conditions, most commonly water boiling tests conducted in simulated kitchens. A handful of studies have been conducted in homes during normal stove use, with the available data suggesting controlled tests underestimate products of incomplete combustion from traditional stoves relative to normal stove use. In addition to emission factors, estimation of carbon offsets from improved fuels and/or stoves requires estimates of fuel consumption and the fraction of non-renewable biomass harvesting (fNRB). Local, field-based assessments provide the most robust estimation of CO_2-equivalent emissions as default emission factors and projections of fuel consumption based on laboratory testing have proved misleading (Johnson et al., 2008; Roden et al., 2009) and are not able to estimate uncertainty in the overall CO_2-eq estimate. Additionally, regional or national estimates of fNRB lack sufficient resolution to characterize fuelwood consumption for specific communities. Improved fuels and/or stoves and shifts from using non-renewable biomass (e.g., unsustainable forest biomass extraction) to using sustainably produced biomass can reduce the climate change effects of traditional bioenergy. Acknowledging the above described uncertainties, some indications of climate change mitigation in this area can be given. A recent study for instance showed that Patsari improved stoves in rural Mexico saved ~3.8 t CO_2-equivalent per year (Johnson et al., 2009). Studies indicate low costs for reducing GHG emissions in traditional bioenergy. For instance, a cost comparison using the carbon emission reduction (tC/kWh ot tC/GJ) between 10 bioenergy technologies substituting fossil fuel and traditional biomass alternatives concluded that out of the ten project case six have negative incremental costs (ICs) (negative ICs indicate that the suggested alternatives are cheaper than the original technologies) in the range of −37 to −688 \$ tC^{-1} and four have positive ICs in the range of 52–162 \$ tC^{-1} mitigation (Ravindranath et al., 2006)

2.5.3 Environmental impacts not related to climate change

Besides the impact on global warming, production, conversion, and use of biomass when transformed to various solid, liquid, and gaseous biofuels causes a wide range of both positive and negative impacts.

Much attention is presently directed to the possible negative consequences of land use change, such as biodiversity losses, greenhouse gas emissions and degradation of soils and water bodies, referring to well-documented effects of forest conversion and cropland expansion to uncultivated areas. However, the production of biomass for energy can generate additional benefits.

For instance, forest residue harvesting also has environmental or silvicultural benefits. It improves forest site conditions for replanting. Stump harvesting (as practised in Nordic Countries) reduces risk of devastating root rot attack on subsequent stands. Thinning generally improves the growth and productivity of the remaining stand. Removal of biomass from over dense stands can reduce wildfire risk. In agriculture, biomass can be cultivated in so-called multifunctional plantations that – through well chosen localization, design, management, and system integration – offer extra environmental services that, in turn, create added value for the systems.

Many such plantations provide water related services, such as vegetation filters for the treatment of nutrient bearing water such as wastewater from households, collected runoff water from farmlands and leachate from landfills. Plantations can also be located in the landscape and managed for capturing the nutrients in passing runoff water. Sewage sludge from treatment plants can also be used as fertilizer in vegetation filters. Plantations can be located and managed for limiting wind and water erosion, and will reduce the volume of sediment and nutrients transported into river systems. They may reduce shallow land slides and local ‘flash floods’.

Perennial crops can also help to reduce soil erosion, improve nutrient flows through the formation of an extensive root system that adds to the organic matter content of the soil and facilitates nutrient retention. Nutrient flow is a key issue for forest and agricultural production systems. When ploughed under or left on the field/forest, primary residues may recycle valuable nutrients to the soil and help prevent erosion, thus only a share may be available for extraction. Prevention of soil organic matter depletion and nutrient depletion are of importance to maintain site productivity for future crops.

2.5.3.1 Emissions to the air and resulting environmental impacts

Pollutant emissions to the air depend on combustion technology, fuel properties, combustion process conditions and emission reduction technologies installed. Comparing with fossil energy systems, SO_2 and NO_x emissions are in general low compared to coal and oil combustion in stationary applications. When biofuels replaces gasoline and diesel in the transport sector SO_2 emissions are reduced but the effect on NO_x emissions depends on substitution pattern and technology applied. The effects of ethanol and biodiesel replacing petrol depend on engine features. For instance, biodiesel has higher NO_x emissions than petroleum diesel in traditional direct-injection diesel

2.5.3.2 Impacts on water resources and quality

Bioenergy production can have both positive and negative effects on water resources. The impacts are also 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). The environmental impacts which result from the biofuel production stage 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.

Besides pollution impacts bioenergy systems can also impact water resource availability. For bioenergy systems that use cultivated feedstock most of the water needed is used in the production of the feedstock (Berndes 2002) where it is lost to the atmosphere in plant evapotranspiration (ET). The subsequent 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), but this 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).

Energy crop irrigation competes for water directly with other irrigation as well as with residential and industrial uses. But rainfed feedstock production can also compete for water by redirecting precipitation from runoff and groundwater recharge to energy crop ET and consequently reduce downstream water availability (Berndes 2008). The net effect of expanding rainfed production depends on which types of energy crops become dominating and also on which vegetation types become replaced by the energy crops. Compared to food crops, shrubs and pasture vegetation, bioenergy plantations can have higher productivity and higher transpiration and rainfall interception, particularly for evergreen species. Expanding such fast growing plantations on low-yielding cropland, shrublands or pastures will therefore often lead to increases in ET and reductions in downstream water availability, especially in drier areas (Jackson et al. 2005, Zomer et al. 2006). Establishment of energy crops that has lower ET than the previous vegetation may conversely lead to increased downstream water availability.

Rising water demand for food, growing freshwater scarcities in many world regions, and the risk that climate change will lead to an increased water stress, have lead to that many analysts see challenges in meeting future demands for the production of food, feed and bioenergy feedstocks (Alcamo et al., 2005, Bates et al., 2008, De Fraiture et al., 2008, Lobell et al., 2008, Lundqvist et al. 2007, Molden et al., 2007, Rosegrant et al., 2002, Varis, 2007, Vorosmarty et al., 2005). However, several regions in the world will not likely be constrained in their bioenergy production by scarce water availability (Berndes, 2002).

Under strategies that shift demand to alternative – mainly lignocellulosic – feedstock bioenergy expansion does not necessarily lead to increased water competition. Given that several types of energy crops are perennial leys 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. 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).

2.5.3.3 Biodiversity impacts

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 one of the major drivers 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. To the extent that bioenergy systems are based on conventional food and feed crops, biodiversity impacts due to pollution resulting from pesticide and nutrient loading can be an expected outcome of bioenergy expansion.

However, bioenergy expansion can also 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).

Besides the general function of contributing to a more varied landscape, 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).

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 landscape promotes more animal life in the area. This applies to cervids such as elk and roe deer, but also foxes, hares, and wild fowl like pheasants.

Properly located biomass plantations can also protect biodiversity by reducing the pressure on nearby natural forests. A study from Orissa showed that with the introduction of village plantations biomass consumption increased (as a consequence of increased availability) but at the same time, the pressure on the surrounding natural forests decreased (Köhling and Ostwald 2001).

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 in some OECD member countries begun to put pressure on areas designated for conservation (Steenblik, 2007). Similarly, the rising demand for palm oil has contributed to extensive deforestation in parts of South-East Asia (UNEP, 2008). In general, since biomass feedstocks can be produced most efficiently in tropical regions, there are strong economic incentives to replace tropical natural ecosystems – many of which host high biodiversity values – with energy crop plantations (Doornbosch and Steenblik, 2007).

Although biomass potential assessments commonly exclude nature conservation areas from being available for biomass production, biodiversity impacts still may arise in the real world. In the short term, impacts from existing agricultural and forest land for bioenergy are dominant. For example, the use of biomass from forests could reduce the quantity or quality of natural vegetation and availability of dead wood, and consequently biodiversity.

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.

2.5.3.4 Impacts on soil resources

Increased biofuel production, especially based on conventional annual crops, may result in higher rates of soil erosion, soil carbon oxidation and nutrient leaching owing to the increased need for tillage (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.

However, 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 particularly true where perennial species are used. 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).

2.5.3.5 Environmental health and safety implications

Dedicated energy crops have not been subject to the same breeding efforts as the major food crops. Selection of suitable crop 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 crops, and traditional plant breeding, selection and hybridization techniques are slow, particularly in woody crops but also in grasses. New biotechnological routes to produce both non-genetically modified (non-GM) and GM plants are possible. For example, it has been shown that down-regulation of the genes for lignin synthesis resulted in taller trees although the structure of the trees was somewhat altered.

GM energy crop species may be more acceptable to the public than GM food crops, but there are still concerns about the potential environmental impacts of such plants, including gene flow from non-native to native plant relatives. As a result, non-GM biotechnologies may remain particularly attractive. On the other hand, GMO food crops have already been widely accepted in many non-EU countries. Finally, it is important to note that, especially for restoration of degraded soils, bioenergy crops must be optimized, not maximized, as low input systems involve limited nutrients and chemical inputs.

2.5.3.5.1 Novel plants utilized for bioenergy production

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 interest today by seed companies and the ethanol industry 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 trigger the need for a pre-market assessment for 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.

2.5.3.5.2 Genetically modified bioenergy plants

As with any genetically modified or enhanced organism, the energy-designed crop may raise significant concerns related to cross-pollination, hybridisation, and other potential environmental impacts such as pest resistance and disruption of ecosystem functions (FAO, 2004).

2.5.3.5.3 Antimicrobial agents

During the fermentation process, antimicrobial agents (drugs or other chemicals) are routinely used to combat the growth of organic acid-producing bacteria that compete with yeast, competitively inhibiting ethanol production. Analysis of the fuel ethanol industry in North America shows that the antimicrobial agents that are currently used or are being considered for use in the production of fuel ethanol contain the following active ingredients either alone or in combination: ampicillin, monensin, penicillin, streptomycin, tylosin, and virginiamycin.

Veterinary drugs biological assessment capacity exists within the North American and European regulatory communities for assessing the potential impact that these antimicrobial agents present to animal and human health. Information about the antimicrobial agents, potential residual concentrations and exposure estimates, along with available literature and information provided by the ethanol industry respecting the breakdown of antimicrobial agents during ethanol production are routinely provided to government officials to conduct health risk assessment as required.

Results from this analysis within the Canadian context TSU: citation missing indicate that the use of ampicillin, penicillin, streptomycin, and virginiamycin, at the maximum inclusion rates indicated during the entire fermentation process should not result in detectable residues and, as such, are unlikely to pose adverse health risks to humans and food animals, or to contribute to the development of antimicrobial resistant bacteria.

Monitoring levels should be aligned with ingredient risks, manufacturing complexity, etc. Limits of detection (LODs) should be around 0.2 mg/kg (parts per million) in Canada and would be specific to the active ingredient. While validated antimicrobial-specific residue methods are not available, new detection methods are currently being developed and may be available shortly and we can build upon them to establish a sense as to where the rest of the global bioenergy community is moving in this regard. Further verification of the absence of residues will need to be considered when appropriate methods are available.

2.5.3.5.4 Alien invasive plant species

Non native species have wreaked havoc on biodiversity throughout the world via a number of processes that include: Facilitating native extinction; altering the composition of ecological communities; changing patterns of disturbances; and, altering ecosystem processes (Sala et al. 2009. see also Sax and Gaines 2008).

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). Similar warnings have also been raised with regard to species of Miscanthus and switchgrass (Panicum virgatum). Other biofuel crops such as Sorghum halepense (Johnson grass), Arundo donax (giant reed), Phalaris arundinacea (reed canary grass) are already known to be invasive in the United States.

Finally, a number of protocols have evolved that will allow for a more system assessment and evaluation of any inherent risk associated prior to the introduction of a new plant species into a host country environment.

2.5.4 Socio-economic impacts

2.5.4.1 Introduction

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, 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 turn out mostly positive depend to 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 created and economic gains-can clearly be identified as a significant driving force in the push for increasing the share of bioenergy in the total energy supply. Other “big issues” such as mitigating carbon emissions, ensuring wider environmental protection, and providing security of energy supply are an added bonus for local communities where the primary driving force is much more likely to be related to employment or job creation. Overall, these benefits will result in increased social cohesion and create greater social stability. For the public, policymakers and decision-makers, energy and bioenergy are becoming increasingly interesting and important subjects as a result of rises in the prices and more insecure supplies of fossil fuels.

On the other hand, substantial opposition has been raised against the large-scale deployment of bioenergy, particularly regarding projects aimed at producing liquid fuels out of first generation feedstocks, based on serious concerns about their 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

The use of sustainability indicators has been proposed as a way to better understand and assess the implications of bioenergy projects (Bauen et al., 2009a). Below we summarize the indicators proposed to address the socio-economic impacts of bioenergy.

2.5.4.2 Socio-economic sustainability criteria for bioenergy systems

Socio-economic impact studies are commonly used to evaluate the local, regional and/or national implications of implementing particular development decisions. Typically, these implications are measured in terms of economic indices, such as employment and financial gains, but in effect the analysis relates to a number of aspects, which include social, cultural, and environmental issues. A complication lies in the fact that these latter elements are not always tractable to quantitative analysis and, therefore, have been excluded from the majority of impact assessments in the past, even though at the local level they may be very significant. The varied nature of biomass and the many possible routes for converting the biomass resource to useful energy make this topic a complex subject, with many potential outcomes .

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). These criteria relate to:

- Human rights, including gender issues;

- Working and wage conditions, including health and safety issues;

- Local food security, and

-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
Land-use competition and food security	Emerging local and macroeconomic competition with other land uses; Reduced access to food
Land tenure	Changing patterns of land ownership and access to common resources; Impacts on poorest farmers

In what follows we review the main socio-economic impacts of bioenergy by main applications, separating them into three broad categories: Heat production, electricity production and production of liquid fuels. As a lot of the impacts are local in nature, we use selected case studies to illustrate the discussion.

2.5.4.3 Socio economic impacts of small scale systems from heat and electricity production

2.5.4.3.1 Rural industries

The small and rural industries sector is a very important component of developing countries' economies. Millions of people depend on these industries for the provision of their daily livelihoods. A large number of small and rural industries use biomass as main source of fuel to meet their thermal energy requirements such as water heating, steam generation and residential heating. There is significant potential to improve energy efficiency in these biomass-consuming industries as well as replacing the present fossil fuel consumption for thermal applications in many small and rural scale industries (FAO, 2005c). In addition to saving of fuel the other benefit that accrued were increase in productivity, better quality of products, saving in labour, water and improvement in the working condition

2.5.4.3.2 Improved cookstoves

In addition to its environmental impacts, the inefficient use of biomass in traditional devices such as open fires leads to significant social and economic impacts in terms of: The drudgery for getting the fuel, the monetary cost of satisfying cooking needs, gender issues, and significant health impacts associated to very high levels of indoor air pollution, which affects in particular women and children during cooking (Romieu et al. 2009; Masera et al. 1997; Bruce et al. 2006).

Recent research on health problems associated to traditional biomass use for cooking in households shows that 4 billion people suffer from continuous exposure to some via the process of cooking food over open wood burning fires most probably, significantly exacerbate ongoing disease processes (Pimentel et al., 2001). Human health effects from wood-smoke exposure have contributed towards an increased burden of respiratory symptoms and problems, further, it has been shown that females in these kinds of environments are particularly affected probably as a result of higher exposure to wood-smoke-polluted indoor air (Boman et al., 2006; Mishra et al. 2004; Schei et al. 2004, Thorn 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). In households with limited ventilation (as is common in many developing countries), 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). The burden for these deceases has been estimated in 1.6 million excess deaths/year - including 900,000 children under five - and the loss of 38.6 millions DALY/yr (Smith and Haigler, 2008) TSU: should be defined. This is similar in magnitude to the burden of disease from malaria and tuberculosis (Ezzati et al., 2002).

The new generation of improved cookstoves (ICS) and dissemination programs have shown that properly designed and implemented ICS projects can lead to improved health (Ezzati et al., 2004). ICS projects compare well with interventions in other major diseases (von Schirnding et al., 2001). Figure 2.5.4 shows high and low estimates of cost effectiveness, measured in dollars per Disability Adjusted Life Year (DALY), for treatment options related to eight major risk factors accounting for 40 percent of the global burden of disease (DCPP, 2006). Evidence from selected case studies around the world document the large socio-economic and health benefits of ICS programs in terms of a very significant reducing indoor air pollution, human exposure and reduction in respiratory and other illnesses (Armendariz et al. 2008; Romieu et al., 2009,)

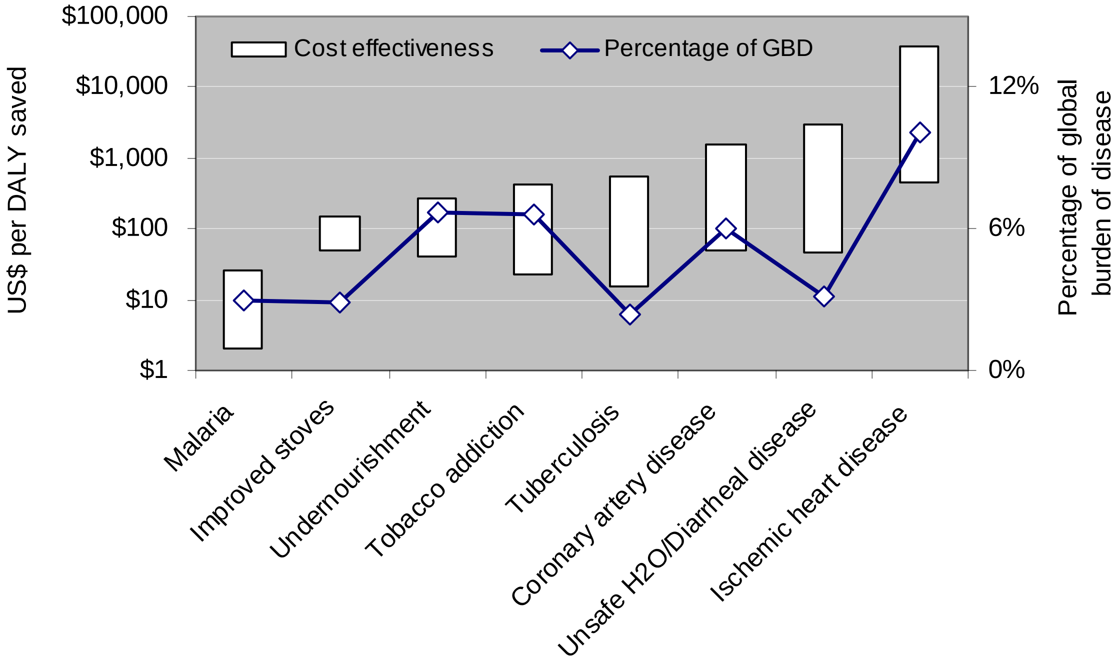


Figure 2.5.4.: Cost effectiveness of interventions in US$ per DALY avoided (DCPP, 2006) and percentage contributions to the global burden of disease from eight major risk factors and diseases. Note the left-hand vertical axis uses a logarithmic scale. Adapted from Bailis et al. 2009. TSU: GBD = global burden of disease; remove linking the GDBs with a like as x-axis is not continuous

Overall cost-effectiveness of ICS programs has been estimated for a series of case studies in Africa, Asia and Latin America. In China, the B/C TSU: define! for a switch from household use of coal for cooking in rural China to use of advanced biomass gasifier stoves that achieve dramatically lower emissions of health-damaging and methane emissions through better combustion efficiency and a cleaner fuel source, crop residues, as well as lower CO_2 emissions (because a nonrenewable fuel, coal, is replaced by crop residues, which are by definition renewable) has been estimated of 6 to 1 with a net benefit of US$ 300/stove (Smith and Haigler, 2008) TSU: maske sure that US$ 2005, see comment on first page. In Malawi, institutional ICS achieved a B/C of 5.6 to 1, while in Uganda the value was 20 to 1 when including local and global co-benefits. In Mexico, a comprehensive study with local measurements of health, social, local and global environmental costs and benefits, showed a B/C ratio of 13 to 1 from the dissemination of Wood burning ICS (Frapolli et al. 2009).

The savings in cooking time has facilitated use of this time for leisure, economic and social activities. Adoption of cookstoves has also been shown to foster other improvements in kitchens and homes leading to improving local living conditions (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).

2.5.4.3.3 Biogas plants

Small-scale biogas plants for household use (either for heat or for electricity generation) have also shown large social and economic benefits including the reduction in time and energy spent by women and children in collecting firewood for cooking, better sanitation to rural households, more employment for skilled people in the construction, maintenance, marketing, and financing of biogas plants. The use of biogas means negligible smoke, hence better family health. Moreover, the residual biological slurry from the biogas plants can be used as superior organic fertilizers to enhance agricultural yields . In the case of electricity villagers benefit from improved household lighting and also for street lighting, school, Panchayat Ghar, and shops. Efforts towards operating these systems sustainably include capacity building and handholding of Village Energy Committees.

2.5.4.3.4 Small Scale Electrification Using liquid biofuels

Decentralized small-scale biofuel production and application has the potential for being a major catalyst for rural development and addressing poverty, which in turn would have benefits in terms of improved livelihoods and quality of lives for the vast majority of the rural households deprived of energy service. Several success cases have been documented worldwide (Practical Action Consulting 2009)

2.5.4.3.5 Socio-economic impacts of large-scale bioenergy systems

TSU: entire section missing!

2.5.4.3.6 Bioenergy systems for heat and electricity production

Large scale systems for heat and electricity generation pose several socio-economic questions, and sustainably implemented can result in very significant benefits in terms of regional economic development, income generation and improved livelihoods, particularly in poorest regions.

As biomass is land-intensive, issues about land-use competition, in this case regarding the use of forests for fiber vs. fuel (or fuel for local needs such as cooking vs. industrial needs) may arise with an increased expansion of forest plantations for bioenergy purposes or with the increased use of native forests for these purposes. A common problem with timber plantations has been the expulsion of indigenous communities (e.g. Indonesia) from their lands. Properly managed, however, forests may sustain many services including timber, fuel and environmental services, with large gains for local populations, as is shown in many cases from developing and industrialized countries.

2.5.4.3.7 Bioenergy systems for liquid biofuels

The planned large-scale expansion of feedstocks needed for the production of liquid biofuels has sparkled a heated controversy around potential associated socio-economic issues such as: impacts on food security, land tenure, the number and type of jobs to be generated and other issues.

2.5.4.3.7.1 Risks to food security

If the food requirements of the world's growing Population are to be met, global food production will need to increase by around 50% by 2030. FAO estimates that the amount of land used for agriculture will need to be increased by 13 per cent by 2030. It is therefore likely that there will be a significant increase in competition for the use of agricultural land and, consequently, a trend towards rising food prices (FAO, 2008b). At the country level, higher commodity 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 food import bills.

Furthermore, a significant increase in the cultivation of energy crops implies a close coupling of the markets for energy and food. As a result, food prices will in future be linked to the dynamics of the energy markets. Political crises that impact on the 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 and these risks must be taken into account by policy-makers (WBGU, 2009).

Economic aspects of sustainability are also particularly important for poorer countries. Many developing countries hope that bioenergy will bring development opportunities – perhaps by tackling rural poverty directly, by reducing dependence on imports of fossil fuels or by increasing energy supply security. They also perceive opportunities in relation to the export of modern energy, which can further a country's economic development. Another crucial issue is whether an expansion of the bioenergy sector is economically sustainable in the sense of being able to continue operations in the long term even without subsidies; if ongoing subsidy of the sector is required, funds will no longer be available for projects of greater social and economic promise.

2.5.4.3.7.2 Impacts on Rural and Social Development

A major study of FAO on the socio-economic impacts of the expansion of liquid biofuels (FAO, 2008b) indicates that in the short run, higher agricultural commodity prices will have widespread negative effects on household food security. Particularly at risk are poor urban consumers and poor net food buyers in rural areas, who tend also to be the majority of the rural poor. There is a strong need for establishing appropriate safety nets to ensure access to food by the poor and vulnerable.

In the longer run, 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.

It is key to focusing on agriculture as an engine of growth for poverty alleviation. This requires strong government commitment to enhancing agricultural productivity, for which public investments are crucial. Support must focus particularly on enabling poor small producers to expand their production and gain access to markets.

2.5.4.3.7.3 Impacts on Income-generation

Production of biofuel feedstocks may offer income-generating opportunities for farmers in developing countries. Experience shows that cash-crop production for markets does not necessarily come at the expense of food crops and that it may contribute to improving food security. Promoting smallholder participation in biofuel crop production requires active government policies and support. Crucial areas are investment in public goods (infrastructure, research extension, etc.), rural finance, market information, market institutions and legal systems (FAO, 2008b).

2.5.4.3.7.4 Impacts on Land tenure

In many cases, private investors will look to the establishment of biofuel plantations to ensure security of supply. Contract farming may offer a means of ensuring smallholder participation in biofuel crop production, but its success will depend on an enabling policy and legal environment.

Development of biofuel feedstock production 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.

Governments need to establish clear criteria for clearly determining the “productive use” of land and legal definitions of marginal land. Effective application of land-tenure policies that aim to protect vulnerable communities is no less important (FAO, 2008b).

2.5.5 Synthesis

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 (see Figure 2.5.5). Bioenergy projects need to account for these interactions to maximize benefits while avoiding or mitigating risks. Climate benefits may also require trade-offs that involve diminished benefits in the short term in exchange for larger benefits in the long term.

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.

Meanwhile, legitimate concerns exist because conversion of additional land can lead to significant emissions in the near term that can take decades to recuperate. It has been impossible to assess whether new land conversion (and associated anthropogenic fires) will increase or decrease in response to bioenergy policies, and the outcome hinges greatly on how those policies affect the underlying drivers of LUC in a given locale. Bioenergy and other policies affecting land-use need to be considered in unison so that they are mutually reinforcing and create incentives that reduce pressure on high-value ecosystems.

Environmental concerns over biofuels are substantially addressed by the UNFCC definition of "renewable biomass," which requires production to comply with national laws and regulations and to originate from areas where "sustainable management practices… ensure … that the level of carbon stocks on these land areas does not systematically decrease over time" TSU: reference missing!

However, compliance with the "renewable biomass" definition and other guidelines requires investments to develop sustainable management plans and monitor their implementation. These investments provide social and environmental dividends, but the additional costs must be compensated through higher returns or other incentives. Otherwise, "renewable biomass" will not be able to compete with less sustainable land uses.

Human welfare, bioenergy and the environment have been intimately entwined since the dawn of society. Yet, our ability to analyze the environmental and social dimensions of global bioenergy development is limited due to gaps in data and knowledge related to the complex and diverse interrelationships among human behavior, land use and climate. There is consensus, however, on the importance of developing more reliable and detailed data and scientific approaches to facilitate due diligence when designing policies and projects related to biofuels, as well as on the need to develop effective incentives for more sustainable land use in all sectors.

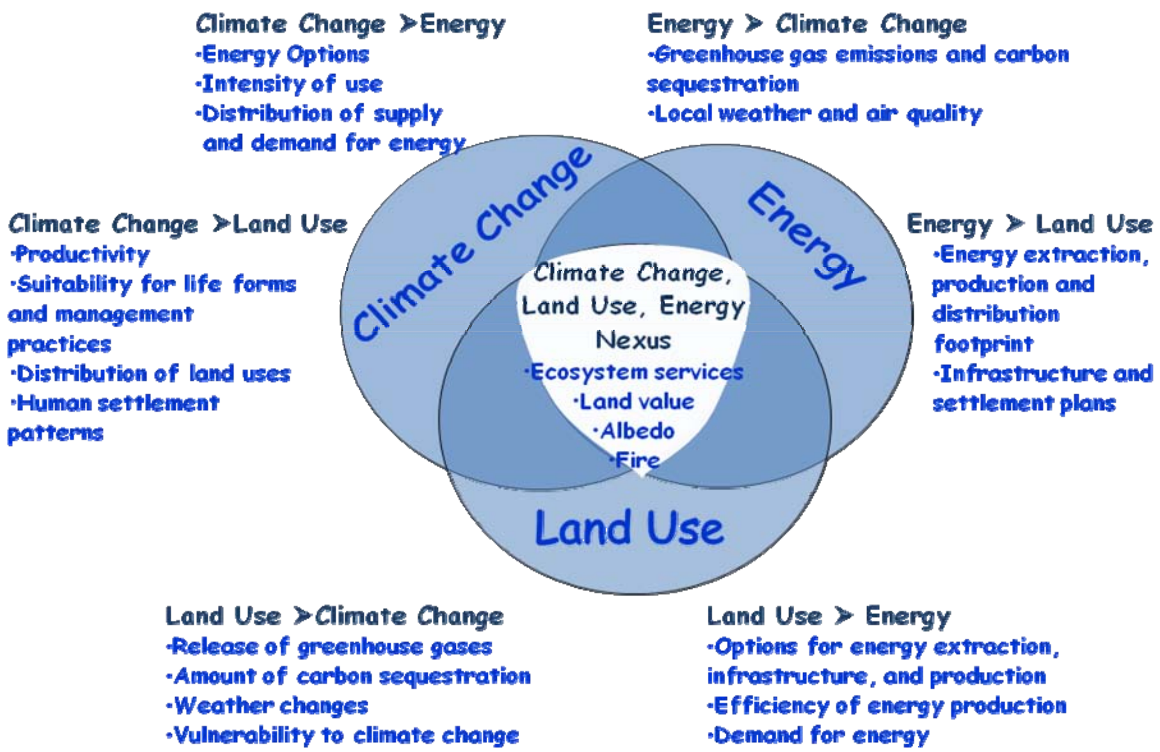


Figure 2.5.5.: Climate Change-Land Use-Energy Nexus. From Dale et al., submitted

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 (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. 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 (Figure 2.6.1). 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.

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	0.8	20%	Breeding, GMOs, irrigation inputs	2,3
SR Willow	Temperate	-	50%	Breeding	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); CO_2 fertilization	4
PRIMARY RESIDUES					
Cereal straw	World	-	15%	Improved collection equipment; breeding for higher residue-to-grain ratios.	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;

These increases reflect present knowledge and technology (Fischer, 2001b: Duvick and Cassman, 1999), and vary across the regions of the world (Figure 2.6.1), 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, e.g. limitations in water availability. 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 they have not been developed considering their characteristics as potential feedstocks for biofuel production. Varieties could be selected with increased biomass per hectare, increased yields of oils (biodiesel crops) or fermentable sugars (bioethanol crops) or with improvements in characteristics relevant for their conversion to biofuels. As little genetic selection has been carried out in the past for biofuel characteristics in most of these species, considerable genetic improvement should be possible (FAO, 2008d). Doubling the current yields of perennial grasses appears achievable through genetic manipulation (Turhollow 1994, Wright 1994, McLaughlin et al., 2002), possibly within 25 years timeframe (USDOE, 2002). Aggressive shifts to sustainable farming practices and large improvements in crop and residue yield could increase residue outputs from arable crops (Paustian et al., 2006). For example, the combination of no-till practices and continuous production of corn (rather than rotation of corn and soybean) is the scenario under which farmers in Iowa could collect the most residues (Sheehan et al. 2002).

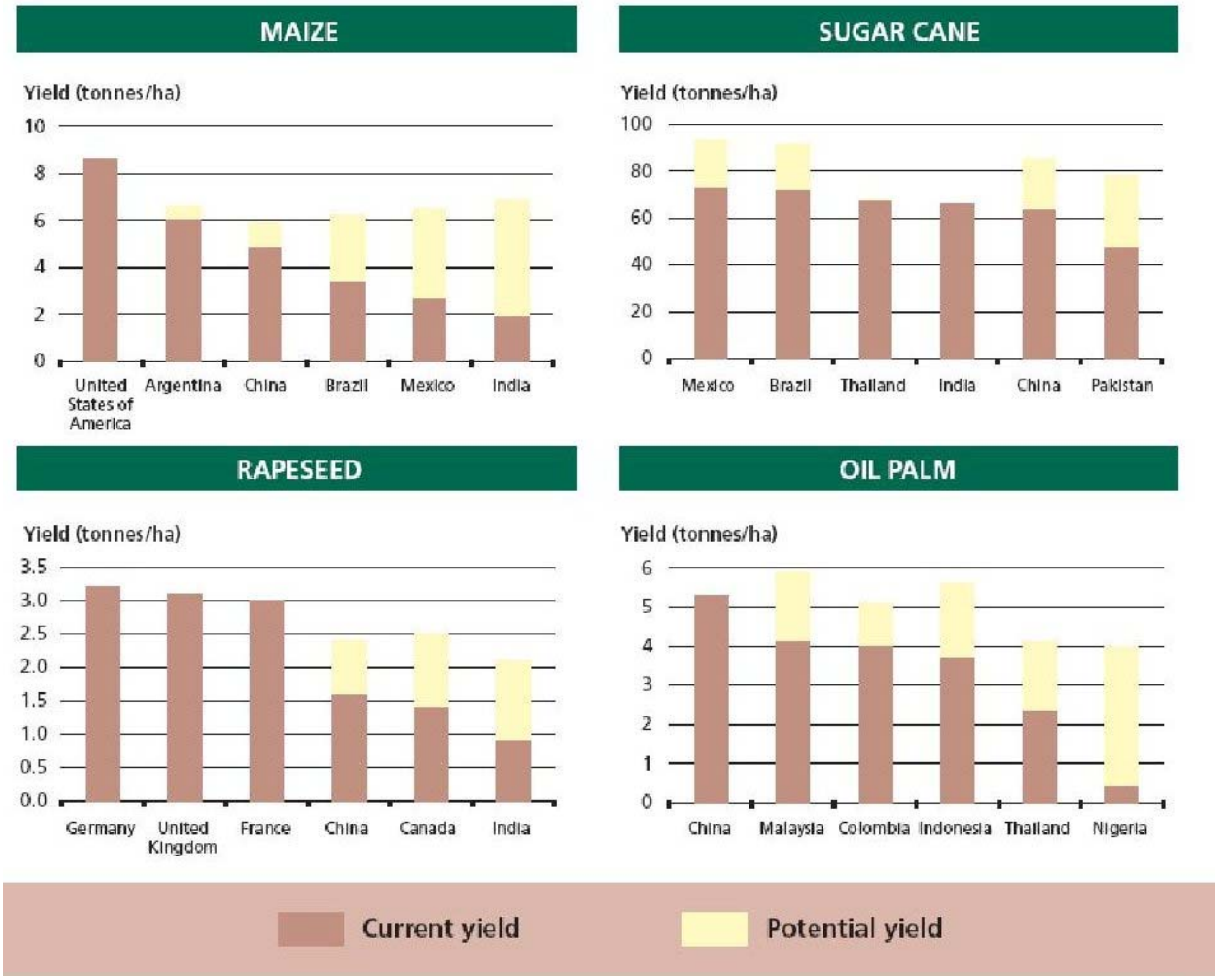


Figure 2.6.1 Potential for yield increase for four crops in various regions of the world. Source: FAO, 2008b.

2.6.1.2 Aquatic biomass

Algae have re-gained attention as an additional source of feedstock for energy in recent years. The term algae can refer to both microalgae and macroalgae (or seaweed). There are also cyanobacteria (so called "blue-green algae") that dominate the world's ocean, contributing to the estimated 350-500 billion metric tons of aquatic biomass produced annually (Garrison, 2008).

Of this diverse group of organisms, oleaginous microalgae have garnered the most attention as the preferred feedstock for a new generation of advanced biofuels. Lipids from microalgae, such as free fatty acids and triacyglycerides, are readily converted to fungible and energy-dense biofuels via existing petrorefinery processes (Tran et al., 2010). Certain species, such as Schizochytrium and Nannochloropsis, reportedly accumulate lipids at greater than 50% of dry cell weight (Chisti, 2007). Microalgae can be cultivated most cost-effectively in un-lined open ponds on currently unproductive land, and in offshore reservoirs (Sheehan et al., 1998; van Iersel et al., 2009). The ability of these microalgal cultivation strategies to utilize marginal lands and wastewater (Woertz et al., 2009) or brackish water (Vonshak and Richmond, 1985) - otherwise unsuitable for agriculture and human consumption- remains among the top drivers to develop algal biofuels as a sustainable energy solution. Despite of the advantages, scaling up microalgae 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).

Over a million metric tons of macroalgae are cultivated and harvested every year for human dietary consumption (Zemke-White and Ohno, 1999). Seaweeds as a bioenergy feedstock are of particular interest for countries with limited land but large coastal reserves. 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.

Interest in exploiting cyanobacteria for biofuels purposes have also begun. Cyanobacteria have long been cultivated commercially for nutraceuticals (Colla et al., 2007; Lee, 1997) and are arguably the most amenable for industrial biotechnology and genetic engineering- both for the production of biofuels (Hellingwerf and Teixeira de Mattos, 2009; Nobles and Brown, 2008; Lindberg et al., 2009) and enhancing the natural capabilities to produce bioproducts (Burja et al., 2001). It is likely that biofuels from cyanobacteria, as well as from eukaryotic microalgae face significant scale-up challenges as well as unclear regulatory status.

Potentials for algae have not been studied as extensively as the land-based biomass resources indicated in Table 2.2.2, but 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). All types of algae, however, have relatively low dry matter content, so their applicability as a biomass feedstock is not straightforward. Other potential introduction barriers, such as ecological impacts of offshore cultivation, have not yet been fully addressed. Therefore, it is still difficult to assess the sustainability and economic competitiveness of algae options.

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, 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 most of the candidate feedstocks are perennial species with cultivation cycles of 20 or more years, climate impacts should be anticipated in the design of bioenergy-oriented agro-ecosystems, and are likely to be stronger than for annul crops (Easterling et al., 2007). However, there is currently limited knowledge on the impacts of climate change on energy feedstocks. In one example, miscanthus would yield more in Northern Europe in 2080 but less in the South, with the southernmost areas of the continent becoming unsuitable for that crop due to pronounced water shortage (Hastings et al., 2008). Whatever the latitude, the inter-annual variability of final yields in this study rose to 20% in 2080, posing a risk that will have to be carefully addressed when designing bioenergy units. Relying on a portfolio of species with various tolerances to water or other climatic stresses is probably the best option to secure a robust supply of biomass, also because it broadens the harvest time windows. Mixtures of species or varieties are also more robust to climate extremes and achieve more stable yields over time under sub-optimal conditions (Tilman et al., 2006). Genetic improvement is also a prime route, since for instance miscanthus has a large variability for environmental traits such as water or radiation-use efficiency (Clifton-Brown and Lewandowski, 2000).

The largest ecophysiological uncertainty in future production changes is the magnitude of the CO_2 fertilisation effect on plant growth, which can cause an enhancement of net primary production of around 20% under doubled free air CO_2 concentration. Most current biogeochemical models assume a strong CO_2 fertilisation effect with a levelling off at large atmospheric concentrations. This causes strong biomass yield increases through enhanced growth and increased water use efficiency as a consequence of decreased photosynthetic losses under conditions of stomatal closure due to water stress. Whether these increases can be expected to materialise under realistic conditions, where down-regulation may be a factor, currently remains unclear (Fischlin et al., 2007). Limitations of CO_2 fertilisation due to co-developing nutrient limitations could be overcome in plantations through fertiliser input.

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 (Figure 2.6.1). 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, both 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, but little empirical evidence is yet available on which to base predictions on how yields will be affected – either directly or indirectly – or how quickly. In one example, ethanol experts in Brazil believe that, even without genetic improvements in sugar cane, yield increases in the range of 20 percent could be achieved 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 highly 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 cost 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 (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 costs 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). 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 Logistics and supply chains

TSU: if not done in previous sections add definition of 1st/2nd-generation here.

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 to improve handling, as a result of which 20-50% of the delivered cost of biomass fuels is due to handling and transport (Allen et al., 1998), emphasizing the importance of supply chain logistical issues.

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. Diversification to several different feedstocks will alleviate the seasonality problem but introduces more complex logistical complications due to the multiple supply chains. Among the characteristics that complicate the biomass supply chain are (Rentizelas et al., 2008):

- 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.

It has been pointed out (Rentizelas et al., 2008) that the impact of different storage solutions with and without out biomass drying still need further investigation. Decision support tools incorporating GIS data have a role in optimization of biomass management systems (Frombo et al. 2009). Figure 2.6.2.1 illustrates a generic supply chain with numerous interlinkages that could be optimized. Biomass is often widely dispersed, and therefore in its utilisation, collection, transportation, and pre-treatment will be important issues (Figure 2.6.2).

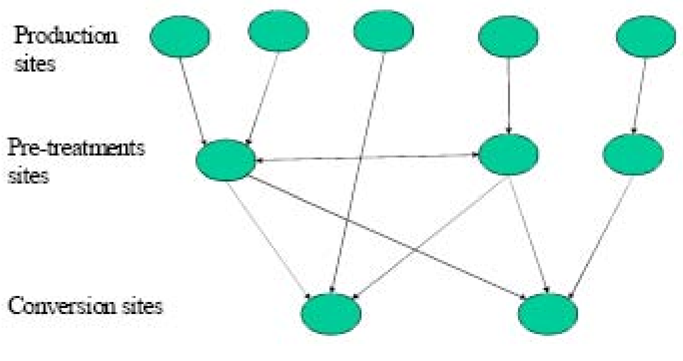


Figure 2.6.2. A generic chain from production to conversion sites. TSU: We hightly encourage the use of figures. This one we suggest to replace by text.

Pre-treatments include chipping, pellet making, and charcoal making as discussed in Section 2.3. In these cases, optimization is a key issue. Optimization could be achieved by studying optimal spatial distributions through linear optimization models that consider the locations of biomass production, transportation costs and scale economy of central plants (Nagatomi et al., 2008).

For the selection of pre-treatment technologies and conversion methods, etc., the integration of business processes from customer-order management to delivery supply chain management has to be considered. Various supply chain models and solution approaches have been extensively studied in literature (Vidal and Goetschalckx, 1997).

Planning models reflect production planning, production scheduling, and distribution planning. Biomass production generally has to address seasonal and scheduling problems as important issues. In addition, autonomous decentralized supply chains can be studied in models as to how they may form a complex biomass supply network (Nishii et al., 2005).

Developing countries have some specific issues. Charcoal in Africa is predominantly produced in inefficient traditional kilns by the informal sector, often illegally. From a developing country perspective, the application of industrial ecology through the lifecycle management concept to the charcoal industry has been advocated as one way to identify opportunities for technological improvement and loss reduction. 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. For example in Kenya the production and transportation of charcoal is illegal, whilst it is legal to buy, sell and use it. 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). In regions where production is causing environmental degradation, such as in the Eastern DR Congo, fuel alternatives have to be developed while phasing out charcoal.

2.6.3 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 of different feedstock types for various applications. Table 2.6.2 shows the most relevant bioenergy systems and chains expected to be in commercial operation at global level by 2030. For each energy end-use the table presents information about the feedstock, processing technology, end-use sector, the country or region, the expected production cost, and the market potential. Additional information about relevant technology development needs, and general comments, are also provided.

Table 2.6.2. Table summarizing the state of the art of the main chains for future production of end use biofuels.

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Technical Advances	Production Cost by 2030 (EU$/GJ)	Present deployment +low/ +++high	References
Ethanol	Transport	Fermentation	Sugar cane syrup	Brazil	Eff. = 0.38 by 2020 [cqvc.pdf] but historical gain is around 1%/yr; Mill size, advanced power generation and optimised energy efficiency and distillation can reduce costs further in the longer term.*	BCCS from sugar fermentation		+++	*UK DFT, 2009
						Efficient use of sugar cane straw as an extra source of heat&power	7 to 8**		
									**IEA Bioenergy: ExCo,2007
						Widespread use of GMO; evolution of biorefinery approach			
	Transport		Molasses	India				+	
				Colombia					
				Thailand					
	Transport	Fermentation	Corn grain	USA	Eff.= 0.67 for wet mill and 0.66 for dry mill*	BCCS from sugar fermentation		+++	*UK DFT, 2009
						R&D improves yield/reduced the time for processing			**Grooms, 2005; ***Rendleman and Shapouri, 2007
						Conversion of CO_2 to fuel**			
						Widespread use of GMO***			
	Transport	Fermentation	sugar beet	EU	Eff.= 0.13*		20 to30**	+	*UK DFT, 2009
	Transport	Fermentation	wheat	EU	Eff= .59*			+	**IEA Bioenergy: ExCo,2007
	Transport	Fermentation	cassava	Thailand			5 to 7**	+	
	Transport	Hydrolysis/Fermentation	Lignocellulosic	USA	Eff. = 0.49 for wood and 0.42 for straw; includes integrated electricity production of unprocessed components*	Enzymes for efficient C5 conversion** *** ****	7 to 9	NA	*UK DFT, 2008; **Jeffries, 2006; ***Jeffries et al., 2007; ****Balat et al., 2008; *****Sims et al., 2008; ******Bom and Ferrara, 2007; *******Tuskan, 2007; ******Kumar et al., 2008; *******NRC, 2009
						Significant amount of investment in R&D*****			
						Engineering of enzymes using advanced biotechnologies******			
						lignin dissolution to produce a cellulose-rich residue******* for 2020 deployable cost estimated is 22 US$/GJ with one to two cumulative volume doublings (20%/doubling)********	11.4 to 13.5 11 - 14********		

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Technical Advances	Production Cost by 2030 (EU$/GJ)	Present deployment +low/ +++high	References
Biomass to liquid	Transport	Fischer-Tropsh	Lignocellulosic	USA	via biomass gasification and subsequent syngas processing	BCCS for CO_2 from processing	20 to 30*	NA	*IEA Bioenergy: ExCo,2007
						For 2020 deployable 27 US$/GJ with one to two cumulative volume doublings (20%/doubling)**; For 2020 deployable Euro 26 US$/GJ with CCS and one to two cumulative doublings (-20%/doubling)**	14-17** 13-16**		**NRC, 2009
	Transport	Fischer-Tropsh	Lignocellulosic	EU	via biomass gasification and subsequent syngas processing	Diesel without BCCS	12.4 to 14.5*	NA	*Sims et al., 2008
Biodiesel	Transport	Tranesterification	Rape seed	OECD	For the total system it is assumed that surpluses of straw are used for power production	new methods using bio-catalysts, supercritical alcohol, and heterogeneous catalyst**	20 to 30***	+++	*Egsgaard et al., 200?
									**Bhojvaidad, 2008
					Excess supply of animal feed (globally) necessitates other uses of glycerine*				***IEA Bioenergy: ExCo,2007
					Nitrogen leakage and pesticide use are higher for annual crops than perennial crops*				
Renewable diesel	Transport	Hydrogenation	Sunflower		Technology well known. Economy is barrier	For 2030 with one or two cumulative volume doublings (-20%/doubling)	10-13*	NA	*Bain, 2007
			Soybeans						
Methanol	Transport	Gasification/Synthesis	Lignocellulosic	USA/EU	Combined fuel and power production possible	BCCS for CO_2 from processing	6 to 8*	NA	*IEA Bioenergy: ExCo,2007
Butanol	Transport	Fermentation	sugar/starch		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*	recent developments in the genetics and downstream processing of biobutanol was recently reported ** ***		NA	*Wu et al., 2007
									Ezeji et al., 2007a;* Ezeji et al., 2007b
Densified biomass						Reduce the cost of fuel, by improved pre-treatment, better characterisation and measurement methods.*		+++	*Econ Pöyry, 2008

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Technical Advances	Production Cost by 2030 (EU$/GJ)	Present deployment +low/ +++high	References
						Working environment problems, caused by dust and micro-organisms, need further attention. *			
briquettes	Electricity	Drying/Mechanical compression	wood residues	EU/USA/ Canada	Large and continuously increasing co-combustion market	Reduce production costs*	5.0**	+++	*Econ Pöyry, 2008
									**Riegelhaupt et al., 2009
wood pellets	Heat	Drying/Mechanical compression	wood residues	EU/USA/ Canada	Large and continuously increasing residential market	Improved supply of feedstocks *	5.3**	+++	*Econ Pöyry, 2008
									**Riegelhaupt et al., 2009
sugar cane residue pellets	Electricity	Drying/Mechanical compression	sugar cane bagasse	Brazil	Large potential availability. Large commercial use		3.1*	+++	*Riegelhaupt et al., 2009
	Heat	Drying/Mechanical compression	sugar cane bagasse	Brazil	Large potential availability. Large commercial use		3.1	+++	
	Electricity	Drying/Mechanical compression	sugar cane straw	Brazil	Large potential availability. Small commercial use	Reduction of chlorine and potassium (to reduce corrosion) and potassium (to reduce slagging), e.g. by washing the biomass prior to combustion.*		+	*Econ Pöyry, 2008
	Heat	Drying/Mechanical compression	sugar cane straw	Brazil	Large potential availability. Small commercial use	Reduction of chlorine and potassium (to reduce corrosion) and potassium (to reduce slagging), e.g. by washing the biomass prior to combustion.*		+	*Econ Pöyry, 2008
straw pellets	Electricity	Drying	straw		straw water content is below 10%	Long-term storage of willow chips is very difficult due moisture content (55-58 %).*	4	NA	*Econ Pöyry, 2008
									Hoogwijk, 2004
	Heat	Drying	straw		straw water content is below 10%	Yield per hectare needs be increased to reduce the cost of fuel *		NA	*Econ Pöyry, 2008
Solid biofuel		Direct combustion	Forestry/agro residues	World wide					

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Technical Advances	Production Cost by 2030 (EU$/GJ)	Present deployment +low/ +++high	References
(small scale)	Cooking	harvested and cut to variable sizes; for briquettes and pellets mechanical densification required	wood; wood residues; agro residues; briquette; pellets; bagasse; straw	World wide	Improved cookstoves are presently available/reduce fuel use (up to 60%)/cut 70% indoor pollution	Optimized design of cookstoves and new materials, gasifier stoves for household use. Combined heat/electric. production already in demonstration. New stoves with 35-50% efficiency. Indoor air pollution reduced more than 90%.		+++	
(small scale)	Residential heat						2.5	+++	
(small scale)	Small industry-process heat				Existing industries have low efficiency kilns with high pollution. Improved kilns cut consumption in 50-60%. There are very large cobenefits of improved technologies in terms of public health and environment.		2.5	+++	
(large scale)	Power&heat				Low costs especially possible with advanced cofiring schemes and BIG/CC technology over 100-200 MWe.*	Gasification technology for large units** ***	Ect3-8 /kWh.	++	*UK DFT, 2009
						Indirect firing with Stirling engine or hot air turbines for medium units**			**Riegelhaupt et al., 2009; ***Electricity from Renewable, 2009
(large scale)	Power			USA	Cost of electricity delivered to consumer in EU/GWe. Cost off biomass EU$ 2/GJ	Widespread use of technology for combustion to electricity in the MW-range*	18	++	*Riegelhaupt et al., 2009
co-firing	electricity	combustion	briquettes/pellets	EU	eff., ~40%			+++	
Charcoal	industry	pyrolysis	wood	World wide		Improvement in the conversion efficiency through moderately capital intensive methods relying in well designed brick/steel kilns with good heat transfer by forcing the hot gases to pass through the unconverted wood and avoid over burning (FAO, 2009).		+++	
							2.1*		*Riegelhaupt et al., 2009
Biomass gases									
(small scale)		gas engine	agro residues		eff., 20%, Japan			+	
(large scale)	power&heat	gasification	wood residue	World wide				NA	
		gas turbine	agro residues						
(large scale)	synthetic diesel	gasification	wood residue	World wide			9*	NA	*Hamelinck, 2004
		synthesis	agro residues						

End use biofuel	Major end use	Processing	Feedstock	Site	Comments	Technical Advances	Production Cost by 2030 (EU$/GJ)	Present deployment +low/ +++high	References
(large scale)	power fuel cells	gasification	all solid biomass	World wide	H2 obtained or methanol synthesized from producer gas used to power fuel cell	improved gasifier efficiency*		NA	*Electricity from Renewable, 2009
Biogas									
household biogas	cooking/heat	digestion	manure	World wide	byproduct: liquid fertilizer	payback time	, 1-2 years	+++	
			human wastes						
biogas (big scale)	electricity	digestion plus gas engine/ steam turbine	MSW	World wide	byproduct: liquid fertilizer	Cost figure for 2020	Ect. 2.6/kWh*	+++	*Bauen et al., 2004
			agro residues		eff., 15-20%				
			industrial waste						
Hydrogen	Transport	Gasification/Syngas processing		USA/EU	Combined fuel and power production possible	research in gasification as basis for hydrogen production for fuel cells*	5 to 8**	NA	*Riegelhaupt et al., 2009
							5 to 10***		**Hoogwijk, 2004; ***Bain, 2007

2.6.3.1 Solid Biomass

Recent developments in the technologies for conversion of solid biomass to fuel ranging from rudimentary stoves to sophisticated large scale heat applications for production of combined heat and power. There has been a worldwide drive in improving the conversion efficiency of charcoal making. Well designed brick/steel kilns have the advantage of good heat transfer by forcing the hot gases to pass through the unconverted wood and avoid over burning (FAO, 2009a).

The use of bagasse as a feedstock for electricity production continues to grow in sugar cane mills. In Brazil, improvements in the technology and material of sugarcane bagasse have allowed an increase in steam pressure and temperature, as has been done already for the pulp and paper sector in OECD countries (Faaij, 2006). Advances in combustion technologies requires improvements in fuel efficiency which can be achieved by maintaining higher temperatures, sufficient air and optimum residence time for complete combustion. Fuel efficiency has been improved in Indian sugar mills by the conversion of boilers to fluidized bed furnace firing for use of rice husk and to traveling grate for bagasse firing (Yokoyama and Matsumura, 2008).

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).

2.6.3.2 Liquid Fuels

Liquid biofuels are obtained either through 1st generation pathways (based on sugar, starch or vegetable oil feedstocks), or 2nd-generation pathways using lignocellulose. Prospects for these routes are covered in the following paragraphs.

As opposed with some views that first generation ethanol uses mature technologies with small room for improvement, future technical progress is expected to occur. 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.

Even in the simple fermentation process, high performance yeast strains[1] have recently been selected and commercialized for dry grind corn ethanol production utilizing batch fermentation processes. Some yeast strains ferment faster or are able to convert substrate to ethanol with increased yields (Knauf and Kraus, 2006). Regarding the starch-based processes, which are a mature technology, seed companies are working to create corn that will boost ethanol yield. Yield increases of 3 to 7 percent in batches using the so-called HTF corn (for High Total Fermentables) compared to unselected varieties, were reported (Haefele, 2002).

A number of process improvements (e.g. germ and fiber separation or improved yeast) are also available to reduce the cost of wet milling (Rendleman and Shapouri, 2007). In particular, CO_2 Recovery - ethanol's most abundant coproduct is CO_2, produced by yeast in about the same proportion as ethanol itself. Most of the ethanol plants, because of the low commercial value of

[1] A 'strain' is a group of organisms of the same species having distinctive characteristics

CO_2, simply vent it into the air. One experiment uses CO_2 to enhance the recovery of oil from depleted oilfields. Another idea is to turn the gas into ethanol or other fuel (Lynn Grooms, 2005).

Internationally, there is an increased interest in the commercialization of ligno-cellulose to ethanol technology (a 2nd-generation pathway). It involves a pre-treatment to 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). Significant investment in RD&D funding by both public and private sources is occurring, but it should be expanded for commercial deployment of these technologies within the next decades (Sims et al., 2008). 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 (Sims et al., 2008).

The transition to an integrated 1st- and 2nd-generation biofuel landscape is therefore most likely to encompass the next one to two decades, as the infrastructure and experiences gained from deploying and using 1st-generation biofuels is transferred to support and guide 2nd-generation biofuel development (Sims et al., 2008).

Regarding **biodiesel**, the difficulty to reduce cost through the first generation process[2] 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. The key remaining challenges relate to the 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 for 2006 TSU: which table is reference here? Do not reference tables outside this document!), although reliability of the process is still an issue for some designs. However, assembling the complete technological platform, including development of robust catalyst for biofuel production and modeling of capital and production costs, will require more R&D investment. It is also recognized that major technical and economic challenges still need to be resolved. 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. Even with significant uncertainty about the commercial take off of any of these technologies (McAloon et al., 2000; Hamelinck et al., 2005, Kumar et al., 2008) IEA was able to make forecast for the price of 2nd-generation biofuels and such results are shown in Table (2030) TSU: see comment above for ethanol from lignocelluloses and for BTL diesel, showing a slight lower cost for the biochemical route by 2030, confirming its the present (2010) cost advantage (Sims et al., 2008). Alternative technologies for diesel and gasoline

[2] In the literature there are still efforts to improve the first generation approach. As an example a paper suggest newer methods of transesterification using bio-catalysts, supercritical alcohol, and heterogeneous catalyst are being explored (Bhojvaidad, 2008**)**.

substitution include biomass pyrolysis oil upgrading in conjunction with hydrodeoxygenation and catalytic upgrading. Proof of principle exists for this route for corn stover-derived pyrolysis oils.

2.6.3.3 Gaseous Fuels

Anaerobic digestion happens slowly in nature and could be accelerated in several ways, such as using more efficient micro-organisms in these processes. 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 (e.g. http://www.jgi.doe.gov/sequencing/why/99203.html TSU: proper reference needed or remove). Recently marine algae have also been studied for biogas generation (Vergana-Fernandez, 2008).

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 "incineration" 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).

Synthesis gas is expected to become more widely used in the future. 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 by distinctly separate drying, devolatalization, gasification and combustion zones. Another promising technology is the development of two stage combined fluidized bed gasifier with combustion process by circulating catalytically active fluidized bed of solids (Fargernas et al., 2006).

2.6.3.4 Biomass with CO_2 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 the 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.

CO_2 capture from sugar fermentation to ethanol is possible (Mollersten, et al., 2003) and a pilot plant is under construction in Decatur, Illinois (http://www.istc.illinois.edu/about/SeminarPresentations/2009-04-15.pdf TSU: proper reference needed or remove!). For corn-based ethanol an evaluation of the impact of this technology on ethanol energy and GHG balance was performed (S&T2 Consultants Inc., 2009) and it is possible to reduce CO_2 emissions from 40,068g CO_2/GJ[3] to 12,362g CO_2/GJ at the expenses of degrading the energy balance by only 3.5%. Biomass and coal with CO_2 capture TSU: add might allow zero emissions TSU remove "–" and add: as Larson et al., 2009 claim that it is possible to install

[3] This is the expected emission by 2015 with incorporation of several improvements in crop practice and ethanol processing according with IEA Task 39, 2008.

facilities co-producing Fischer-Tropsch Liquid (FTL) fuels and electricity from a co-feed of biomass and coal, with capture and storage of by-product CO_2. Comparing these combined feedstock plant with one fed only with coal, the cost of production on US$/GJ is still higher but the difference is not very big when accounting for a CO_2 value of US$ 20/t. Essentially the coal-based FT plant is cost effective for oil price of US$ 59/bb, while the biomass/coal one is cost effective at US$ 89. Nevertheless, with biomass and coal is possible to obtain zero emissions of CO_2 while even carrying CCs TSU: define in the coal fed plant the amount of GHGs emission is 94 kg CO_2/GJ of liquid fuel produced.

2.6.3.5 Biorefineries

The conversion of biomass to energy carriers and a range of useful products, including food and feed, can be carried out in multi-product biorefineries. 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. It may be argued that advanced biorefineries have a distinct advantage over conventional refineries (mineral oil) and first generation 'single product focus' operations e.g., recovered vegetable oil (RVO), or rapeseed oil to biodiesel plants, in that a variety of raw materials may be utilised to produce a range of added-value products. Advanced or second generation biorefineries are developing on the basis of more sustainably-derived biomass feedstocks, and cleaner thermochemical and biological conversion technologies to efficiently produce a range of different energy carriers and marketable co-products (de Jong et al., 2009).

A main driver for the establishment of biorefineries is sustainability. All biorefineries should be assessed through the entire value chain for environmental, economic, and social sustainability. A biorefinery is the integrated upstream, midstream and downstream processing of biomass into a range of products.

A general classification of biorefineries as found in the literature (Denmark; de Jong et al., 2009) is:

- The **energy-driven biorefinery**, of which the main target is the production of biofuels/energy. The biorefinery aspect adds value to co-products.
- The **product-driven biorefinery**, which the main target is the production of food/feed/chemicals/materials, in general by biorefinery processes. Often side-products are used for the production of secondary energy carriers (power/heat) both for in-house applications as well as for distribution into the market.

Task 42 TSU: not defined, not referenced! has further classified the different biorefineries. The classification approach consists of four main features that identify, classify and describe the different biorefinery systems: platforms, energy/products, feedstocks, and conversion processes. Some examples of classifications are: C6 sugar platform biorefinery for bioethanol and animal feed from starch crops, and syngas platform biorefinery for FT-diesel and phenols from straw.

An overview of all the biorefinery demonstration plants, pilot plants, and R&D initiatives within the Task 42 Participating Countries can be found on the Task website (www.iea-bioenergy.task42-biorefineries.com). TSU: please reference, no "ads" for websites They can produce a spectrum of bio-based products (food, feed, materials, chemicals) and bioenergy (fuels, power and/or heat) feeding the full bio-based economy. There is general international agreement TSU: too bold statement; reference? that biomass availability is limited so raw materials should be used as efficiently as possible, hence the development of multi-purpose biorefineries in a framework of scarce raw materials and energy.

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 labour, crop yields, prices of various inputs (such as fertilizer) 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. Supply chains ranges from use on-site (e.g. fuel wood or use of bagasse in the sugar industry) up to international supply chains with international shipment of pellets or liquid fuels such as ethanol.
- For final conversion to energy carriers (or biomaterials): scale of conversion, interest rate, load factor, production and value of co-products and costs of energy carriers (possibly) required for the process. Factors vary between technology and location.

Biomass supplies are, as any commodity, subject to pricing mechanisms. Biomass supplies are strongly affected by fossil fuel prices (see e.g. Schmidhuber, OECD analysis, GTAP analysis TSU: reference missing) 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. At present market dynamics determine the costs of the most important feedstocks for biofuels, such as corn, rapeseed, palm oil and sugar. For the wood pellets, another important fuel for modern biomass production which is internationally traded, prices have been strongly influenced by oil prices (since wood pellets are partly used to 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). 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 (see Junginger et al., 2001).

On a global scale and longer term, the analyses of Hoogwijk et al. (2009) provides a long term outlook of potential biomass production costs (focused on perennial cropping systems) on the long term, related to the different SRES scenarios (see Table 2.7.1, and Figure 2.7.1). 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 2 Euro/GJ TSU: US$2005 as currency.

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$2000) for the two extreme land-use scenarios A1 and A2. (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	11	14	0	8	9
USA	0	18	34	0	7	19
C. America	0	7	13	0	2	3
S.America	0	12	74	0	5	15
N.Africa	0	1	2	0	1	1
W Africa	7	26	28	8	15	15
E. Africa	8	24	24	4	6	6
S.Africa	0	13	17	0	0	1
W.Europe	0	3	12	0	6	12
E. Europe	0	7	9	0	6	6
F.USSR	0	79	85	1	42	47
Middle East	0	0	3	0	0	1
South Asia	0	12	15	1	8	10
East Asia	0	16	64	0	0	6
S. East Asia	0	9	10	0	7	7
Oceania	1	33	35	2	17	18
Japan	0	0	0	0	0	0
Global	16	271	438	15	129	177

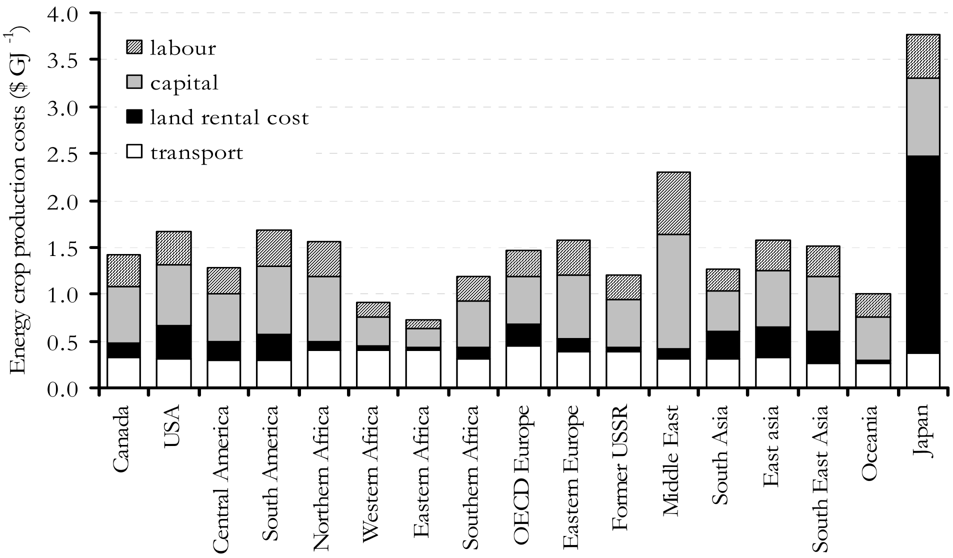


Figure 2.7.1: Cost breakdown for energy crop production costs in the grid cells with the lowest production costs within each region for the SRES A1 scenario in year 2050.

The costs figures reported here aim to summarize and aggregate the information compiled in sections 2.3, 2.5, and 2.6. Below, a preliminary compilation of costs data for bioenergy chains for current and future performance is given (Table 2.7.2, for power and heat and table 2.7.3 for biofuels)

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). TSU: are there more sources that were considered or is data in table set of examples and there could be many more?

Biomass feedstock category	**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$ct for state-of-the art waste incineration and co-combustion. Economics strongly affected by tipping fees and emission standards.	Similar range; improvements in efficiency and environmental performance, in particular through IG/CC technology at large scale.
Residues: - Forestry - Agriculture	Major market in developing countries (<1-5 U$/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.

Table 2.7.3: Global overview of current and projected performance data for the main conversion routes of biomass to fuels (e.g. based on: Hamelinck and Faaij, 2006, Faaij, 2006, Bauen et al., 2009, IEA Bioenergy, 2007.

	Energy efficiency (HHV) + energy inputs		**Investment costs (Euro/kWth input capacity)**		**O&M (% of inv.)**	**Estimated production costs (Euro/GJ fuel)**	
Concept	**Short term**	**Long term**	**Short term**	**Long term**		**Shorter term**	**Longe r term**
Hydrogen: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible; for production of liquid hydrogen additional electricity use should be taken into account.	60% (fuel only) (+ 0.19 GJe/GJ H2 for liquid hydrogen)	55% (fuel) 6% (power) (+ 0.19 GJe/GJ H2 for liquid hydrogen)	480 (+ 48 for liquefying)	360 (+ 33 for liquefying)	4	9-12	4-8
Methanol: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible	55% (fuel only)	48% (fuel) 12% (power)	690	530	4	10-15	6-8
Fischer-Tropsch liquids: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible	45% (fuel only)	45% (fuel) 10% (power	720	540	4	12-17	7-9
Ethanol from wood: production takes place via hydrolysis techniques and subsequent fermentation and includes integrated electricity production of unprocessed components.	46% (fuel) 4% (power)	53% (fuel) 8% (power)	350	180	6	12-17	5-7
Ethanol from beet sugar: production via fermentation; some additional energy inputs are needed for distillation.	43% (fuel only) 0.065 GJe + 0.24 GJth/GJ EtOH	43% (fuel only) 0.035 GJe + 0.18 GJth/GJ EtOH	290	170	5	25-35	20-30
Ethanol from sugar cane: production via cane crushing and fermentation and power generation from the bagasse. Mill size, advanced power generation and optimised energy efficiency and distillation can reduce costs further on longer term.	85 litre EtOH per tonne of wet cane, generally energy neutral with respect to power and heat	95 litre EtOH per tonne of wet cane. Electricity surpluses depend on plant lay-out and power generation technology.	100 (range depending on scale and technology applied)	230 (higher costs due to more advanced equipment)	2	8-12	7-8
Biodiesel RME: takes places via extraction (pressing) and subsequent esterification. Methanol is an energy input. For the total system it is assumed that surpluses of straw are used for power production.	88%; 0.01 GJe + 0.04 GJ MeOH per GJ output Efficiency power generation on shorter term: 45%, on longer term: 55%		150 (+ 450 for power generation from straw)	110 (+ 250 for power generation from straw)	5 4	25-40	20-30

- Assumed biomass price of clean wood: 2 Euro/GJ. RME cost figures varied from 20 Euro/GJ (short term) to 12 Euro/GJ (longer term), for sugar beet a range of 12 to 8 Euro/GJ is assumed. All figures exclude distribution of the fuels to fueling stations.
- For equipment costs, an interest rate of 10%, economic lifetime of 15 years is assumed. Capacities of conversion unit are normalized on 400 MWth input on shorter term and 1000 MWth input on longer term

2.7.2 Technological learning in bioenergy systems

Cost trends and technological learning in bioenergy systems have long been less well described compared to e.g. solar and wind energy. 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 gives an overview of a number of analyses that have quantified learning and experience curves for e.g. sugarcane based ethanol production (Van den Wall Bake et al.; 2009), corn based ethanol production (Hettinga et al., 2009), wood fuel chips and CHP in Scandinavia (Junginger et al., 2005 and a number of other sources.

Table 2.7.4. Overview of experience curves for biomass energy technologies / energy carriers

Learning system	PR (%)	Time frame	Region	n	R2	Data qual.
Feedstock production						
Sugarcane (tonnes sugarcane) Van den Wall Bake et al.; 2009	68±3	1975-2003	Brazil	2.9	0.81	II
Corn (tonnes corn) Hettinga et al., 2009	55±0.02	1975-2005	USA	1.6	0.87	II
Logistic chains						
Forest wood chips (Sweden) Junginger et al., 2005	85-88	1975-2003	Sweden / Finland	9	0.87-0.93	II
Investment & O&M costs						
CHP plants (€/kWe) Junginger et al., 2005	75-91	1983-2002	Sweden	2.3	0.17-0.18	II
Biogas plants (€/m3 biogas/day) Junginger et al., 2006a	88	1984-1998		6	0.69	II
Ethanol production from sugarcane Van den Wall Bake et al.; 2009	81±2	1975-2003	Brazil	4.6	0.80	II
Ethanol production from corn (only O&M costs) Hettinga et al., 2009	87±1	1983-2005	USA	6.4	0.88	II
Final energy carriers						
Ethanol from sugarcane Goldemberg et al., 2004	93 / 71	1980-1985	Brazil	~6.1	n.a.	II
Ethanol from sugarcane Van den Wall Bake et al.; 2009	80±2	1975-2003	Brazil	4.6	0.84	II
Ethanol from corn Hettinga et al., 2009	82±1	1983-2005	USA	6.4	0.96	II
Electricity from biomass CHP Junginger et al., 2006a	91-92	1990-2002	Sweden	~9	0.85-0.88	II
Electricity from biomass IEA, 2000	85	Unknown	EU (?)	n.a.	n.a.	n.a.
Biogas Junginger et al., 2006a	85- 100	1984-2001	Denmark	~10	0.97	II

n Number of doublings of cumulative production on x-axis.
I cost/price data provided (and/or confirmed) by the producers covered
II cost/ price data collected from various sources (books, journals, press releases, interviews)
III cost/price data (or progress ratio) being assumed by authors, i.e. not based on empirical data

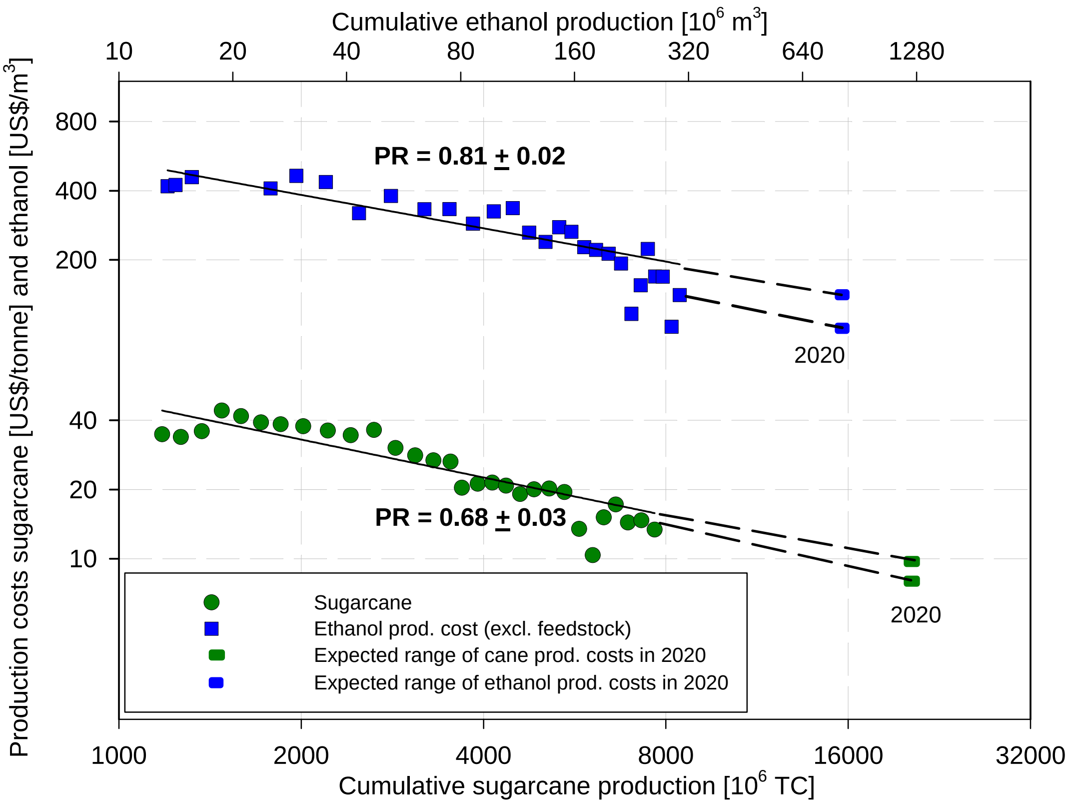


Figure 2.7.2: Experience curves for sugarcane production costs and ethanol production costs in Brazil between 1975-2005, and extrapolation to 2020 (Wall-Bake et al., 2009).

As discussed above, biomass energy systems are differing strongly in terms of feedstock, conversion technology and scale and final energy carrier. 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 yields have been the main driving force behind cost reductions.
- Specifically for sugarcane, also increasing strength of different varieties of sugarcane (developed through R&D efforts by research institutes), prolongation of the ratoon systems, increasingly efficient manual harvesting and the use of larger trucks for transportation reduced feedstock costs (Wall Bake et al. 2009). For the production of corn, highest cost decline occurred in costs for capital, land and fertilizer. Main drivers behind cost reductions are higher corn yields by introducing better corn hybrids and the upscaling of farms (Hettinga et al., 2009). While it is difficult to quantify the effects of each of these factors, it seems clear that both R&D efforts (realizing better plant varieties) 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 240US$$_{2005}$/m^3 in the early 1980's to 130$$_{2005}$/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 automated 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 340 US$/m3 ethanol (16 US$/GJ). Based on the experience curves for feedstock and industrial costs, total ethanol production costs in 2020 are estimated between US$ 200-260/m3 (9.4-3 12.2 US$/GJ).

- For ethanol from corn (Hettinga et al., 2009), production costs of corn are estimated to amount to 75US$2005 per tonne by 2020 and ethanol processing costs could reach 60 - 77 US$/m3 in 2020. Overall ethanol production costs could decline from currently 310 US$/m3 to 248 US$/m3 in 2020. This estimate excludes the effect of probably higher corn prices in the future.

In the REFUEL project that focused on deployment of biofuels in Europe, (Wit et al., 2009, Londo et al., 2009) specific attention was paid to forecasts for learning for 2nd-generation biofuels. The analyses showed two key things:

- 2nd-generation biofuels do have 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. Clearly, 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 (cheaper) residues over time. Note that the results shown indicate that 2nd-generation biofuel production cost can compete with gasoline and diesel from oil of around 60-70 U$/barrel.

- The penetration of 2nd-generation 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 TSU: reference properly, especially between 2020 and 2030 sees a rapid increase in production of 2nd-generation biofuels, 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 2nd-generation biofuels is given in figure 2.7.3.

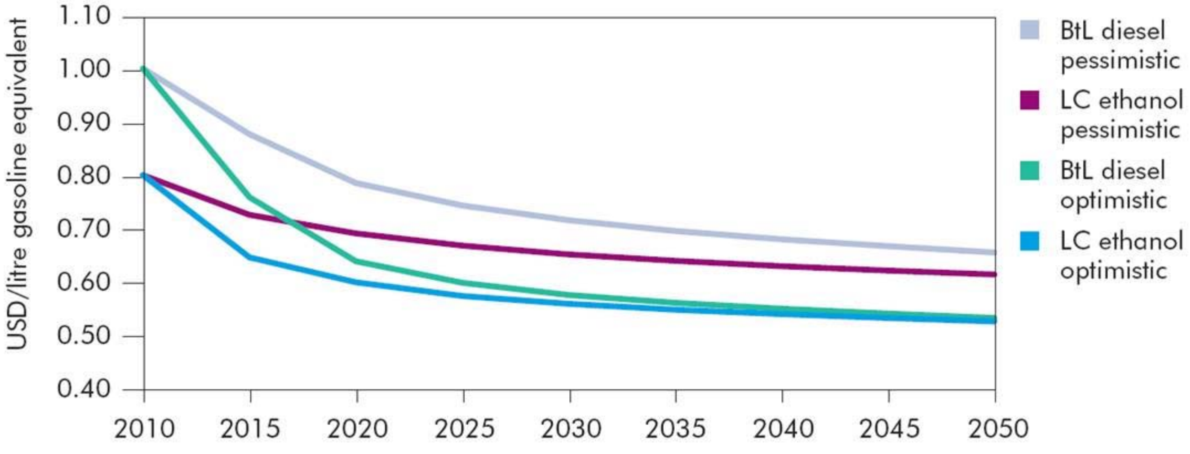


Figure 2.7.3. Cost projections for lignocellulosic ethanol and BTL diesel. Source: IEA-ETP, 2008 and see also IEA (2008) for data figures.

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 production and heat and power generation from residual and waste biomass that can be deployed competitively.
- 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 power (and heat) generation from biomass down to attractive cost levels in many regions, especially when competing with natural gas. In case carbon taxes of some 20-30 U$/ton would be deployed (or when CCS would be deployed), biomass can also be competitive with coal based power generation. Nevertheless, the competitive production of bio-electricity depends also on the performance of alternatives such as wind and solar energy, CCS and nuclear energy.
- There is clear evidence that technological learning and related cost reductions do occur with comparable progress ratio's as for other renewable energy technologies. This is true for cropping systems (following progress in agricultural management when annual crops are concerned), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (ethanol production, power generation, biogas and biodiesel).
- With respect to second generation biofuels, recent analyses have indicated that the improvement potential is large enough to make them compete with oil prices of 60-70 US$/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 (depending on oil price developments as well as carbon pricing). 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 estimations of for example production of chemicals from biomass are very rare in peer reviewed literature and future projections and learning rates even more so. This is also the case for bio-CCS concepts, which are not deployed at present and cost trends are not available in literature. Nevertheless, recent scenario analyses indicate that advanced biomaterials (and cascaded use of biomass) as well as bio-CCS may become very attractive mitigation options on medium term. It is therefore important to gain experience and more detailed analyses on those options.

2.8 Potential Deployment

In total, bioenergy has a significant potential for both near and longer term greenhouse gas emission reductions.

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 non-commercial and relates to charcoal, wood and manure used for cooking 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 9 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 2.8.1). 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 simple inefficient stoves.

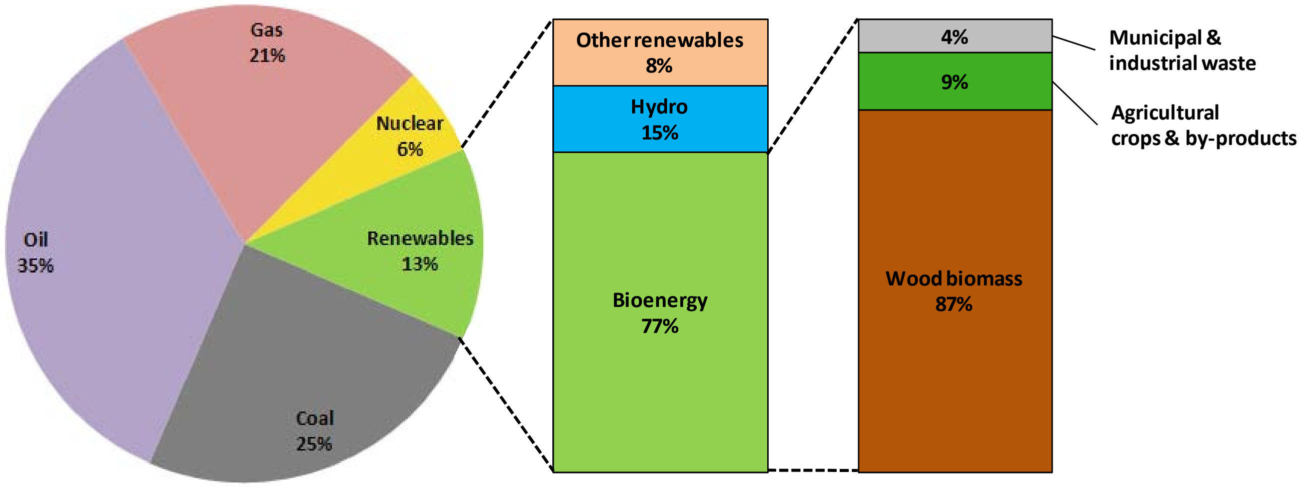


Figure 2.8.1. Share of bioenergy in the world primary energy mix. Source: based on IEA (2008) and IPCC (2007).

The expected deployment of biomass for energy on medium to longer term differs considerably between various studies. A key message from the review of currently available insights on large scale biomass deployment is that it's role 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, e.g. efficient and complete use of primary biomass energy from most promising first generation and new generation biofuels.

2.8.1 Summary of IPCC AR 4 results on the potential role of biomass

2.8.1.1 Demand for biomass

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. 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.

2.8.1.2 Biomass supplies

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. 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 (12-74 EJ/yr) and agriculture (15-70 EJ/yr) as well as waste (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 current energy potential of waste is approximately 8 EJ/yr, which could increase to 13 EJ in 2030. The biogas fuel potentials from waste, landfill gas and digester gas, are much smaller.

2.8.2 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 2.8.2 and 2.8.3.

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 30-117EJ. 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.

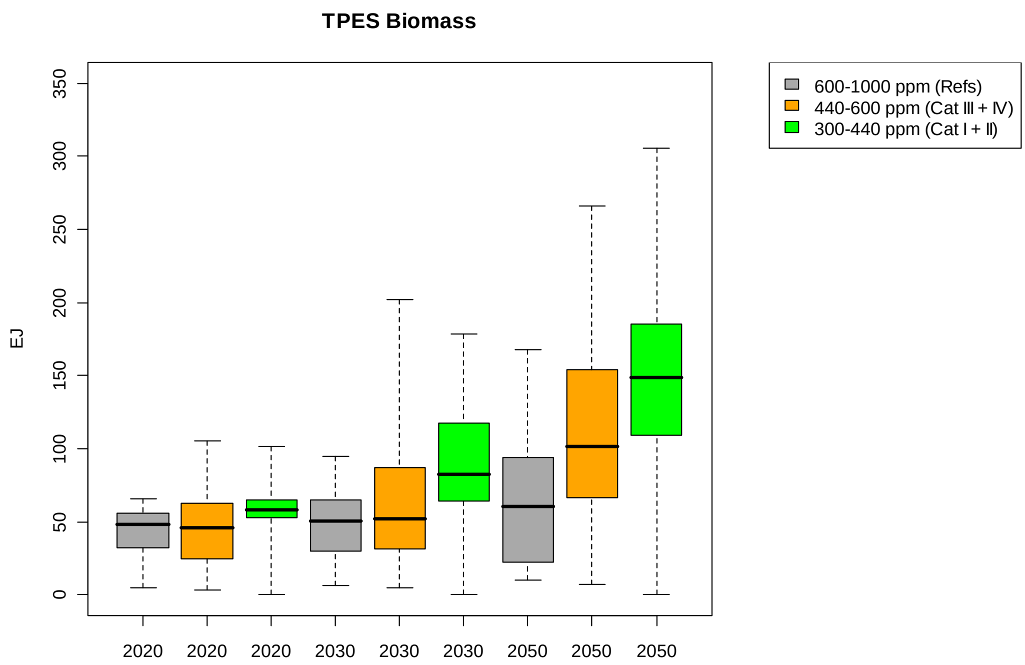


Figure 2.8.2. The primary biomass utilization according to the scenario review of Chapter 10, divided into projections for reference scenarios, scenarios that target 440-600 ppm and scenarios that target 330-440 ppm. The colored bars represent the 25-75% quantiles of the obtained results. The dotted bars represent the full range of estimates.

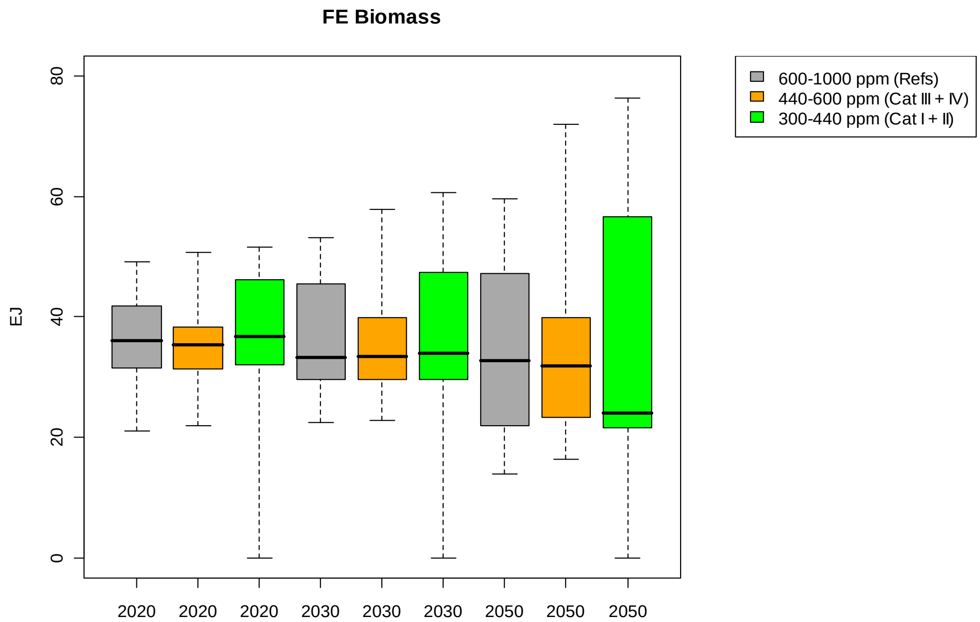


Figure 2.8.3. The final energy delivered via biomass utilization according to the scenario review of Chapter 10, divided into projections for reference scenarios, scenarios that target 440-600 ppm and scenarios that target 330-440 ppm. The colored bars represent the 25-75% quantiles of the obtained results. The dotted bars represent the full range of estimates.

In the reference scenario of the WEO (IEA 2009), biomass is expected to contribute 1604 Mtoe TSU: SI units, please (66 EJ) in 2030 (compared to 1176 Mtoe (48 EJ) in 2007), this includes traditional biomass use. Biofuels contribute 5% of world road transport energy demand (2.7 Mb/day), an almost four-fold increase compared to current production. One fifth of this increase is expected to come from second generation technologies.

Biomass for power increases from 259 TWh in 2007 (about 1 EJ_e) to 839 TWh (about 3 EJ_e) in 2030, mostly from CHP, as well as co-firing.

In the 450 ppm scenario, the contribution of biomass is projected to be 1952 Mtoe (81 EJ), a 22% difference compared to the reference scenario. In addition it should be noted that in this scenario a decreased contribution of traditional biomass is assumed and the relative increase of modern bioenergy is larger than the 22% compared to modern biomass use in the reference scenario.

Use of biomass in CHP and electricity only increases to 172 Mtoe (67% higher than the ref scenario). Biofuel production increases to 278 Mtoe (more than double that in the ref scenario). Especially between 2020 and 2030 sees a rapid increase in production of 2nd-generation biofuels, accounting for all incremental biomass increase after 2020.

The latter is also confirmed by the results of the IEA-ETP study of 2008 (IEA-ETP, 2008). The analysis on biofuels projects a rapid penetration of 2nd-generation biofuels after 2010 and an almost complete phase out of cereal and corn based ethanol production and oilseed based biodiesel after 2030. This was a sharp contrast to the World Energy Outlook studies of 2006 and 2007 (IEA-WEO 2006, IEA-WEO 2007) where 2nd-generation biofuels were excluded from the scenario analysis and thus biofuels at large played a marginal role in the projections for 2030. This is clear example of the importance of high quality data on performance prospects (and thus learning potential and rates) of energy technologies and in general for such strategic studies.

2.8.3 Synthesis of findings from this chapter and chapter 10

Although there is an impressive literature base on the global potentials of bioenergy and the impacts the development of those potentials may have on the environment, there are very few analyses available that provide a coherent and integrated picture taking all key relevant relations (see section 2.2 of this chapter) into account. Over the past few years, many analyses have focused on the possible conflicts and limitations for the deployment of first generation biofuels (see e.g. FAO's State of Food & Agriculture, 2008 for an overview).

However, the use of biomass for heat and power, biomaterials and second generation biofuels, taking into account different potential biomass resources as residues and organics wastes and perennial crops cultivated on arable, pasture and marginal and degraded lands, provide a different outlook. Furthermore, the ecological and socio-economic impacts further deployment of bioenergy can have is also fully conditional. 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, where this is demonstrated for future land-use and bioenergy scenarios for Argentina).

It is therefore impossible to deliver conclusive information on the deployment of biomass for energy and climate change mitigation on shorter and longer term. Based on the current state-of-the-art analyses that take key sustainability criteria into account, 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 (see also van Vuuren et al., 2009). These findings are summarized in Figure 2.8.4 based on an extensive assessment of recent literature and additional modelling exercises with the IMAGE-TIMER modelling framework that include future water limitations, biodiversity protection, soil degradation and competition with food (Dornburg et al., 2008).

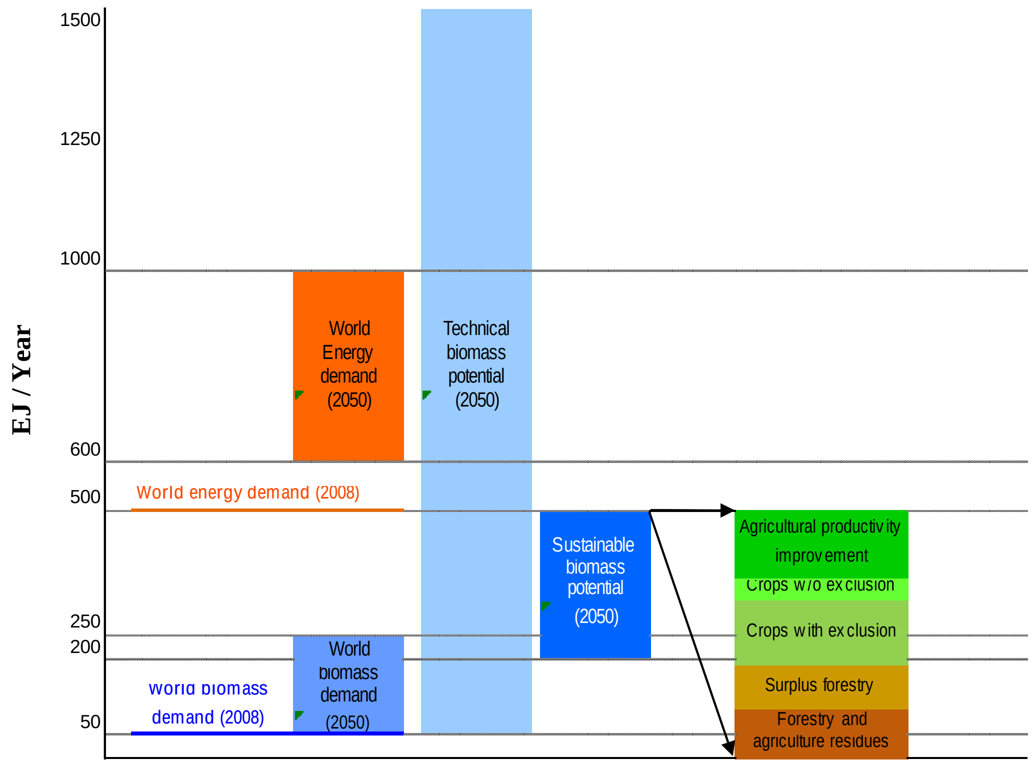
Table 2.8.1 provides an overview (derived from an assessment reported in Dornburg et al., 2008) of key factors and their impact on biomass resource potentials as they have been discussed and identified in this chapter. It is also briefly described under what conditions (policies, technology choices, etc.) the mentioned potentials may be developed over time.

Table 2.8.1. Key factors influencing bioenergy potentials, their respective weight and key recommendations on how potentials could be developed and uncertainties reduced.

Issue/effect	**Importance**	**Recommended activities to reduce uncertainties**
Supply potential of biomass		
Improvement agricultural management	***	Insight in development pathways in how efficiency of agriculture and livestock can be increased in a sustainable manner and for different settings and feasible rates of improvement need to be integrated in modelling frameworks.
Choice of crops	***	Importance of lignocellulosic biomass production systems for different settings. Under certain conditions, sugar cane and palm oil could still be feasible options on longer term as well. Much more market experience with such production systems needed in different settings, including degraded and marginal lands, intercropping schemes (e.g. agro-forestry) and management of grasslands. The latter is an important land-use category on which current understanding and data needs improvement.
Food demand	***	Increases in food demand beyond the base scenarios (e.g. up to 9 billion people in 2050) that were the focus in this study will strongly affect possibilities for bio-energy.
Use of degraded land	***	Represents a significant share of possible biomass resource supplies. Experiences with recultivation and knowledge on these lands (that represent a wide diversity of settings) are limited so far. More research is required to assess the cause of marginality and degradation and the perspectives for taking the land into cultivation.
Competition for water	***	Energy crop production potentials may be constrained by water availability in different regions, which is significant already in some regions and will increase in the future. Constraints in water supplies and sustainable management need ultimately to be studied at water basins scale.
Use of agricultural /forestry by-products	**	Their net availability can be improved by better infrastructure and logistics. Key areas for research and sustainable management are maintaining sound organic matter levels in soils and nutrient balances.
Protected area expansion	**	Increased ambition levels for nature reserves on global scale can have a significant impact on net land availability for biomass production. Land exclusion assumptions in the available studies, however, seem to overlap with the potential future land claims for nature and further modelling work and improved databases are desired. Furthermore, more insights are desired in how land use planning including new bio-energy crops can maximize biodiversity benefits. Evaluating biodiversity impacts on regional level is still a field under scientific development and more fundamental work is needed in this arena.
Water use efficiency	**	An important factor in the equation is improvement of water use efficiency in both current agriculture (and of biomass production itself. This suggests that for various areas water management is prime design parameter for sustainable biomass production and land-use management.
Climate change	**	The impact of climate change on agricultural production and productivity of lands could be significant, but exact effects are also uncertain. Although agriculture may face serious barriers due to climate change, this may also enhance the need for alternative adaptation measures to avoid soil losses and maintain vegetation covers. Biomass production (again especially via perennial systems) may than play a role as adaptation measure.
Alternative protein chains	**	Possible but very uncertain reversal of current diet trends, i.e. introduction of more novel plant protein products (as alternative for meat) could on the longer term strongly reduce land and water demand for food.
Demand for biomaterials	*	Demand for biomass to produce biomaterials (both conventional as building material as new ones as bulk bio-based chemicals and plastics) can be a significant factor, but is limited due to market size (compared to demand for energy carriers). Furthermore, biomaterials will also end up as (organic) waste material later in their lifecycle, indirectly adding to increased availability of organic wastes. In many cases this 'cascaded use' of biomass increases the net mitigation effect of biomass use. For some biomaterial markets

		specific cropping and plantation systems may be required due to demands of the biomass composition. Biomaterials are so far poorly integrated as a factor in energy models and as mitigation option. This can be improved in further work to understand the interactions between different flows and markets better (also in macro-economic terms).
GHG balances of biomass chains	*	The net GHG performance of biomass production systems is not identified as a limiting factor for the potential provided perennial cropping systems are considered. Also, striving for biomass production that is similar or better than previous land use (e.g. grasslands that remain grasslands or trees that replace annual crops) generally improves the overall carbon balance. This can also be true for replanting of degraded lands. The key factor in the net carbon balance is leakage. Avoiding leakage is directly related to increased efficiency in agriculture and livestock and net carbon impacts of biomass production should include this dimension. Such dynamics should ideally also be incorporated in future modelling exercises.

Importance of the issues on the range of estimated biomass potentials: ***- large, ** - medium, * – small



Current world energy demand (500 EJ/year)

Current world biomass use (50 EJ/year)

Total world primary energy demand in 2050 in World Energy Assessment (600 - 1000 EJ/year)

Modelled biomass demand in 2050 as found in literature studies. (50 - 250 EJ/year)

Technical potential for biomass production in 2050 as found in literature studies. (50 - 1500 EJ/year).

Sustainable biomass potential in 2050 (200-500 EJ/year). *Sustainable biomass potentials consist of: (i) residues from agriculture and forestry; (ii) surplus forest material (net annual increment minus current harvest); (iii) energy crops, excluding areas with moderately degraded soils and/or moderate water scarcity; (iv) additional energy crops grown in areas with moderately degraded soils and/or moderate water scarcity and (v) additional potential when agricultural productivity increases faster than historic trends thereby producing more food from the same land area.*

Figure 2.8.4. Technical biomass supply potentials, sustainable biomass potential, expected demand for biomass (primary energy) based on global energy models and expected total world primary energy demand in 2050. Sustainable biomass potentials 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) based on several review studies.

The following ranges are found for the different main biomass resource categories:

- Residues from forestry and agriculture and organic waste, 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, although competing applications may push the 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 is likely to be 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 (“with exclusion of areas” in figure 2.8.4)
    - 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 (“no exclusion” in figure 2.8.4).
    - 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.

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 2.8.4. At the same time, scenario analyses predict 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 2.8.4 results in a contribution bioenergy of some 30% to total primary energy demand.

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 sugar cane based ethanol production). Biomass supplies may than remain limited to an estimated 100 EJ in 2050. Also this is discussed in van Vuuren et al., 2009 and confirmed by the scenario review in chapter 10 of the SRREN.

A more problematic situation arises when the development of biomass resources (both residues and cultivated biomass) may fail to keep up with demand. Although the higher end of biomass supply estimates (2050) further than the maximum projected biomass demand, the net availability of biomass can also be considerably lower than the 2050 estimates. If biomass supplies fall short, this is likely to lead to significant price increases of raw material, thereby directly affecting the economic feasibility of various biomass applications. Generally, biomass feedstock costs can cover 30-50% of the production costs of secondary energy carriers, so increasing feedstock prices will quickly slow down growth of biomass demand (but simultaneously stimulate investments in biomass production). To date, very limited research on such interactions, especially on global scale, is available.

2.8.4 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 especially be 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 CO_2 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. When such pathways are strived for, 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. So far, the impact of electric vehicles on reducing baseline demand for liquid transport fuels seems very limited. This is to a large extent explained by the impossibility to implement electric drives for aviation and marine transport (where energy demand grows strongly), as well as for truck transport (which is roughly responsible for half the demand for road transport fuels).

The data on potential biomass demand in future energy scenarios reviewed hint that biomass demand may in fact be lower than the biomass supplies that could be generated in baseline scenarios used. At ambitious levels of climate change abatement, the key demand factor is likely to be the use of biomass for transport fuels due to the very few alternatives available for oil and reducing CO_2 emissions in the transport sector. Nevertheless, long term energy demand projections are also characterized by considerable variability (especially caused by GDP and population growth and the rate of deployment of energy efficiency measures at large). Demand for example transport fuels could therefore also be significantly higher than projected in this report and this could be further enhanced when policies target increased energy security and rural development as other priorities that are likely to favour biomass and biofuels.

It is recommended to incorporate (dynamic) biomass supply projections and a more diverse portfolio of conversion options (e.g. including hydrogen production from biomass and combined with CCS) in current models to obtain more coherent analyses and scenarios.

The costs of biomass supplies in turn are influenced by the degree of land-use competition, availability of (different) land (classes) and optimisation (learning) 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. Nevertheless, the variability of biomass production costs seems far less than that of oil or natural gas, so uncertainties in this respect are relatively limited.

To date, limited modelling efforts are available to fully interlink macro-economic/market models with biomass potential studies, especially when lignocellulosic biomass is concerned. To date, price dynamics and, longer term, responses of agriculture (in terms of increased land use and/or increased efficiency) are also addressed to a limited extent. Although the long term impacts on actual physical biomass resource potentials may be limited, understanding the economic responses to increased demand for food and bio-energy and how these affect the relative competitiveness of bio-energy compared to other energy supply options is extremely important for defining balanced policy strategies. Linked to this, the understanding of socio-economic implications (such as impacts on rural income, rural employment) of bioenergy production should be understood better.

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. 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. 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 CO_2 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.

2.8.5 Key messages and policy

Table 2.8.2 describes key preconditions and impacts for two possible extreme biomass scenarios.

Table 2.8.2. 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, - 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	- 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	- 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

between OECD and DC's.	food markets	linked to high oil prices. - Limited net GHG benefits. - Socio-economic benefits sub-optimal.

2.8.6 Key messages and policy recommendations from the Cchapter 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 management, investment in infrastructure, good governance of land use and introduction of strong sustainability frameworks.
- 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 natural resources (e.g. soil carbon enhancement and restoration, water retention functions) and contributing to rural development are possible. Logically, such synergies should explicitly be targeted in new 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 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 second generation biofuel options does drive bioenergy to more sustainable directions.
- Technology for lignocellulose based biofuels and other advanced bioelectricity options, CCS, 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 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.
- 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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INTERGOVERNMENTAL PANEL ON climate change

Chapter 3

Direct Solar Energy

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Chapter 3 has been allocated a total of 68 pages in the SRREN. The actual chapter length (excluding references & cover page) is 102 pages: a total of 34 pages over target.

Expert reviewers are kindly asked to indicate where the Chapter could be shortened in terms of text and/or figures and tables.

References of figures/tables are often missing; references from the text that are found missing in the reference list have been highlighted in yellow. In the same manner, references found in the reference list but missing from the text have also been highlighted.

In addition, all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 3: Direct Solar Energy

CONTENTS

EXECUTIVE SUMMARY

This Chapter summarizes the current status of the direct use of solar energy as an agent for mitigating 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 adaptation, 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, the world's energy requirements 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 blessed with solar energy, every country receives enough to 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). Production of *electricity* can be achieved in either of two ways. The first (concentrating solar power or CSP) uses solar thermal conversion to produce high-temperature heat, which is then converted to electricity via a heat engine and generator. In the second, solar energy is converted directly into electricity in a solid-state semiconductor device called a photovoltaic (PV) cell. 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 solar 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. In addition, solar devices can deliver process heat and cooling, and other devices are being developed that will deliver *fuels* such as hydrogen.

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, but 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 energy budget as heat. Service hot-water heating for domestic and commercial buildings is now a mature technology growing at a rate of about 20% per annum and employed by about 50 countries around the world. The time-average combined production of thermal power of the existing devices is estimated to be 20 GW. 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 annum—making it one of the fastest-growing energy technologies. Currently, it claims a time-averaged power production of about 2 GW, with most installations being roof-mounted and grid-connected. Energy from PV panels and solar domestic water heaters can be especially valuable because the energy production can occur at times of peak loads on the grid. 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 developing countries because they are modular, quick to install, and can forestall the need for a large national grid. The production of electricity from CSP installations has seen a huge increase in just the last few years and has now reached a cumulative installed capacity within a few countries of about 0.5 GW. 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 the 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 6000 tonnes of CO_2 per year from entering our atmosphere.

Looking to the future, we can expect that further technological improvements will be achieved. For example, much work is under way to improve the efficiency and reduce the materials requirements of PV cells. And judging from the past track record of improvements in solar semiconductor devices, one may expect the steep learning curve to continue into the future. However, these learning curves will only continue if market volumes for the respective technologies increase in parallel, because these curves depend on production volume, not on the mere passage of time. Without rapidly increasing production volumes, the learning curves with respect to time will slow and increase the total cost of 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—the direct use of solar energy produces essentially no greenhouse gases (except the modest amount produced in the manufacture of conversion devices), and it has the potential to displace large quantities of fossil fuels.

Some of the solar energy absorbed by the Earth appears later in the form of wind, wave, ocean thermal, 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—a subject with a long and significant impact on human history.

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. But these devices could not compete with fossil fuels, which were highly abundant in the years leading up to the mid 1900s.

The modern age of solar research began in the 1950s, with the establishment of the International Solar Energy Society. The Society's founders recognized that the age of fossil fuels was limited, and that a sustainable replacement was needed for coal, oil, and natural gas. Sometime later, it also became clear that the mitigation of adverse climate change was an equally important incentive for developing renewable sources of energy. At about the same time, national and international networks of solar radiation measurements were developed. And, in concert with recommendations of the World Meteorological Organization, these networks have been expanding steadily ever since.

With the oil crisis of the 1970s, most countries in the world developed programs for solar energy research and development (R&D). These efforts, which have, for the most part, continued up to the present, have borne fruit: one of the fastest-growing renewable energy technologies, solar energy is now poised to play a vital and environmentally friendly role on the world energy stage.

3.1.2 Theoretical Potential

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—5.5×10^6 exajoules (EJ) per year—dwarfs the rate at which the world's population consumes energy, which is 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. Beneath this atmosphere with clear skies on Earth, this figure becomes roughly 1000 W/m^2. 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 also be viewed as a flux of electromagnet particles or photons. Photons from the sun are highly energetic. They range in energy from about 2.2×10^{-19} to 2.6×10^{-18} joules (J)—or from 1.4 to 16 electron-volts (eV). This means that many have energies larger than those associated with electrons in their shells, and consequently, can promote chemical reactions such as photosynthesis and generate conduction electrons in semiconductors, thereby 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. Later sections 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. But more often, market barriers and the lack of a pricing scheme that values the attributes of clean energy have forestalled wide scale use of these solar technologies. Thus, part of the effort to increase solar energy's contribution in mitigating climate change entails creating the market conditions for adopting solar energy technologies, as some countries have done. In these jurisdictions, very large solar-electricity (both PV and solar-thermal) installations approaching 1000 megawatts of power have been realized.

Another part of the effort is the R&D needed to bring well-positioned solar technologies to the final stage of market readiness, through pilot plants and system trials to accelerate the technology and manufacturability development. Particularly important are ways to integrate solar energy with conservation methods and other renewable energy so as to maximize the role it can play. Solar energy has reached this stage of readiness through R&D expenditures that are very modest compared to other energy sources such as nuclear. A larger expenditure in basic solar research will undoubtedly bring forth new solar technologies that will play an important role in the more distant future.

3.1.4 Context Summary

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 a year, or over a large geographical area such as a continent, solar energy becomes much more reliable. Using both of these concepts has enabled designers to produce more reliable solar systems.

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 portion of the world's energy demands.

The rest of this Chapter will include the following topics. The next section summarizes the research that has gone into characterizing this solar resource. It shows that, in principle, only a relatively small part of the Earth's solar resource is required to meet the energy needs of the entire world's population. We find that the energy flux of 1000 W/m^2 mentioned above is only a rough upper bound for solar radiation: the actual radiation depends on the orientation of the surface, date and time of day, latitude, haziness, and cloud cover, and the following section deals with this variability.

Later sections highlight the different technologies: passive solar heating and lighting for buildings, active solar heating and cooling for buildings and industry, solar PV electricity generation, concentrating solar power electricity generation, and solar fuels conversion. These sections will describe each technology and give its applications. Later sections will review the current status of market development, the integration of solar into other energy systems, the environmental and social impacts, and finally, the prospects for future developments. The two final sections cover cost trends and the potential for deployment of these solar technologies.

3.2 Resource Potential

3.2.1 Resource Characteristics

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 to 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 amounts of 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: 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 beam and diffuse components. Figure 3.1 shows the average global solar flux as it varies across the Earth for two different three-month time periods.

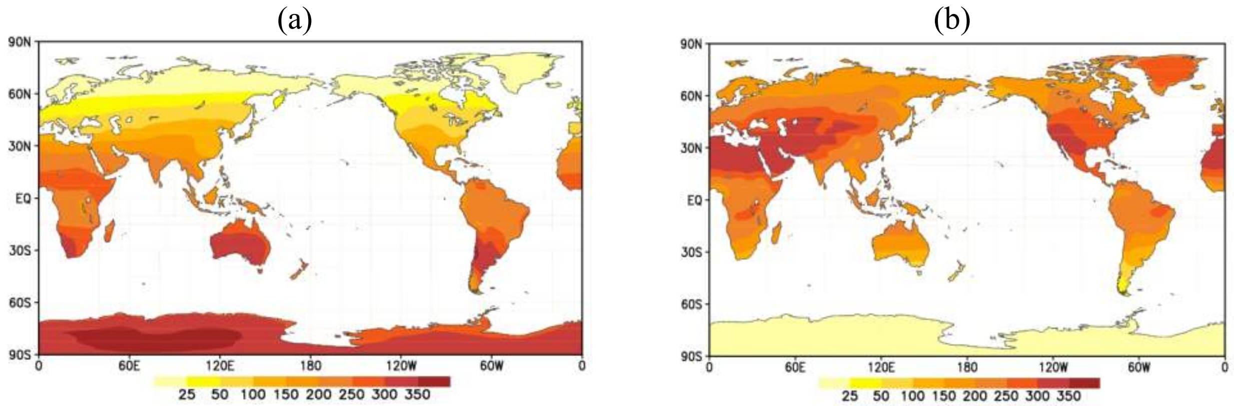


Figure 3.1: The global solar flux (in W m^{-2}) at the Earth's surface—derived from the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)—averaged over two 3-month periods: (a) December-January-February and (b) June-July-August.

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 that is theoretically available for energy purposes. It has been estimated as 10.8×10^{11} gigawatt- hours (GWh) per year (World Energy Assessment, 2001). The large-scale generation of solar energy requires land availability and significant area for installation of solar energy collectors. 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 (FAO, 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 4.4×10^8

GWh per 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 (IEA, 2007).

The technical potential varies over the different regions of the Earth. 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.) In addition, in the bottom three panels, the table shows the ratio of the global technical potential to the current and projected primary energy consumptions out to 2100. From these last three panels, solar energy’s potential is projected to extend well beyond the current century. Thus, the contribution of solar energy to global energy supplies will not be limited by resource availability. Rather, technological, social, and economic factors will determine the extent to which solar energy is used in the longer term.

Table 3.1: Annual technical potential of solar energy for various regions of the world (modified from Nakićenović et al., 1998).

Region	Minimum, 10^5 GWh	Maximum, 10^5 GWh
North America	500	20000
Latin America and Caribbean	300	9000
Western Europe	70	2500
Central and Eastern Europe	12	400
Former Soviet Union	550	24000
Middle East and North Africa	1100	31000
Sub-Saharan Africa	1000	26000
Pacific Asia	100	2800
South Asia	100	4000
Central Asia	300	11000
Pacific OECD	200	6000
TOTAL	4000	140000
Ratio to current primary energy consumption (1117×10^5 GWh)	3.6	125
Ratio to projected primary energy consumption in 2050 (1639×10^5 – 2917×10^5 GWh)	2.4–1.4	85–48
Ratio to the projected primary energy consumption in 2100 (2444×10^5 – 5275×10^5 GWh)	1.6–0.8	57–27

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 variety of factors, namely, 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, 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

3.2.2.1 User Needs

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 location. The performance of different empirical relations has been studied in large number of publications. None of the available empirical relations reproduces the actual measurements within limit up to ±30 W/m^2 on a monthly basis. This figure equals roughly 3% of maximum clear-sky flux.

Members of the solar energy community require radiation data so they can choose the most suitable locations where appropriate collectors and storage systems must be installed and operated successfully to meet the national and local needs of end-users. Such data can be provided by the world solar radiation network supported by national meteorological services. The World Radiation Data Centre (WRDC, Saint Petersburg, Russia) 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 ground-based solar radiation measuring sites from which solar data are available at the WRDC for period 1964-2007.). 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 site. It is also the only ground-based method available when the density of ground stations is low.

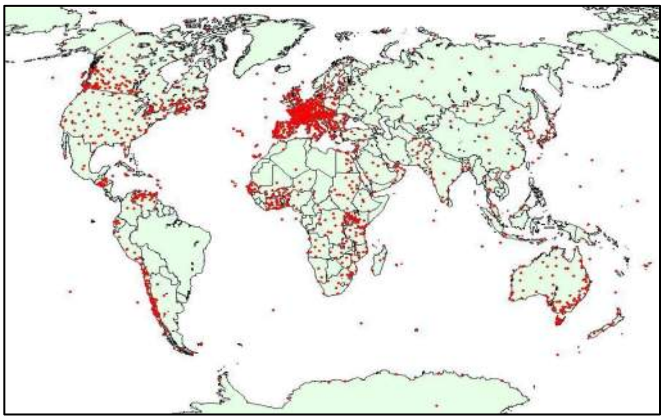


Figure 3.2: The ground-based solar radiation measuring sites from which solar data are available at the WRDC for period 1964-2007.

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.

3.2.2.2 Solar Databases

Various national institutions also provide information on the solar resource: 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.

For projects in the USA, NREL has recently released an updated version of the National Solar Radiation Database (NSRDB) that now 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 (PV) and concentrating solar power (CSP) 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.

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 (ESRA, 2000a, 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, 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, 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.

3.2.2.3 Impact of Climate Change on Potential Solar Resources

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 conversion. Each section also describes applications of these technologies.

3.3.1 Passive Solar

This subsection discusses passive solar technologies and applications.

3.3.1.1 Passive Solar Technologies

Passive solar energy technologies absorb solar energy, store and distribute it in a natural manner without using mechanical elements, and also use natural ventilation (Energía Solar Térmica, 1996). Basic principles are based on the characteristics and location of the materials used in construction, being part of the building's structure. One main advantage is durability, because the materials are associated with the building.

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. Forced convection based on mechanical means such as pumps and fans is not considered to play a major role in the heat-transfer processes. 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 (see Figure 3.3.1). 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 (Figure 3.3.1), 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.

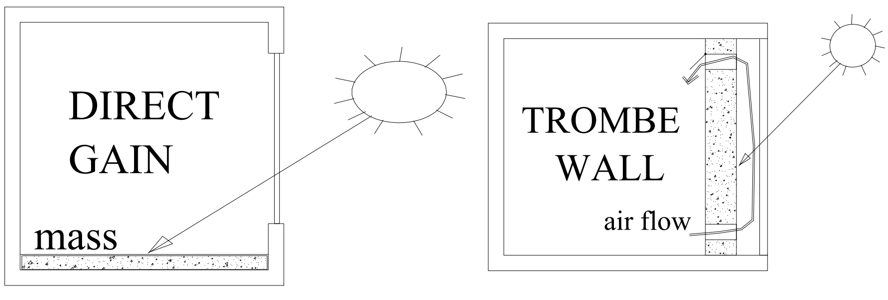


Figure 3.3: The two most-common types of passive systems: direct gain (left) and collector-storage wall or Trombe wall (right).

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 (Eurec, 2001).

Country	Solar Fraction (%)	Total Solar Gains (TWh)	Total CO2 Reduction (Mt)
Norway	10	4.4	0.4
Finland	18	8.6	2.4
UK	15	57	22.5
Ireland	11	2.0	1.2
Germany	13	76	26
Belgium	12	13	4.4
Greece	18	8.9	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 (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 (UNEP, 2007). Solar gain control is particularly important during the “shoulder” seasons when some heating may be required, and it can be fully satisfied by part of the solar gains through the direct-gain windows; controls such as motorized shading or electrochromic coatings may be used to optimally control the amount of solar radiation entering a space. 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 building envelop can reduce the cooling energy demand in such buildings 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.

3.3.1.2 Solar Passive Applications

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. Figure 3.4 illustrates an example demonstration project with row houses in Sweden (Hastings and Wall, 2009). The space-heating demand is estimated to be about 15 kWh/m²a.

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 3.5a).

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 3.5b 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 3.5a illustrates the passive-hybrid solar design concept in the EcoTerra EQuilibrium demonstration solar home in Canada (Athienitis, 2008). It has a 15-cm concrete slab in the family room and a 13-cm ventilated concrete slab (VCS) in the basement that stores heat from the building-integrated photovoltaic/thermal system in the roof, but with passive discharge of the heat. The basement slab also acts as a direct-gain system, storing solar gains from the south-facing windows in the basement. The VCS is also used for night cooling in the summer by passing outdoor air though the hollow cores because night temperatures are usually lower than 20ºC. This example illustrates a possible trend in the design of both residential and commercial buildings, where thermal mass is used in a hybrid mode for heating and cooling purposes.

Figure 3.4: Lindas demonstration project (Sweden)—passive row houses (Hastings and Wall, 2009).

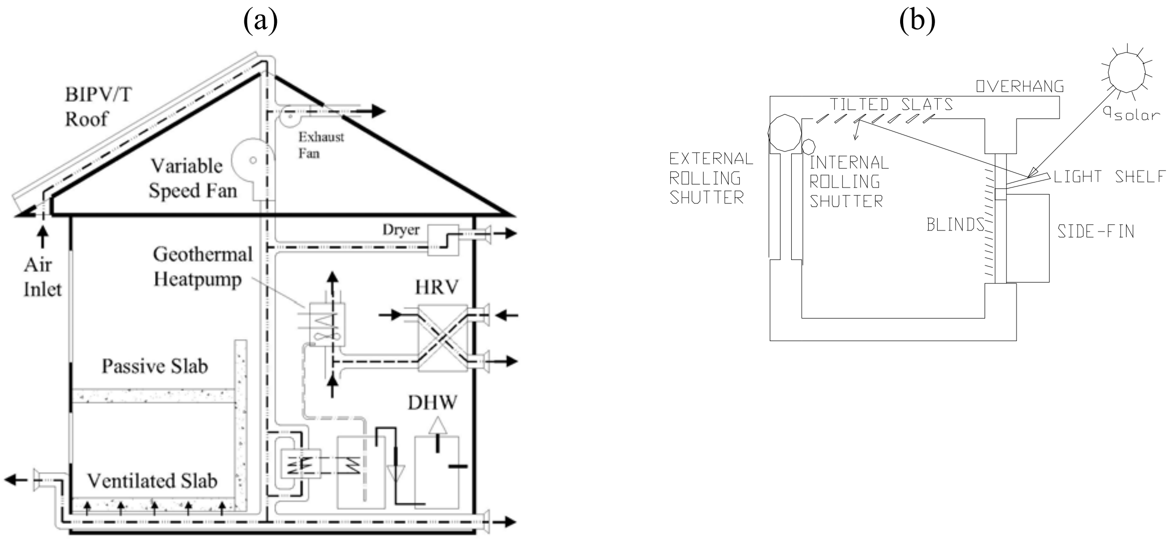


Figure 3.5: (a) Schematic of thermal mass placement and passive-active systems in EcoTerra house; (b) schematic of several daylighting concepts designed to redistribute daylight into the office interior space.

Figure 3.5a illustrates several commonly used fixed shading and daylight redirection systems. Fixed shading devices such as overhangs and side fins work during specific times of the year that depend on solar altitude and azimuth. However, with increasing window areas—both in residential and office buildings—there is increasingly a need for active control of solar gains. Therefore, motorized venetian blinds or louvers are one option that is becoming more popular. Some companies such as Pella Windows and Unicel Architectural integrate the controlled shading device between the glazings, which significantly reduces the amount of solar radiation that is absorbed by the shades/louvers and reemitted as heat into the room interior.

Recent trends include the use of photovoltaic panels as overhangs that can be partly transparent, thus providing some shading while producing electricity, as well. Figure 3.6 shows two examples combining a daylighting and direct solar-gain function with photovoltaics and shading: (a) Queen's University in Ontario, Canada and (b) the Mataro Library in Barcelona, Spain (Lloret *et al.,* 1995). The Mataro library includes a 53-kW grid-connected semitransparent PV/thermal system. The semitransparent PV façade has a daylighting function, acting like a side luminaire to distribute the daylight.

(a) (b)

Figure 3.6: PV panels as overhangs, Queen's University, Ontario); (b) semitransparent PV/thermal modules integrated in curtain wall, Mataro Library, Spain (the facade is also used for fresh-air preheating) (Lloret et al., 1995).

3.3.2 Active Solar Heating and Cooling

This subsection discusses active solar heating and cooling technologies and applications.

3.3.2.1 Active Solar Heating and Cooling Technologies

This subsection describes various technologies that use the sun to provide either heating or cooling. Also discussed is thermal storage and research directions in the area of solar heating and cooling.

3.3.2.1.1 Solar heating systems

A solar heating system is composed of a solar collector and storage tank. 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 3.7 illustrates the relationship of temperature difference between the collector and ambient versus the efficiency of a collector.

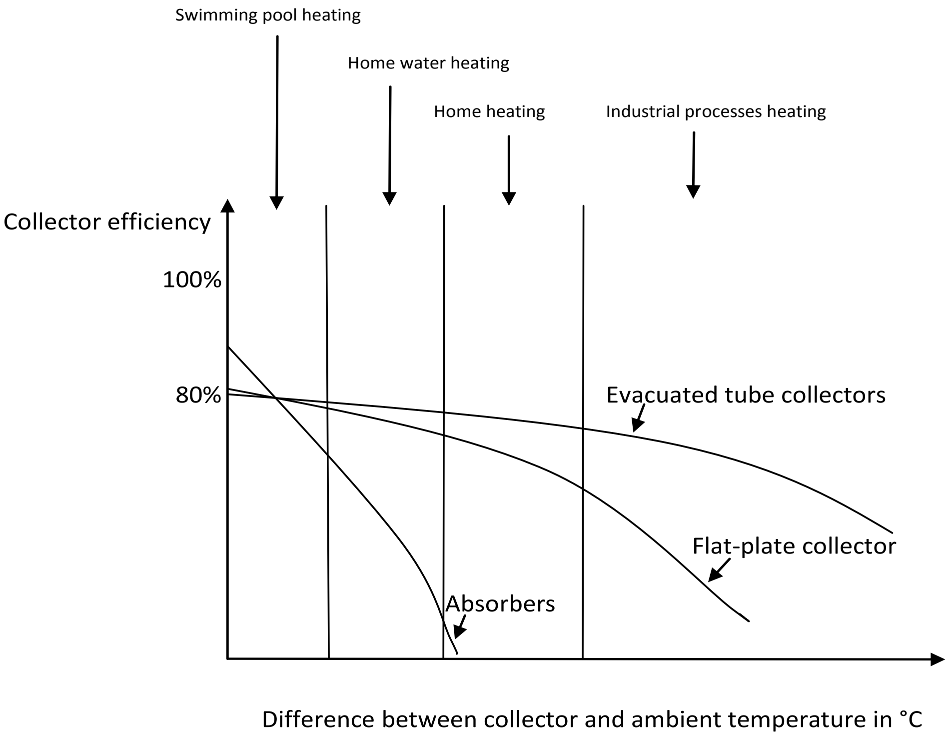


Figure 3.7: Selection of the most suitable solar collector for different applications. The x-axis indicates the difference in temperature between the collector and ambient, and the y-axis indicates the relative efficiency of the collector.

3.3.2.1.1.1 Solar collectors

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. It consists primarily of an absorber, which is usually made of several narrow metal strips using a wide range of materials such as copper, stainless steel, mild steel, aluminum, and plastics. Absorbers are usually black, because dark surfaces demonstrate a particularly high absorptance. The absorptance indicates the fraction of short-wavelength solar radiation falling on the surface that is being absorbed and transformed into heat. Matte-black paints mechanically applied to the absorber have been widely used for many years because they are relatively inexpensive and easy to apply with brushes or sprays.

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 3.8a). 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 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 3.8: Thermal solar collectors: flat-plate (a) and evacuated-tube (b) collectors.

Evacuated-tube collectors are usually made of parallel rows of transparent glass tubes connected to a header pipe (Figure 3.8b). To reduce heat loss within the frame by convection, the air can be pumped out of the collector tubes. These evacuated-tube collectors must be re-evacuated every one to three years. This makes it possible to achieve very high temperatures (more than 150°C), useful for cooling (see below) or industrial applications.

Two main types of evacuated tubes are in use in the solar industry: the direct-flow tube and heat-pipe tube. The *direct-flow evacuated-tube collector* has two pipes running down and back, inside the tube, and the heat-transfer fluid circulates in the pipes. In the case of concentric fluid inlet and outlet pipes, the rotational symmetry allows the absorber to have the desired tilt angle even if there is no flexibility in the collector mounting (e.g., when the collector is mounted in the roof itself). The most common type of direct-flow tube is where the two pipes are at the two extremities of the absorber. To increase the radiation received by the absorbers, some direct-flow evacuated-tube collectors include reflectors mounted behind the collector or inside the glass tube.

In *heat-pipe evacuated-tube collectors*, the heat-transfer fluid exchanges both sensible and latent heat. This type of collector generally contains copper heat pipes attached to an absorber plate, inside a vacuum-sealed solar tube. The heat pipe is hollow and the space inside is evacuated. In this case, the purpose is not insulation, but rather, to lower the vapourization temperature of the small quantity of liquid inside. This liquid is usually alcohol or purified water and some special additives. Due to the vacuum of the tube, the liquid boils at a lower temperature, typically 30ºC. When solar radiation strikes the surface of the absorber, the liquid in the heat tube is heated above 30ºC and quickly turns to hot vapour that rises rapidly to the top of the heat pipe and transfers its sensible and latent heat to the carrier fluid that flows through a manifold and absorbs the heat. As the heat is extracted at the condenser, the vapour condenses to form a liquid and it flows back down to the bottom of the heat pipe while the carrier fluid in the main pipe is heated and the process starts again.

Evacuated tubes offer the advantage that they work efficiently with high absorber temperatures and with low radiation. Higher temperatures also may be obtained for applications such as hot-water heating, steam production, and air conditioning. Conventional evacuated-tube collectors are more expensive than flat-plate collectors, with unit area costs about twice that of flat-plate collectors. However, a new evacuated-tube design has the potential to become cost-competitive with flat plates. This design features two concentric glass tubes separated by a vacuum, and an absorber made of the inside tube with a selective coating. Water is typically allowed to thermosyphon down and back out of the inner cavity to transfer the heat to the storage tank.

3.3.2.1.1.2 Types of solar water heaters

Thermal solar 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 3.9). 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.

Thermosyphon systems are an economical and reliable option, especially in new homes. The design is based on the natural convection of warm water, leading to water circulation through the collectors and to the tank located above the collector. As water in the solar collector heats, it becomes lighter and rises naturally into the tank above. Meanwhile, the cooler water flows down the pipes to the bottom of the collector, enhancing the circulation.

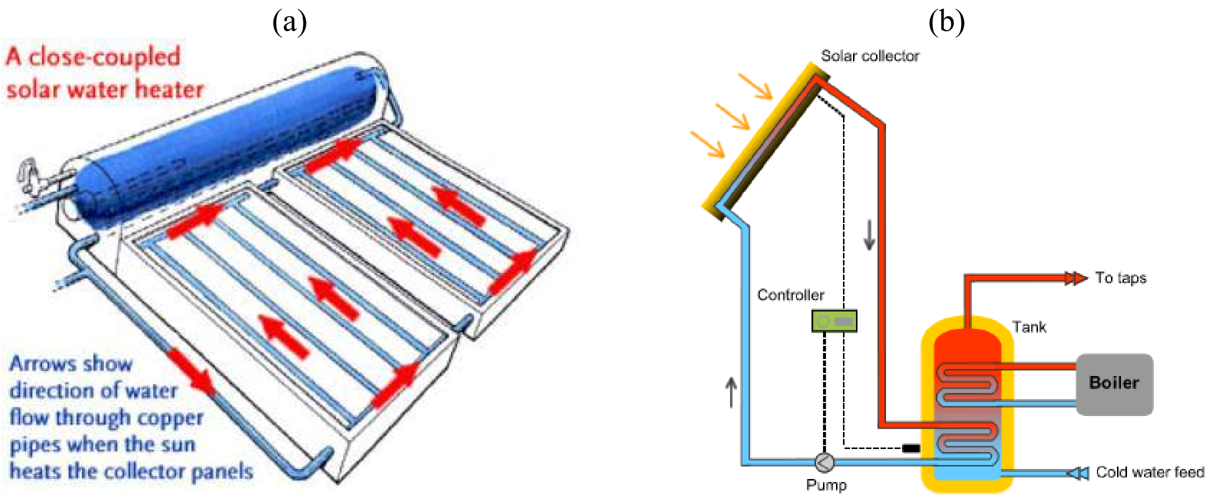


Figure 3.9: Thermal solar system: passive (a) and active (b) system.

Active solar water heaters rely on electric pumps and controllers to circulate the carrier fluid through the collectors (Figure 3.9). 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.

3.3.2.1.2 Active solar cooling

Solar cooling is used when solar heat powers an absorption heat pump. This system can be used as an air-conditioning system in any building. Deploying such a technology depends heavily on the industrial deployment of small-power absorption heat pumps.

3.3.2.1.2.1 Open cooling cycles (or desiccant cooling systems)

These 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, which is available from several suppliers for different air volume flows. 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.

3.3.2.1.2.2 Closed heat-driven cooling cycles

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.

3.3.2.1.3 Thermal storage

Within thermal solar systems, thermal storage 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).

3.3.2.1.3.1 Sensible heat storage systems

These 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.

3.3.2.1.3.2 Latent heat storage systems

In these systems, thermal energy is stored 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.

3.3.2.1.3.3 Sorption heat storage systems

In these systems, heat is stored 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.

3.3.2.1.3.4 Thermochemical heat storage systems

In these systems, heat is stored 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 3.3.4.1.

Thermal energy storage is also used for seasonal storage. In this case, underground thermal energy storage (UTES) is used, which 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. It can easily be explained that aquifer cold storage is gaining increasing interest: 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.

3.3.2.1.4 Direction of research

Improved designs are expected to address longer lifetimes, lower installed costs, and increased temperatures. The following are some design options:

- The use of plastics in residential solar water-heating systems
- Powering air-conditioning systems using solar-energy systems, especially focusing on compound parabolic concentrating collectors
- The use of flat-plate collectors for residential and commercial hot water
- 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.

3.3.2.2 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 a new 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. While 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 coefficient of performance, 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.

Other options exist in addition to sorption-based cycles for converting solar energy into useful cooling. In an ejector cycle, heat is transformed into kinetic energy of a vapour jet, which enables the refrigerant to evaporate. In a solar mechanical refrigeration cycle, a conventional vapour-compression system is driven by mechanical power that is produced with a solar-driven heat power (e.g., Rankine) cycle, in which a fluid is vapourized at an elevated pressure by heat exchange with a fluid heated by solar collectors. Finally, electricity generated by a PV system can be used to operate ordinary vapour-compression machines.

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.

The production of potable water using solar energy has been adopted practically 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. 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. Nowadays, 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 (Aqua, 2009) and discussion of SolarPACES Task VI (SolarPACES web, 2009).

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 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).

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 solar electricity generation technologies and applications.

3.3.3.1 PV Technologies

Photovoltaic technologies generate electricity directly from solar radiation. PV 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 3.10). The excited electrons leave behind positively charged "holes," which can also migrate through the semiconductor. Second, the generated electrons and holes are separated spatially at a selective interface (or junction), which leads to a build-up of 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) over the interface. In most solar cells, the junction is formed by stacking two different semiconductor layers: either different forms of the same semiconductor (in a homojunction) or two different semiconductors (in a heterojunction). Homojunctions can be formed by adding different types of impurities (dopants) to the layers on both sides of the junction. 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 junction are contacted and an electrical circuit is formed, a current can flow—that is, electrons flow from one side of the device to the other. The combination of a voltage and a current represents electric power. Thus, when the cell is illuminated, electrons and holes are generated and collected continuously and the solar cell can generate power.

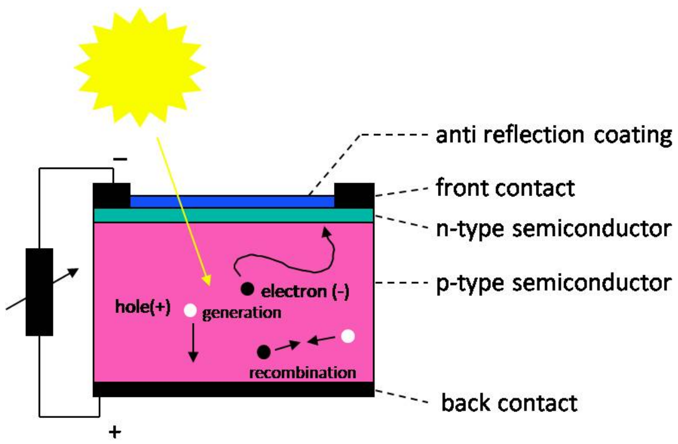


Figure 3.10: Schematic cross-section of a solar cell.

Various PV technologies have been developed in parallel and are discussed below under the headings of first- and second-generation PV—relating to the stages of research and development (R&D) maturity that the technologies represent.

3.3.3.1.1 First-generation PV

Mono- and poly(multi)crystalline silicon (Si) solar cells have dominated the PV market, with a 2008 market share of 87%. In the laboratory, the record cell conversion efficiency is up to 25% for monocrystalline silicon and 20.3% for multicrystalline cells (Green *et al.*, 2009) under standard reporting conditions (i.e., 1000 W m^{-2}, AM1.5, 25°C). A typical silicon solar cell is composed of *n*-type and *p*-type layers, and a *p-n* junction. Light absorption generates electron-hole pairs by exciting electrons from the valence band to the conduction band. The electric field across the junction separates these pairs and drives the photogenerated electrons and holes in opposite directions, causing a flow of electrons in the external circuit and thus generating electricity. The theoretical Shockley-Queisser limit of a single-junction Si solar cell is 31% conversion efficiency (Shockley and Queisser, 1961).

Several variations for higher efficiency have been developed using a heterojunction and/or back-contact structure. The heterojunction consists of a c-Si/a-Si combination—known as a heterojunction with intrinsic thin layer (HIT)—with an advantage of higher performance at high operating temperature under outdoor conditions. The highest efficiency of heterojunction solar cells is 23% for a 100-cm^2 cell (Sanyo, 2009). The back-contact structure avoids the shading effect of the top electrode, but the manufacturing process is more complicated than for the standard cell. The average efficiency of the commercial back-contact cell is reported as 23.4% (Swanson, 2004).

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 240 cm^2. Modules have increased in efficiency from about 10% in 1990 to typically 13% today, with the best performers above 17%. And manufacturing facilities have increased from the typical 1 to 5 MWp annual outputs in 1990 to hundreds of MWp for today's largest factories.

Crystalline silicon modules are typically produced in a processing sequence along a value chain that starts with purified silicon, which 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 packages designed to last for at least 25 years. The processes in the value chain have progressed significantly during recent years, but they still have potential for further large improvements.

Module assembly is still material-intensive. The assembly must protect the cells from the outdoor environment--typically for a minimum of 25 years—while allowing the cell to function as efficiently as possible. The current standard design, using rigid glass/polymer encapsulation in an aluminium frame, fulfils these basic requirements. But it represents about 30% of the overall module cost, contains considerable embedded energy (which increases the energy payback time of the module), and is a challenge to manufacture on automated lines even at current wafer thicknesses.

3.3.3.1.2 Second-generation PV

Second-generation technologies refer to thin-film solar cells, cells that have demonstrated relatively high conversion efficiencies and potentially lower costs per watt than crystalline silicon, and cells using novel materials.

3.3.3.1.2.1 Thin-film cells

Thin films include a range of material systems, from silicon-related cells, to cadmium telluride (CdTe), to copper indium gallium diselenide (CIGS).

The *amorphous Si* (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 solar cell 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 1000 times thinner than that of a crystalline Si (c-Si) cell. Developing better efficiencies for a-Si has been limited by light-induced degradation—the Staebler-Wronski effect (Staebler and Wronski, 1977)—which originates from defect creation during electron-hole recombination and causes a maximum loss of cell efficiency of about 50%. 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 result is a stabilized efficiency of 10.1% (Meier *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).

Alternative technology combining amorphous silicon with thin-film crystalline silicon (microcrystalline silicon) has recently developed in combination with sophisticated light management techniques (Meier, 1996; Yamamoto, 2003), and conversion efficiencies of more than 15% in the initial stage have been reported.

Thin-film c-Si, also known as nano- or microcrystalline, is an important PV technology, although not as commercially successful as c-Si and a-Si (Green et *al.*, 2004). These nanocrystalline cells have achieved an efficiency of 10.1%.

CdTe solar cells using a heterojunction with CdS have shown significant promise, 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 16.7% (Green *et al.*, 2008b), and commercially available modules have an efficiency of around 10%. Goncalves *et al.* (2008) predicted that the maximum efficiency will be 17.6%, and future improvements will focus on how to further reduce manufacturing costs, which are already the lowest in the industry. The toxicity of cadmium and the relative scarcity of tellurium are issues with this technology. Although CdTe itself is not a toxic material, metallic Cd can potentially be a source of contamination. But this potential hazard is mitigated by using a glass-sandwiched module design and by recycling the entire module, as well as industrial waste.

$CuInSe_2$ (CIS) solar cells are another leading thin-film technology (Kazmerski *et al.*, 1976). 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 yield a maximum efficiency of 19.9% (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, CIGS cells are a promising candidate in the future. The limitation of the indium resource will be the most significant issue in the future.

3.3.3.1.2.2 High-efficiency cells

Solar cells based on GaAs and InGaP (i.e., III-V semiconductors) are also very efficient, but expensive, devices. Better results are obtained in multijunction (or tandem) cells, with semiconductors of different energy bandgaps, thus harvesting energy from a wider solar spectrum. Double- and triple-junction devices are currently being commercialized; the most-common three-junction device is GaInP/GaAs/Ge, with a record cell efficiency of 40.7% and a submodule efficiency of 27% (Green *et al.,* 2009) To achieve an economically suitable transition for terrestrial purposes, the only feasible solution is to add these cells to a concentrator system, due to the advantage that the cell efficiencies may even increase with higher irradiance (Bosi and Pelosi, 2007).

3.3.3.1.3 Novel materials

Despite the many advances discussed above, the cost of fabricating Si solar cells is still too high for many low-cost applications. An alternative approach is to use molecular and polymer-based organic solar cells. These cells are characterized by high optical absorption coefficients and potentially low manufacturing costs. Much attention has been given to these cells recently because they are expected to play a key role in the future PV market.

Dye-sensitized solar cells (DSSCs) are a very promising alternative for low-cost production of energy. State-of-the-art DSSCs have achieved conversion efficiencies of up to 12.5% (Gratzel, 2009). Despite the gradual improvements in efficiency since discovery in 1991 (O'Reagan and Grätzel 1991), long-term stability is a key issue in commercializing these PV cells against ultraviolet light irradiation and high temperature. Electricity generation by DSSCs is based on the injection of an electron from a photoexcited state of the sensitizer dye (typically a bipyridine metal complex and sometimes organic dye) that is adsorbed on the nanoporous oxide semiconductors (e.g., TiO_2) as a cathode electrode into the conduction band of the electrode semiconductor. Excited dye is regenerated by the exchange of an electron with an iodide ion, which is oxidized in this reaction to tri-iodide at a platinized counter electrode (Gratzel, 2001). The module efficiency typically ranges between 6% and 8% using a double-sided glass structure. Because the electrolyte is a key issue in determining lifetime, scientists are developing semi-solid and fully solid electrolytes. However, efficiencies are generally lower than for the Graetzel-type solar cells.

Organic PV (OPV) cells, in contrast to DSSC, use stacked solid organic semiconductors. A typical structure of an OPV cell consists of p-type and n-type semiconductors such as P3HT and C60-related materials. The absorption layer is made of a mixture of p- and n-type materials to form a nanoscale phase separation. This bulk-heterojunction structure plays a key role in improving the efficiency. The main disadvantages associated with OPV cells are low efficiency, stability, and strength compared to inorganic PV cells.

The efficiency that can be achieved in OPV cells with single-junction cells is about 5% (Li et al. 2005; Ma et al., 2005), although predictions indicate about twice that value or even higher (Forrest, 2005; Koster et al., 2006). The efficiency of OPV cells recently reached 6.5% in a tandem cell (Kim et al., 2007). Although stability is an important issue to be addressed in OPV, the cost and processing (Brabec, 2004; Krebs, 2005) of materials have caused OPV research to advance further.

3.3.3.2 PV Applications

PV power systems are classified into two major applications: 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. Historically, in the beginning stages, PV power systems were used in isolated areas, such as outer space and deserts, as independent power sources. The importance of the role of off-grid systems has been and will be recognized particularly in remote area. However, the remarkably rapid growth of grid-connected systems has led to the majority of applications.

Off-grid systems have a significant potential in the unelectrified areas of developed countries. In those areas, a centralized system may not work economically due to low population density and the lack of infrastructure for constructing the power stations and transfer lines. Figure 3.11 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-PVPS Task 1, 2009).

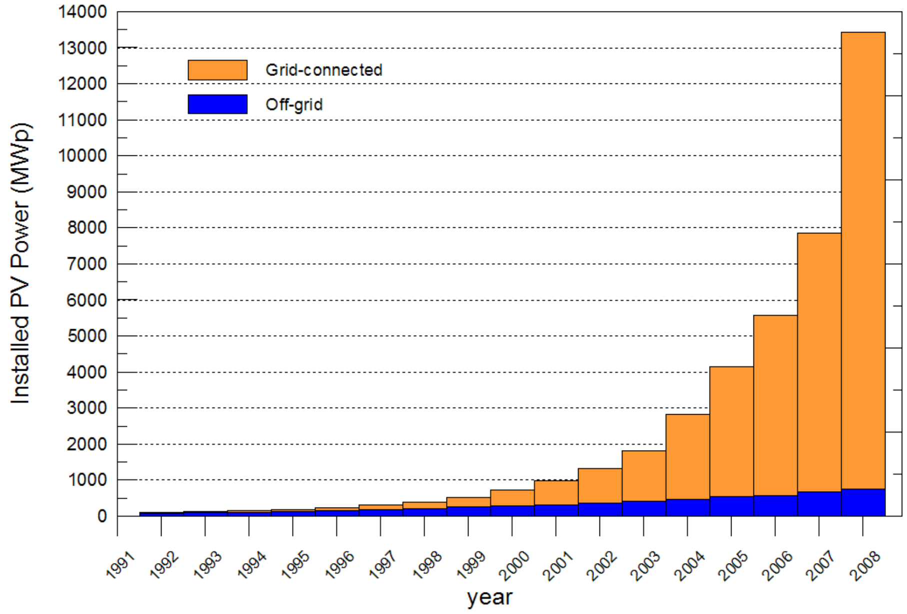


Figure 3.11: Historical trends of off-grid and grid-connected systems in the Organisation for Economic Co-operation and Development (OECD) countries (IEA-PVPS Task 1, 2009).

3.3.3.2.1 Off-grid (standalone) PV

The off-grid system provides direct current (DC) and/or alternating current (AC) power for domestic and non-domestic purposes. Off-grid domestic systems, Solar Home Systems, generally offer an economic alternative to extending the power line from an existing grid. Off-grid non-domestic systems provide power for telecommunications, water pumping, navigational aids, and other applications where small amounts of electricity have a high value. Other examples include uninterruptible power sources for information systems and communications technology, and power for cathodic protection of oil and gas pipelines.

The off-grid PV system is cost competitive with other small electricity sources. The PV system fluctuates in power depending on season, time of day, and weather; therefore, the off-grid system must have a storage system, usually batteries, to levelize its output power. The off-grid PV systems are also used in centralized hybrid systems to provide electricity to isolated village, and represent an important tool to reduce and avoid fossil fuel consumption.

3.3.3.2.2 Grid-connected PV

The grid-connected PV system uses an inverter to convert electricity from direct current (DC) as produced by the PV array to alternating current (AC), and it then supplies generated electricity to the electricity network. Electricity is often fed back to the grid when the on-site generated power exceeds the building loads.

Compared to an off-grid installation, system costs are lower because energy storage is not generally required, and also, they improve the system efficiency and decrease the environmental impact. The annual output yield ranges from 300 to 2000 kWh/kW (IEA PVPS Task 2, 2007; IEA PVPS Task 10, 2007; IEA PVPS Task 8, 2007; PV GIS, 2008) for several installation conditions in the world. The average annual performance ratio ranges from 0.7 to 0.8 (IEA PVPS Task 2, 2007).

Moreover, the grid-connected PV system is classified into two types of applications: distributed and centralized.

3.3.3.2.2.1 Distributed grid-connected PV

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 perceived 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) (IEA PVPS Task 7, 2002; Ecofys Netherlands BV, 2007; IEA PVPS Task 10, 2008).

The disadvantages include: greater sensitivity to grid-interconnection issues, compared to centralized systems, such as overvoltage and unintended islanding (Cobben et al., 2008; Ropp et al., 2007; Kobayashi and Takasaki, 2006); the designed output characteristic may not be optimal because the installation configuration depends on the land or roof area and configuration; and conditions in urban areas may not be suitable for PV systems, e.g., there may be issues related to shading effects (Ransome and Wohlgemuth, 2003; Keizer et al., 2007; Otani et al., 2004; Ueda et al., 2009).

3.3.3.2.2.2 Centralized grid-connected PV

Grid-connected centralized 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 (Figure 3.12).

Figure 3.12: A portion of the 42-MW grid-connected PV power plant in Moura, Portugal.

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.

The disadvantage is the cost of the installation land, especially in developed countries. At the end of 2007, Europe had more than half of all installations of grid-connected centralized systems, and about 30% of all systems have tracking arrays (including single- or double-axis tracking). The feasibility of very large-scale PV power generation systems, with capacities ranging from several megawatts to gigawatts, is also being studied (IEA PVPS Task 8, 2007).

3.3.3.2.3 Multi-functional PV and solar thermal components

Multi-functional 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; 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 solar electricity generation technologies and applications.

3.3.4.1 CSP Technologies

Electricity can be produced 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:

- Can be installed in a range of capacities to suit varying applications and conditions, including 10s of kW (dish/Stirling systems) through multiple MWs (tower Brayton systems) to large centralized plants (tower and trough systems)
- Can integrate 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
- Modular and scalable components
- Use no exotic materials.

Below, we discuss the various types of CSP systems and thermal storage for these systems.

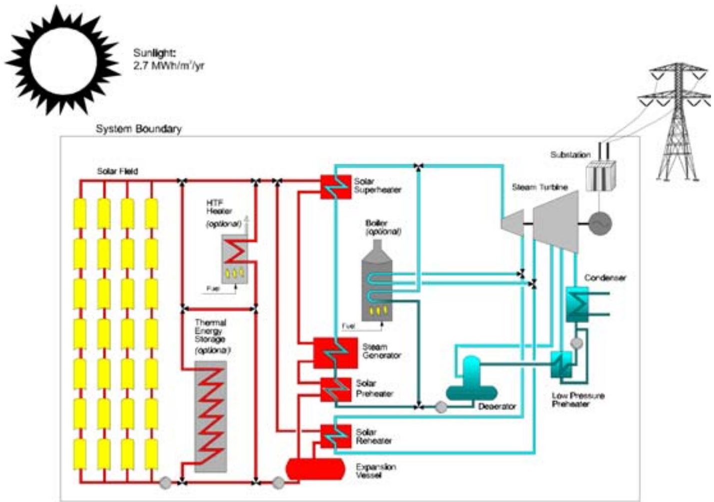
3.3.4.1.1 CSP systems

For large-scale CSP plants, the most common form of concentration is 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.

3.3.4.1.1.1 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. A 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 MWelec plant. Alternative heat-transfer fluids to the 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 storage in the case of molten salt (Figure 3.13).

(a)



(b)

Figure 3.13: Schematic (a) showing the operation of a trough plant, and photo (b) of a trough reflector and irradiated heat-collection element (white tube). [TSU: figure 3.13a too small]

3.3.4.1.1.2 Linear Fresnel reflectors

Presently, large trough reflectors use thermal bending to achieve the curve required in the glass surface. In contrast, 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. 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.

3.3.4.1.1.3 Central receivers (or power towers)

Thermodynamic cycles used for generating electricity are more efficient at higher temperatures. Point-focus collectors such as central receivers are able to generate much higher temperatures than troughs and linear Fresnel reflectors, though requiring two-axis tracking. 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 (Figure 3.14).

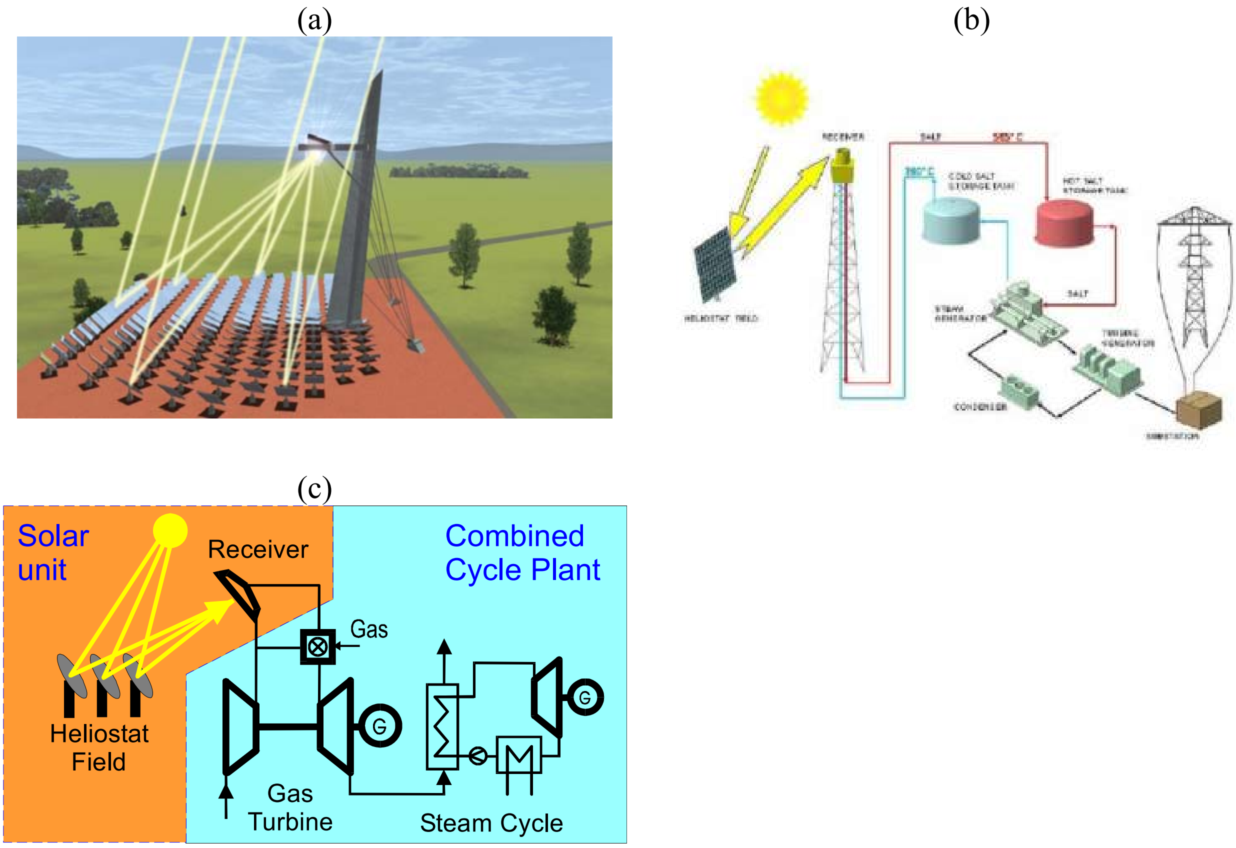


Figure 3.14: Central receiver (or power tower) technology, including: (a) an illustration of the operating principle of tracking heliostats (courtesy CSIRO); (b) a schematic of the principle of using towers and molten salts; and (c) a schematic showing the principle of using towers to drive a Brayton cycle (courtesy DLR). [TSU: Figure 3.14b is too small]

3.3.4.1.1.4 Dish systems

The dish is the ideal optical reflector and therefore is 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 kWe. 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 (Figure 3.15).

(a) (b)

Figure 3.15: (a) Photo of a typical dish/Stirling system, and (b) a 400-m^2 dish system at Australian National University in Australia.

3.3.4.1.2 Thermal storage for CSP

An important attribute of CSP is the ability to integrate thermal storage. 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. Solar Tres, a 17-MW solar tower being developed in Spain, is designed for 6500 hours per year operation—or a 74% capacity factor.

In thermal storage, the heat from the solar field is stored prior to reaching the turbine. Storage takes the form of sensible, latent, or chemical (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. 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. Although not strictly thermal, it integrates well with large-scale CSP systems where compressors are driven by turbines during the sunlight hours and then the air turbines are driven by the stored energy as required. Another form of storage associated with high-temperature CSP is thermochemical storage. This is discussed more fully in 3.3.5 and 3.7.5.

3.3.4.2 CSP Applications

Concentrating solar power can be applied from 10s of kW all the way to large centralized power stations of hundreds of MW.

3.3.4.2.1 Distributed Generation

The dish/Stirling technology 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 kWe, power stations having a large capacity up to 800 MW have been proposed by aggregating many modules (Figure 3.16a). 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 3.16: (a) Rendering of aggregated dish/Stirling units, and (b) a sister tower of one to be used for powering a Brayton cycle microturbine (courtesy CSIRO).

An alternative to the Stirling engine is the microturbine based on the Brayton cycle (Figure 3.16b). 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 CSP application, 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.

3.3.4.2.2 Centralized CSP

An attraction of CSP has been 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, the benefits of larger scale have also tended to be an inhibitor until recently because of the much larger commitments required by investors.

Table 3.3 shows the earliest commercial CSP plants, most of which are still in operation 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 presently mandate that the largest-capacity unit that can be installed is 50 MW, which is to help stimulate industry competition. In the United States, proposals have been put forward for much larger plants—280 MW in the case of troughs and 100- and 200-MW plants based on towers. Abengoa Solar has recently commissioned commercially operational towers of 10 and 20 MW, and all tower developers plan to increase capacity in line with technology development, regulations, and investment capital. Figure 3.17 provides photos of various large-scale CSP plants.

Table 3.3: Development of early trough CSP plants.

SEGS Plant	1st Year of Operation	Net Output (MW_e)	Solar Field Outlet Temp. (°C/°F)	Solar Field Area (m^2)	Solar Turbine Eff. (%)	Fossil Turbine Eff. (%)	Annual Output (MWh)
I	1985	13.8	307/585	82,960	31.5	-	30,100
II	1986	30	316/601	190,338	29.4	37.3	80,500
III & IV	1987	30	349/660	230,300	30.6	37.4	92,780
V	1988	30	349/660	250,500	30.6	37.4	91,820
VI	1989	30	390/734	188,000	37.5	39.5	90,850
VII	1989	30	390/734	194,280	37.5	39.5	92,646
VIII	1990	80	390/734	464,340	37.6	37.6	252,750
IX	1991	80	390/734	483,960	37.6	37.6	256,125

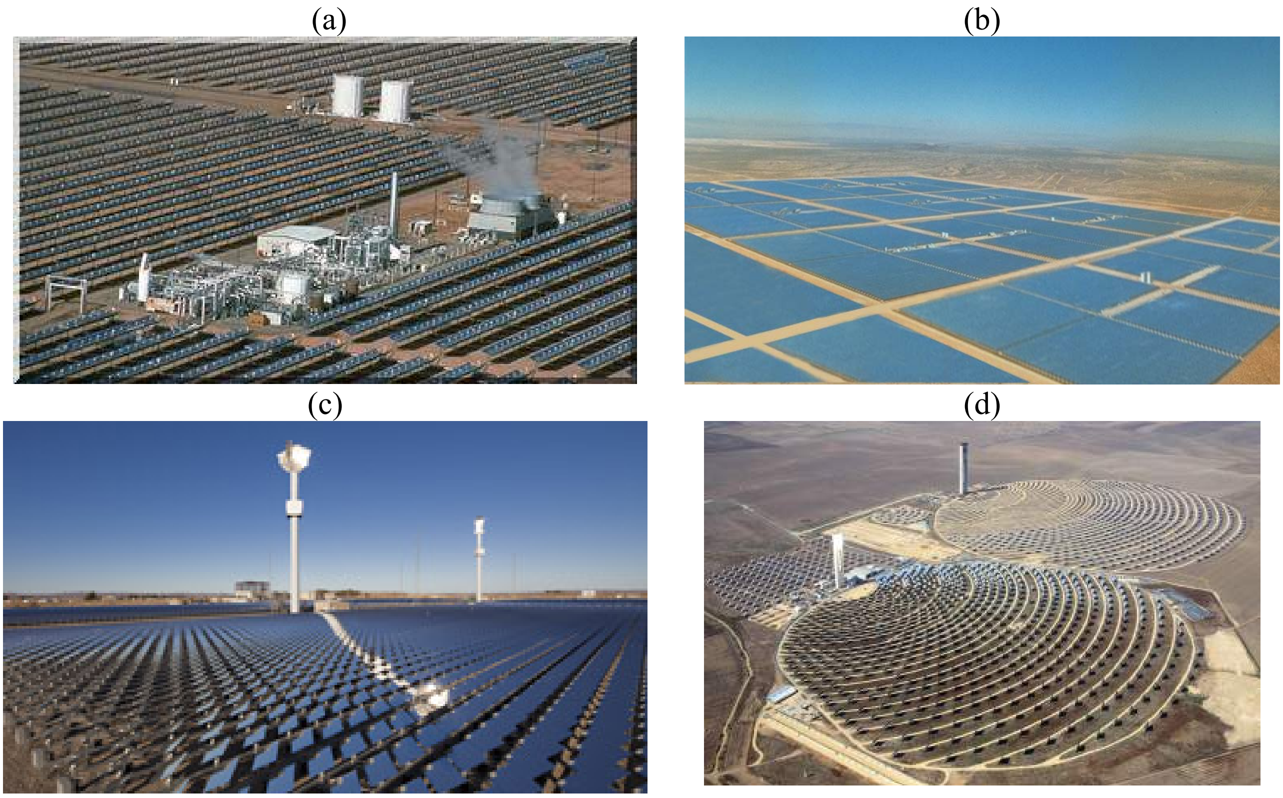


Figure 3.17: Large-scale CSP plants: (a) one of the original LUZ plants in California, operating for 20 years, showing the trough collectors and steam turbine plant; (b) an aerial view of the LUZ plants at Kramer Junction, California; (c) photo of eSolar's 5-MW demonstration plant in California; (d) aerial view of Abengoa Solar's PS10 and PS20 near Seville, Spain.

3.3.5 Solar Fuels Conversion

This subsection discusses solar fuels conversion technologies and applications.

3.3.5.1 Solar Fuels Conversion Technologies

Solar-driven methods for fuel processing include thermal decomposition, thermochemical, photochemical, electrochemical, biochemical, and hybrid reactions. Feedstocks include inorganic compounds such as water and carbon dioxide, and organic sources such as coal, biomass, and methane. The forms of solar fuels are hydrogen (H_2) gas, synthesis gas (mixed gas of H_2 and CO_2), and their derivatives such as methanol, dimethyl ether (DME), and synthesis oil.

Direct conversion of solar energy to fuel is an emerging CSP technology, and as such, it is not yet widely demonstrated or commercialized. But two options appear commercially feasible: (1) the solar hybrid fuel production system (including solar methane reforming, and solar biomass reforming/gasification), and (2) PV- or CSP-solar electrolysis. These technologies are key for reducing greenhouse gas 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 broadens with high-temperature CSP electricity generation systems, and high-temperature thermochemical technology is demonstrated through pre-commercial systems, hybrid solar fuels can begin to integrate seamlessly into the present global fuels supply chain. Ultimately, the use of fossil fuels can be phased out and hybrid solar fuels could be replaced by pure solar fuels.

The equivalent of 0.5 terawatt 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.

3.3.5.1.1 Solar hybrid fuel production system

Solar hybrid fuel—such as methanol, DME, and synthetic oil from syngas—can be produced by supplying the concentrated solar thermal energy to the endothermic process of methane- and biomass-reforming.

Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) is running a 250-kW reactor and plans to build a 4-MWchemical 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, the concept is that solar fuels can be produced in liquid form in sunbelts such as Australia and solar energy be shipped on a commercial basis to Asia and beyond.

At present, the simplest feedstock for conversion by solar energy is methane, whether from natural gas or coal-bed methane. Other possibilities are under development such as supercritical gasification of biomass and thermal decomposition of coal and petcoke.

The O_2 gas produced by electrolysis with electricity from either CSP or PV can be used for coal gasification and partial oxidation of natural gas. Electricity generated by CSP-solar electrolysis can be used in place of PV-solar electrolysis to decompose water. 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 only the solar electrolysis process.

3.3.5.2 Solar Fuels Conversion Applications

Solar hydrogen and solar hybrid fuels can replace conventional gasoline and diesel as transportation fuels. Some solar fuels can also be used for cars using fuel cells.

Solar hydrogen is effectively an energy carrier, and as such, it is one means of solar energy storage and transport. It offers an alternative to batteries, and there are many advocates supporting the concept that hydrogen could be the ultimate transport fuel, as long as it is generated sustainably and cost effectively.

Energy storage is an issue at the solar power stations themselves. To take full advantage of energy sources such as solar, power stations must be able to store large amounts of energy for use when the sun is not shining. Thermochemical storage could play a role here, as a typical power station environment and energy flow paths can integrate thermochemistry. More advanced coal cycles such as integrated gasification combined cycle (IGCC) involve thermochemistry for separating CO_2 and H_2 production.

The solar hybrid fuels such as methanol, DME, and synthetic oil can be used as a liquid fuel. Synthetic oil can be used directly for automobiles and power station. Methanol and DME can be used for fuel cells after reforming. DME can also be used in place of liquefied petroleum gas.

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, and then on industry capacity and supply chain.

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 fuels conversion.

3.4.1.1 Passive Solar Technologies

At this time, no estimates are available for the installed capacity of passive solar or the energy generated through this technology.

3.4.1.2 Active Solar Heat and Cooling

The world global solar heating market totalled an estimated 19.9 GWth in 2007 (Figure 3.18) and about 19 GWth in 2008 (REN21, 2009). Flat-plate and evacuated-tube collectors accounted for 18.4 GWth, which is 92.5% of the overall market. The main markets for unglazed collectors are in the USA (0.8 GWth) and Australia (0.4 GWth). South Africa, Canada, Mexico, The Netherlands, Sweden, Switzerland, and Austria also have notable markets, but all with values below 0.1 GWth 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.

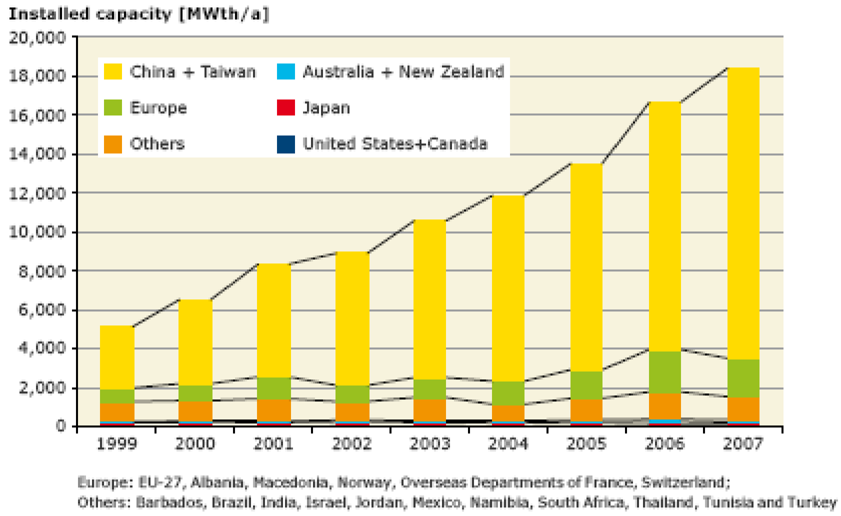


Figure 3.18: Installed solar thermal collector capacity (IEA SHCP 2009).

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}.

3.4.1.2.1 Current trends

Solar thermal energy is increasingly popular in a growing number of countries worldwide (

Table 3.4), with the worldwide market having grown continuously since the beginning of the 1990s (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.

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 totalled an estimated 19.9 GW_{th}. In China, the installation rate has been growing by almost 30% per year, and 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.

Table 3.4: Solar hot water installed capacity, top 10 countries and world total, 2007 (from REN 21, 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 GWth. China added an estimated 14 GWth in 2008, which, along with extrapolating 2007 additions for other countries, yields a 2008 estimate of 145 GWth. Source: Werner Weiss and Irene Bergmann, and IEA Solar Heating and Cooling Programme, Solar Heat Worldwide: Markets and Contributions to Energy Supply 2007, edition 2009; also estimates by the China Renewable Energy Industries Association.

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 Europe, the market size more than tripled between 2002 and 2008 (Figure 3.19). 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.

Figure 3.19: Market development of annual solar thermal installations in the European Union (ESTIF, 2009).

The use of solar thermal energy clearly varies greatly in different countries (Figure 3.20). 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.

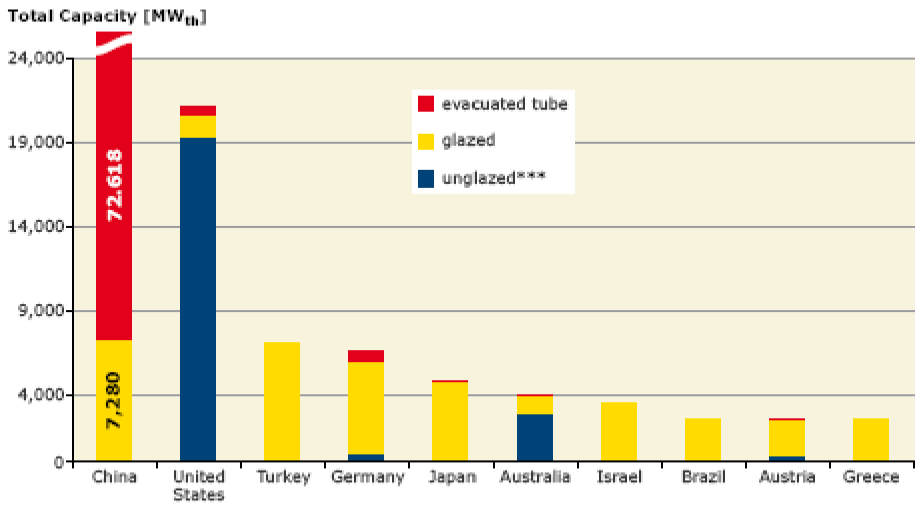


Figure 3.20: Total capacity in operation of water collectors of the 10 leading countries at the end of 2007 (IEA SHCP, 2009).

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 m2 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 totalled 785 MW_{th}, with 57% of the installations in Hawaii and Florida (EIA, 2008).

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.

3.4.1.2.2 Short-medium-term solar thermal potential

According to 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 (ESTTP, 2008).

ESTIF set the goal of 1 m^2 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.

3.4.1.3 Photovoltaic Electricity Generation

Newly installed capacity in 2008 with 5.6 GW more than doubled from 2007, with Europe, Japan, the USA, and Korea together installing 5.4 GW. This addition brought the cumulative installed PV capacity worldwide to almost 15 GW—a capacity able to generate up to 18 TWh per year. More than 80% of this capacity is installed in three leading markets: the EU27 with 9.5 GW (63%); Japan with 2.2 GW (14%); and the USA with 1.2 GW (8%). 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 3.21 illustrates the cumulative installed capacity for the top seven PV markets through 2008, including Germany (5351 MW), Spain (3405 MW), Japan (2619), USA (1173 MW), Korea (352 MW), Italy (358 MW), and PR China (140 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. The top seven markets for 2008 additions were Spain (2671 MW), Germany (1505 MW), the USA (342 MW), Korea (274 MW), Japan (252 MW), Italy (197 MW), and France (44 MW).

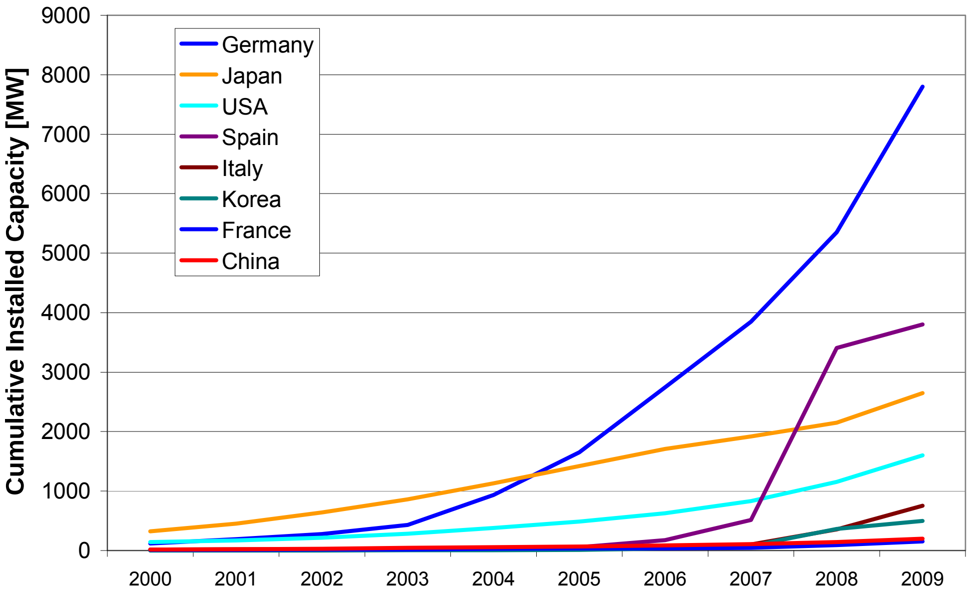


Figure 3.21: Installed PV capacity in eight markets (data source: IEA PVPS Task 1, 2009; REN21, 2009; EurObserv'ER, 2009; Jäger-Waldau, 2009)

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-normal irradiance (DNI), 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 predictions for 2009 and 2010 are 30 MW and 100 MW annual installations, respectively.

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 and the Strategic Energy Technology plan is calling for electricity in Europe for up to 12% in 2020.
- The 2009 Indian Solar Plan 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;
- USA Plans – add U.S targets.

3.4.1.4 CSP Electricity Generation

Between 1985 and 1991, some 354 MW of solar trough technology were 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. Financially, CSP technology is most viable in large-scale installations. However, with such worldwide market conditions, there were insufficient market signals or greenhouse gas incentives to support large installations. 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 2004.

At this time, more than 650 MW of grid-connected CSP plants are installed worldwide, with another 1800 MW under construction. 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. Table 3.5 lists installed CSP plants worldwide as of the end of 2008.

Table 3.5: Global installed (operational) CSP plants (Wikipedia, 2009)

Name	Country	Location	Technology	Capacity (MW)	Notes
Solar Energy Generating Systems	USA	Mojave Desert California	Parabolic trough	354	Collection of 9 units
Nevada Solar One	USA	Boulder City, Nevada	Parabolic trough	64	
Andasol solar power station	Spain	Granada	Parabolic trough	100	Andasol 1 completed, 2008; Andasol 2 completed, 2009
Energia Solar De Puertollano	Spain	Puertollano, Ciudad Real	Parabolic trough	50	Completed May 2009
Alvarado 1	Spain	Badajoz	Parabolic trough	50	Completed July 2009
PS20 solar power tower	Spain	Seville	Power tower	20	Completed April 2009
PS10 solar power tower	Spain	Seville	Power tower	11	Europe's first commercial solar tower
Kimberlina Solar Thermal Energy Plant	USA	Bakersfield, California	Fresnel reflector	5	Ausra demonstration plant
Sierra SunTower	USA	Lancaster, California	Power tower	5	eSolar demonstration plant, USA's first commercial solar tower, completed August 2009
Liddell Power Station Solar Steam Generator	Australia	New South Wales	Fresnel reflector	2	electrical equivalent steam boost for coal station
Jülich Solar Tower	Germany	Jülich	Power tower	1.5	Completed December 2008

THEMIS Solar Power Tower	France	Pyrénées-Orientales	Power tower	1.4	Hybrid solar/gas electric power, using solar energy to heat the air entering a gas turbine
Puerto Errado 1	Spain	Murcia	Fresnel reflector	1.4	Completed April 2009
Saguaro Solar Power Station	USA	Red Rock Arizona	Parabolic trough	1	
Keahole Solar Power	USA	Hawaii	Parabolic trough	1	
Kibbutz Samar Power Flower	Israel	Kibbutz Samar	Power tower	0.1	
Overall Operational Capacity (MW)				**667.4**	

In 2007, after more than 15 years, the first new major CSP plants came on line with Nevada Solar One (64 MW, USA) and Planta Solar 10 (11 MW, Spain). In Spain, Royal Decree 436/2004 dated 12 March 2004 is a major driving force for CSP plant construction and expansion plans. The guaranteed feed-in tariff is 0.27 €/kWh for 25 years. In the *Plan de Energías Renovables en España* (PER) (2005 to 2010), a total capacity of 500 MW is foreseen. In 2008, at the coal-fired Liddell Power station (2,000 MW) in New South Wales, Australia, some of the station's boiler feedwater was replaced by hot water from an 18,000 m^2 CSP array. Figure 3.22 and Table 3.6 show the current and planned developments to add more CSP capacity in the near future.

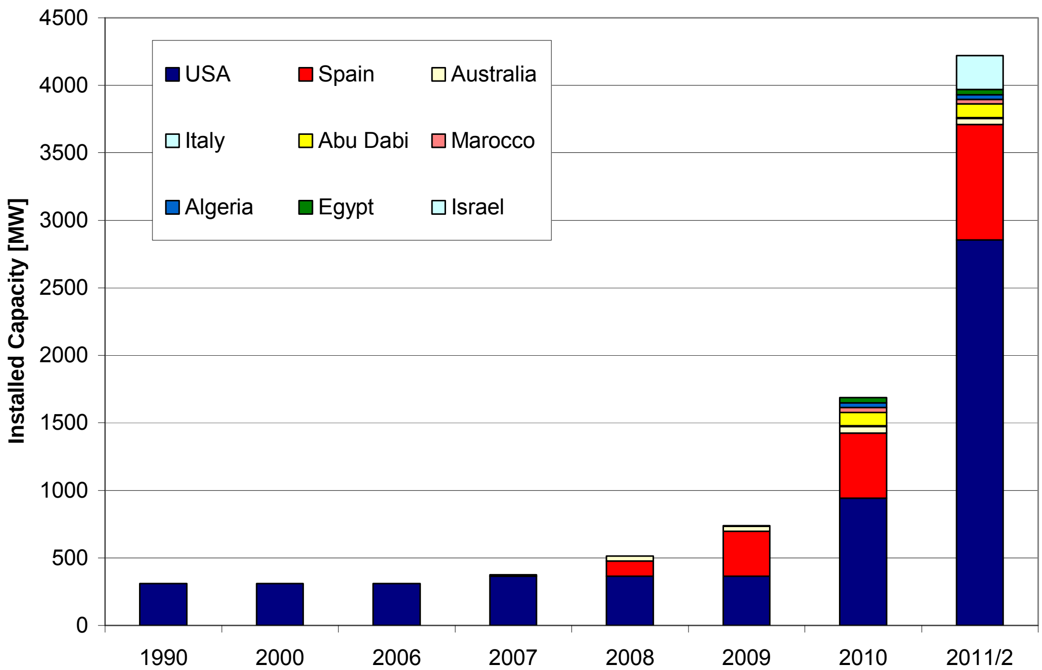


Figure 3.22: Installed and planned concentrated solar thermal electricity plants by country. (Kautto and Jäger-Waldau, 2009).

Table 3.6: CSP projects currently under construction or in test phase (Wikipedia, 2009). [TSU: other reference source is needed here]

Name	Country	Location	Technology	Capacity (MW)	Notes
Martin Next-Generation Solar Energy Center	USA	Florida	Integrated Solar Combined Cycle (ISCC)	75	Steam input into a combined cycle
Andasol 3–4	Spain	Granada	Parabolic trough	100	With heat storage
Palma del Rio 1, 2	Spain	Cordoba	Parabolic trough	100	
Majadas de Tiétar	Spain	Cacares	Parabolic trough	50	
Solnova 1, 3, 4	Spain	Seville	Parabolic trough	150	
Extresol 1-3	Spain	Torre de Miguel Sesmero (Badajoz)	Parabolic trough	150	
Helioenergy 1, 2	Spain	Ecija	Parabolic trough	100	With heat storage
Solaben 1, 2	Spain	Logrosan	Parabolic trough	100	
Valle Solar Power Station	Spain	Cadiz	Parabolic trough	100	With heat storage
Lebrija-1	Spain	Lebrija	Parabolic trough	50	
Manchasol-1	Spain	Ciudad Real	Parabolic trough	50	With heat storage
La Florida	Spain	Alvarado (Badajoz)	Parabolic trough	50	
La Dehesa	Spain	La Garrovilla (Badajoz)	Parabolic trough	50	
Aste 1A, 1B	Spain	Alcázar de San Juan (Ciudad Real)	Parabolic trough	100	
Axtesol 2	Spain	Badajoz	Parabolic trough	50	
Arenales PS	Spain	Moron de la Frontera (Seville)	Parabolic trough	50	
Serrezuella Solar 2	Spain	Talarrubias (Badajoz)	Parabolic trough	50	
El Reboso 2	Spain	El Puebla del Rio (Seville)	Parabolic trough	50	

Termosol 1+2	Spain	Navalvillar de Pela (Badajoz)	Parabolic trough	100	
Helios 1+2	Spain	Ciudad Real	Parabolic trough	100	
Kuraymat Plant	Egypt	Kuraymat	ISCC	20	
Hassi R'mel integrated solar combined cycle power station	Algeria	Hassi R'mel	ISCC	25	
Beni Mathar Plant	Morocco	Beni Mathar	ISCC	20	
Gemasolar, former Solar Tres Power Tower	Spain	Fuentes de Andalucia (Seville)	Power tower	17	
Overall Capacity Under Construction (MW)				**1757**	

The average investment costs for a CSP plant are given in various projects at about 4.62 $/W (2005 $) (4 €/W; 2008 €). The project costs can increase up to 16.16 $/W (2005 $) (14 €/W 2008 €), depending on the level of storage or other backup provided. In this case, even though capital cost increases, so too does annual capacity factor; therefore, the levelized cost of energy (LCOE) does not necessarily change dramatically. Indeed, even if storage caused the LCOE to increase marginally, this increase would be more than recovered by the ability to dispatch electricity at times of peak tariffs in the market. Thus, the internal rate of return improves.

More than 50 CSP electricity projects are currently in the planning phase, mainly in North Africa, Spain, and the USA. In the USA, more than 4,500 MW 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). In Spain, CSP projects with about 1,800 MW have provisional registration, and projects with more than 10 GW have filed grid-access applications. In Australia, the federal government has called for 1,000 MW of new solar plants, covering both CSP and PV, under the Solar Flagships program.

3.4.1.5 Solar Fuel Conversion

At this time, data are not available on installed capacity and generated energy for solar fuel conversion.

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 fuels conversion.

3.4.2.1 Passive Solar Technologies

This subsection discusses industry capacity and supply chain issues of passive solar technologies within the areas of the overall building industry, windows, and thermal storage.

3.4.2.1.1 Building industry

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 (Passive House Institute web, 2009; Cepheus, 2009; PHPP, 2004).

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, 2009)—SHC Task 40—ECBCS Annex 52, which focuses on net-zero energy solar buildings. In Canada, the EQuilibrium™ net-zero energy home demonstration program conducted by Canada 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 3.23 shows photos of one of these homes—the EcoTerra™—which is a prefabricated home (Chen et al., 2007). 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 3.23: Photos from the EcoTerra™ demonstration solar house assembly and the final completed house.

Another IEA Annex—ECES IA Annex 23— was initiated in November 2009 (IEA ECES IA web, 2009). 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.

3.4.2.1.2 Windows

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. 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 tradeoff between the cooling, heating, and lighting requirements (Figure 3.24). New technologies such as transparent photovoltaics and electrochromic windows provide many possibilities in the design of solar houses and offices with abundant daylight. Another possibility is the provision of summer shading for direct-gain windows by using photovoltaic overhangs. Triple-glazed, low-emissivity, argon-filled windows with efficient framing were used in the EQuilibrium™ 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.

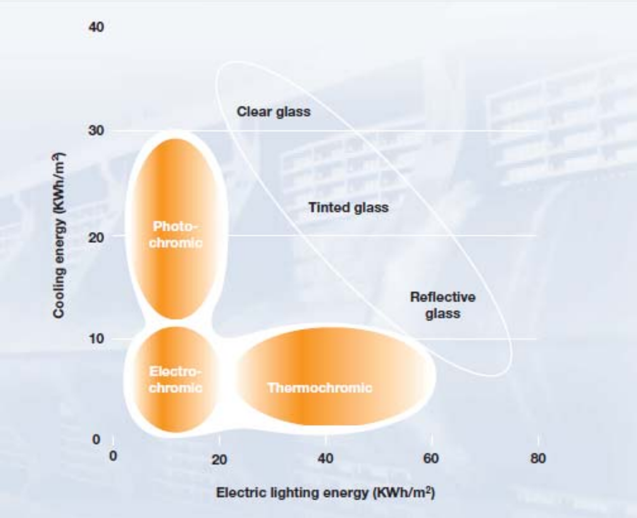


Figure 3.24: Lighting energy versus cooling energy for different glazing types (UNEP, 2007).

3.4.2.1.3 Low-temperature thermal storage

The primary materials for 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.

3.4.2.2 Active Solar Heat 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 GWth corresponded to 28.4 million m2 of solar collectors. Flat-plate and evacuated-tube collectors accounted for 18.4 GWth, 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 Russian, the research and production association “Engineering Industry” produces solar collectors made of aluminium. One company produces aluminium-copper solar collectors, and another enterprise produces copper-steel collectors.

3.4.2.3 PV Electricity Generation

This subsection discusses 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.

3.4.2.3.1 Solar cell production

Global PV cell production reached more than 7 GW in 2008—almost doubling the 2007 production level of 3,715 MW. Figure 3.25 depicts the increase in production from 1990 through 2008, showing regional contributions (Jäger-Waldau, 2009). The five-year compound annual growth rate in production from 2003 to 2008 was more than 50%. Solar cell production capacities for wafer silicon-based solar cells represent only the cells; for thin films, the complete integrated module is considered. Only those companies that actually produce the active circuit (solar cell) are counted. Companies that purchase these circuits and make cells are not counted.

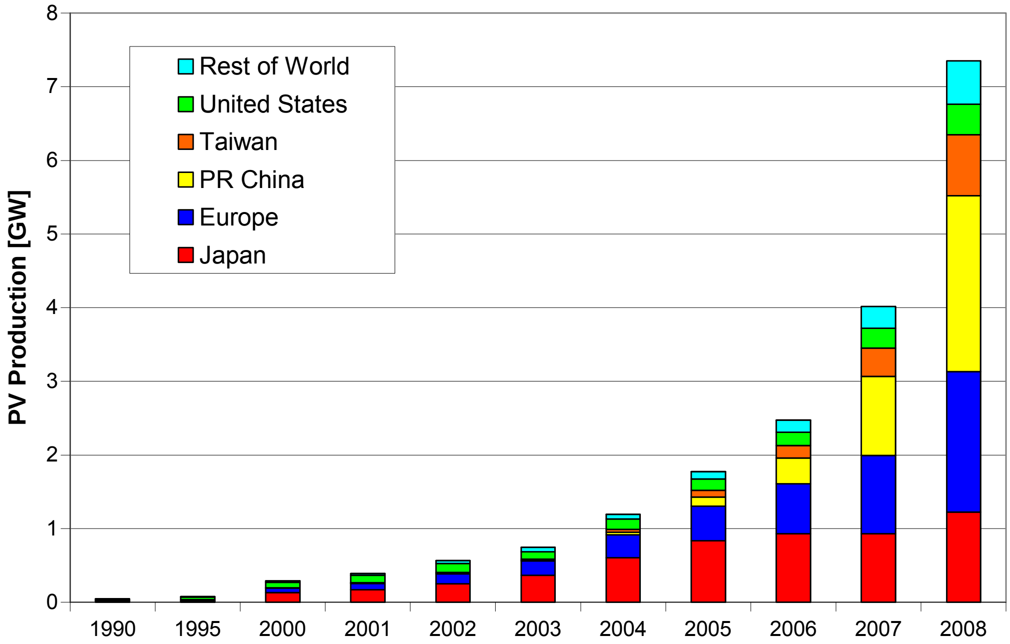


Figure 3.25: Worldwide PV production from 1990 to 2008 (Jäger-Waldau, 2009).

These estimates show a significant growth in production despite tight silicon supply and resulting high silicon costs. The announced increases of production capacities—based on a survey of about 200 companies worldwide—again accelerated in 2008 and early 2009 (Figure 3.26). Only published announcements of the respective companies and no third-party information were used. The cut-off date of the information included was February 2009. 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.

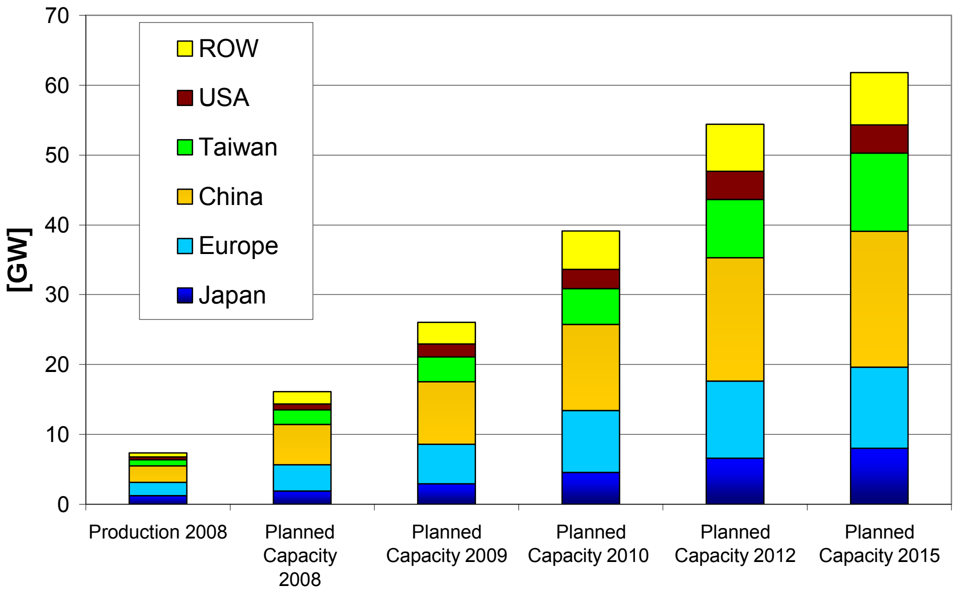


Figure 3.26: Worldwide PV production and with future planned production capacity increases.

Both Chinese (PRC) and Taiwanese PV production increased at a greater rate than the industry as a whole. The PRC is the top producer with 2 to 2.5 GW. This is significantly more than Europe with

1.5 to 1.8 GW, Japan with 1.2 to 1.5 GW, and Taiwan with 0.5 to 0.8 GW. Market estimates vary between 5 and 6 GW with shipments to first point in the market estimated at 5.5 GW (Mints, 2009).

In terms of company production, the largest producer came from Germany with 570 MW, followed by a company in China with 550 MW, an international producing company (USA / Germany / Malaysia) with 503 MW, and a Japanese company producing 470 MW.

If all current plans can be realized by 2012, China will have about 28% of the worldwide production capacity of 48 GW, followed by Europe with 22%, and Japan and Taiwan with 15% each. However, it is expected that the capacity utilization rate will further decrease from 56% in 2007 and 54% in 2008 to less than 50% in 2012.

3.4.2.3.2 Wafer-based silicon cell and module production

Worldwide, some 200 factories produce silicon wafer-based solar cells and more than 300 produce solar modules. In 2008, silicon-based solar cells and modules represented about 85% of the worldwide market (Figure 3.27). Despite a massive increase in production capacities, the total market share of wafer-based silicon is expected to decrease over the next few years.

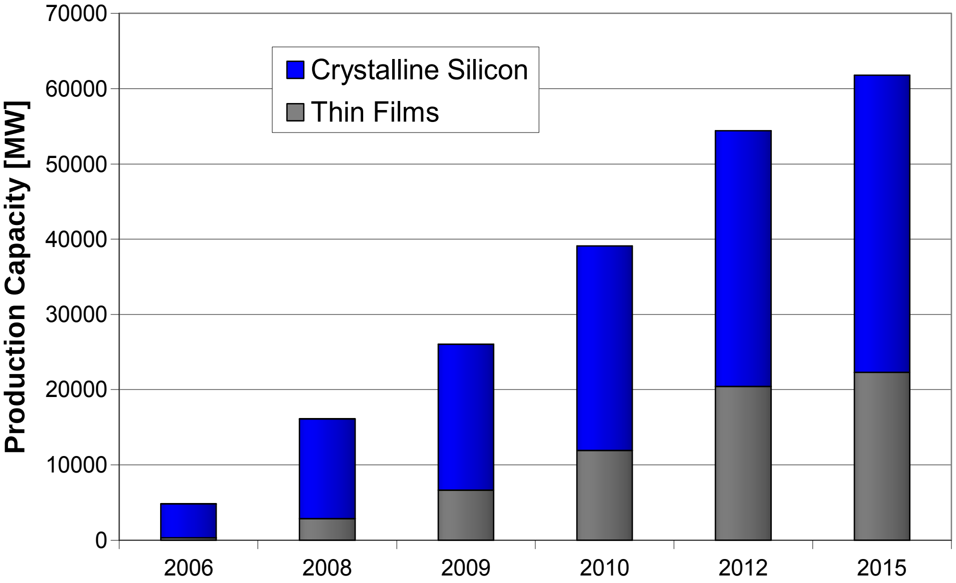


Figure 3.27: Actual and planned production capacities of thin-film and crystalline silicon-based solar modules (Jäger-Waldau, 2009).

In 2008, the main production clusters were in China, Europe, Japan, and Taiwan, accounting for more than 87% of worldwide production. With current economic constraints, the trend has accelerated to move production to Asia. If the current trend continues, only 25% of the worldwide cell production capacity will be in Europe and the USA by 2015.

Due to the nature of module manufacturing and that the heaviest components are glass and a metal frame, production capacities close to the final market are still a favourable option. However, an emerging trend is a move to large original design manufacturing (ODM) units, similar to the developments in the semiconductor industry.

3.4.2.3.3 Thin-film module production

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 10% in 2007 and 12% to 14% in 2008. Thin-film shipments in 2008 increased by 129% compared to 2007, and the utilization rate of thin-film production capacities is 60%—somewhat higher than the 54% overall utilization rate of the PV industry.

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 11.9 GW or 30% of the total 39 GW in 2010 and 20.4 GW in 2012 of a total of 54.3 GW. The first thin-film factories with GW production capacity are already under construction for various thin-film technologies.

3.4.2.3.4 Polysilicon production

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 which 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, 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 PV products.

The regional distribution of the polysilicon production capacities are as follows: China 20,000 metric tons, Europe 17,500 metric tons, Japan 12,000 metric tons, USA 37,000 metric tons (RTS, 2009; Chinese Academy of Science, 2009).

Projected silicon production capacities available for solar in 2010 vary between 99,500 metric tons (PV News, 2008) and 245,000 metric tons (EuPD, 2008). In addition, the possible solar cell production will depend on the material use per Wp.

3.4.2.4 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, were built by Luz, and they continue to operate today, although with new owners.

The next commercial plant was the 64-MW Nevada Solar One, built and owned by Acciona, and commissioned in 2007 in Nevada, USA. This plant uses, for the first time, troughs constructed of aluminium 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 are capable of supplying large orders of tubes. The trough concentrator itself comprises know-how in both structures and thermally sagged glass mirrors. And 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 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 receivers 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. Apart from Abengoa Solar with PS10 and PS20, the new players presently have projects at the demonstration level. The accepted standard was for large heliostats, but new players 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 1,400 MW either commissioned or under construction, with the diversity of sites shown in Figure 3.28. 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. Figure 3.29 illustrates the relative maturity of the various CSP technologies and shows how the CSP market may develop over time.

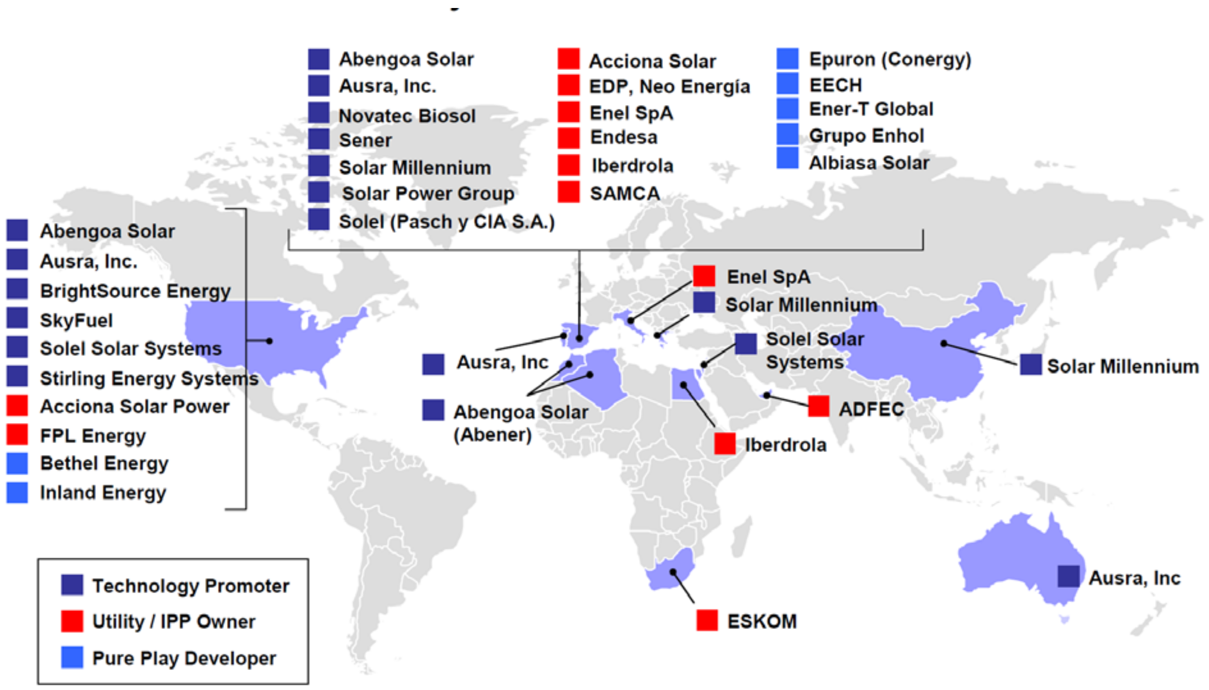


Figure 3.28: The global nature of the CSP industry is shown in this illustration. (Courtesy Emerging Energy Research, 2007).

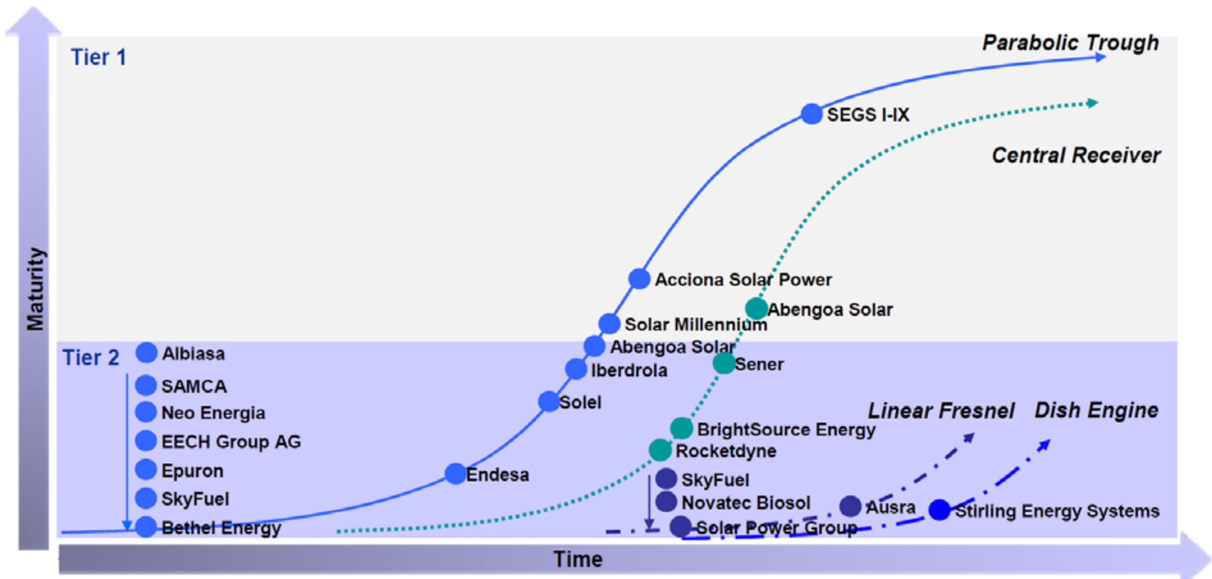


Figure 3.29: Illustrates the relative maturity of the various CSP technologies and shows how the CSP market may develop over time.

The supply chain is not limited by raw materials, because the majority of required materials are glass, steel/aluminium, and concrete. At present, Schott and Solel are the only two recognized suppliers of evacuated tubes with sufficient capacity to supply tubes to service several hundred MW/yr. However, expanded capacity can be introduced fairly readily through new factories with an 18-month lead time.

3.4.2.5 Solar Fuel Conversion

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 solar towers, with solar fuels requiring a different reactor at the focus and different downstream processing and control. However, much of the downstream technology would come from expertise in the petrochemical industry. The scale of solar fuels demonstration plants is being ramped up to build confidence for industry, which will eventually expand operations.

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) and 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 meeting 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. Figure 3.30 shows a house that is expected to meet the requirements for a net-zero energy solar building.

Figure 3.30: Photo of the Eco-Terra home in Quebec, Canada, illustrating at least four types of solar technology integrated into one building and designed to achieve zero net-energy consumption over one year (Athienitis, 2008).

3.5.2 Low-Capacity Electricity Demand

Solar energy is an abundant potential source of renewable energy, and it is available in all areas of the world. However, solar energy technologies are relatively expensive compared to other energy technologies and are economically viable only in certain areas. There is a need to further develop solar energy technologies, such as to increase the efficiency of solar energy generation and to reduce the capital cost of solar energy technologies. This would allow more countries to increase the amount of solar energy in their fuel mix. There can be comparative advantages for using solar energy rather than fossil fuels in many developing countries. Within a country, the comparative 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.

For rural electrification, a common approach is to consider any mature technology and to make the final choice based on economic efficiency. This 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 some developing 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 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. 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.

3.5.3 District Heating and Other Thermal Loads

3.5.3.1 Solar water heater systems

In Australia, China, Greece, Israel, and the USA, solar water heaters make a significant contribution to residential energy demand. 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. 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).

3.5.3.2 Biomass and solar thermal electricity

Combining biomass and 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 might be a critical constraint of PV integration into a power system.

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 (Figure 3.31). 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.

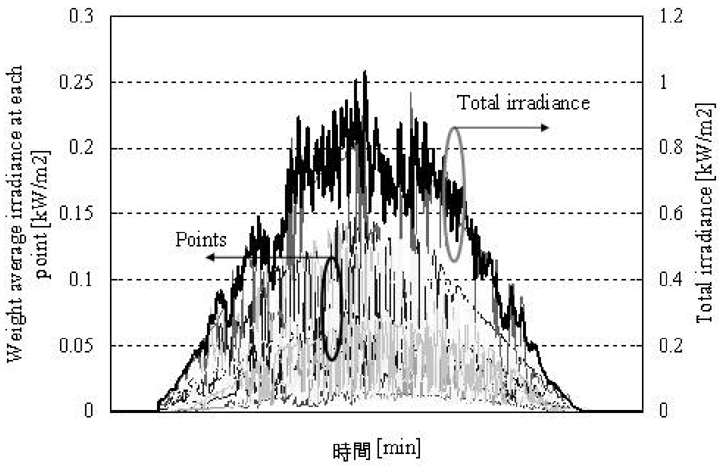


Figure 3.31: Image of smoothing effect of multiple PV systems

However, the critical impact on supply-demand balance of a power comes from the total generation of the PV system of a power system.

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 will contribute to the economical and reliable integration of PV into the energy system.

3.6 Environmental and Social Impacts

The section first discusses the environmental impacts of direct solar technologies, then describes potential social impacts.

3.6.1 Environmental Impacts

3.6.1.1 Clean energy benefit estimates

No consensus exists on the premium, if any, that society should pay for cleaner energy. However, in recent years, there has been progress in analysing 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 3.7 correspond to the "uniform world model," with a regional average (land and water) population density of 80 persons per km2. For other regions, these numbers should be scaled according to population density.

Table 3.7: Unit damage costs for air pollutants in €2000 per elementary flow (source: NEEDS, 2009).

		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 kilowatt-hour. The results of studies such as NEEDS (2009), summarized in Table 3.8, confirm that this is usually the case, but not always. There are no explicit results for solar thermal, but there is no reason to expect larger damage costs than for wind and PV.

Table 3.8: Quantifiable external costs: photovoltaic, tilted-roof, single-crystalline silicon, retrofit, average European conditions; in €ct2000/kWh (NEEDS,2009).

	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 3.9: Quantifiable external costs: concentrated solar thermal power; in €ct2000/kWh (NEEDS, 2009).

	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—shown in

Table **3.10**, for example, for existing or near-term solar thermal electricity technology (taken from Kolb, 1998; Mills and Dey, 1999).

Table 3.10: Characteristics of six types of hybrid solar thermal electric plants, with their calculated emissions avoidance costs at a fuel cost of US$ 0.02 per kWh(e).

Option Plant details	LS3 Gas hybrid	LS3 Coal saver	C.R. Coal saver	CLFR PH coal saver	CLFR Coal saver
Aperture (m^2)	470880	470880	529120	610288	492925
Net cap MWe equiv. peak	80	80	103	147.06	147.06
Insolation (kWh/m^2 a)	2694	2694	2500	2250	2250
Avg. daily output (MJ_{th}/m^2)	11.5	11.5	10.25	11	10.4
Turbine efficiency	0.37	0.39	0.39	0.315	0.39
Site works	7733	7733	2963	included	included
Solar field (m^2)	101091	101091	56222	82846	66914
HTF system/boiler	21054	21054	12963	included	Included
Power block	38037	0	0	0	0
Balance of plant	17395	0	0	0	0
Land	498	498	470	254	205
Indirect costs	34312	28769	39940	45705	36915
Project total (000s US$)	220120	159145	112560	128805	104034
Unit cost (US$/kW(e))	2751	1989	1090	876	707
Equiv. full load (hours/a)	4238	2680	2076	1458	1378
Electric output (GWh/a)	339	214	214	214	203
Solar share	0.6	1	1	1	1
Annual solar output (GWh/a)	203	214	214	214	203
Fuel cost (US$/kWh(e))	0.02	0.02	0.02	0.02	0.02
Annual fuel cost (000s US$)	2713	0	0	0	0
Annual O and M cost (000s US$)	4764	3444	2436	2788	2252
LEC (US$/MWh(e))	89	93	66	75	64
US$/kWh(e) less displaced fuel	69	73	46	55	44
Net US$/tonne CO_2	154	80	50	61	49

All energy technologies have land requirements that differ quite significantly. A recent study 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.

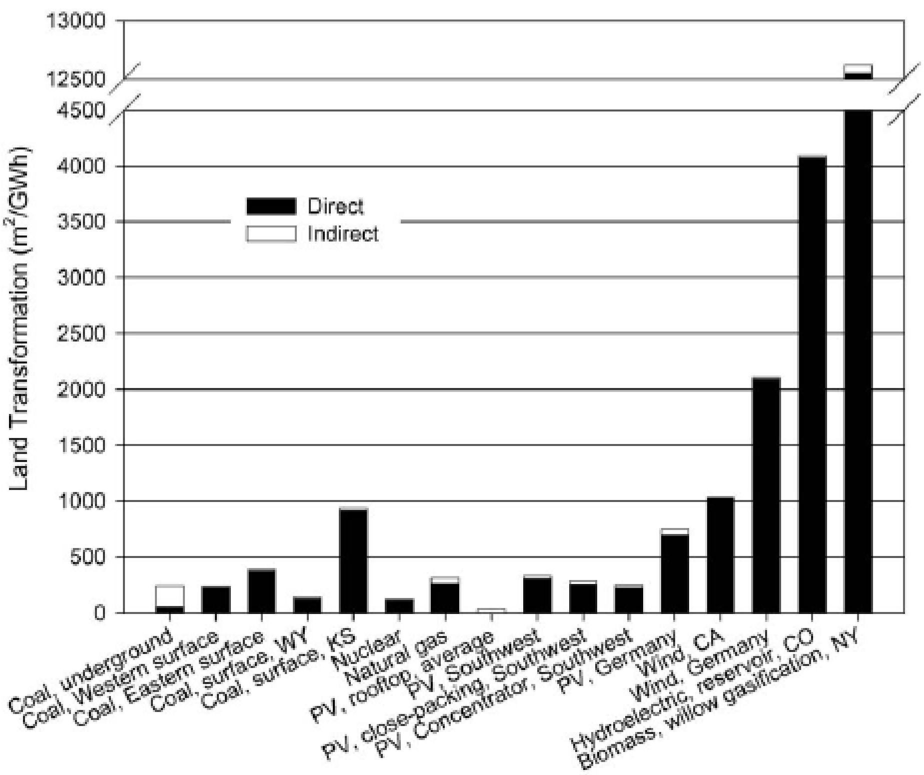


Figure 3.32: Life-cycle land transformation for fuel cycles based on 30-year timeframe (U.S. cases, unless otherwise specified). The estimates for PV are based on multicrystalline PV modules with 13% efficiency. The reference case refers to a ground-mount installation with the U.S. Southwest insolation 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 *et al.,* 2009).

3.6.1.2 Passive solar technology

Higher insulation levels provide many benefits in addition to reducing heating loads and associated costs (Danny, 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.

3.6.1.3 Active solar heat 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.

3.6.1.4 PV electricity generation

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 time for a complete installed PV systems ranges from 0.8 to 2.7 years, taking into account its use in locations having moderate solar irradiation levels around 1,700 kWh/m^2/year (Fthenakis and Alsema, 2006). Perpiñan *et al.* (2009) show payback times of grid-connected PV systems that range from 2 to 5 years for the latitude and global irradiation ranges of geographical areas between -10^o to 10^o longitude, and 30^o to 45^o latitude. The emission of CO_2 for one PV power unity is between 40 and 180 g CO_2-eq/kWh (Fthenakis and Kim, 2007).

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, 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.

3.6.1.5 CSP electricity generation

The environmental consequences of solar power stations vary depending on the technology. Land use is often quoted as an issue; however, the cost of land generally represents only a very minor cost proportion of the whole plant. A 100-MW CSP plant 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 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 not suitable for other agricultural pursuits, which might be the case for wind farms. For this kind of system, sunny deserts close to the electricity infrastructure are needed. In California, the Mojave Desert is ideal. 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.

However, the availability of water is a critical issue that must be addressed for large-scale CSP deployment because CSP plants require a continuous water supply for their steam generation, cooling, and cleaning of the solar mirrors. To address water limitations and environmental regulations, air cooling or a combination of wet/dry hybrid cooling can be used. However, dry cooling performs least efficiently during the summer months, when solar energy is most abundant and the plants should have the greatest output to meet the higher electricity demand (WorleyParsons, 2008).

3.6.1.6 Solar Fuels

[AUTHORS: At present, we do not have content for the environmental impact of solar fuels.]

3.6.2 Social Impacts

Solar energy has the potential to meet rising energy demands and decrease greenhouse gas emissions in the industrialized world. But in addition, 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 approximately 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 (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. One 15-W compact fluorescent light bulb supplies light output equivalent to more than 100 simple kerosene lamps (Mills, 2003). 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 can reduce the 190 million metric tons of estimated annual CO_2 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 (ESMAP, 2003).

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 (ESMAP, 2003; Brower *et al.,* 1997). Risks to women collecting fuel include injury, snake bites, landmines, and sexual violence (Manual, 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.,* 2000). 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 fuels conversion, 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 (see Table 3.11 for a general summary):

- Reduction of thermal conductance through use of dynamic exterior night insulation (night shutters)
- Use of evacuated glazing units

- 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:

- Use of cool roof technologies involving materials with high solar reflectivity and emissivity
- More systematic use of heat dissipation techniques such as use of the ground and water as a heat sink
- Use of advanced pavements and outdoor structures to improve the microclimate around the buildings and decrease urban ambient temperatures
- 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 sections 3.4.1.1 and 3.4.2.1, 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.

Anticipatory control of solar buildings based on real-time weather forecasting—usually one day ahead—will become increasingly possible and feasible with the adoption of building automation systems. For example, in the case of the Alstonvale EQuilibrium demonstration house (Candanedo and Athienitis, 2010), the room-temperature set-point can be lowered during the night when a sunny day is expected so as to allow more direct solar gains to be stored. Such control increases the effective thermal storage of a solar home and improves comfort by reducing the room-temperature peak. One-day weather prediction from agencies such as Environment Canada is now highly reliable and available through the internet to building automation systems. Advanced control systems may also optimize the operation of the passive cooling systems and techniques during the summer period. For example, the appropriate use of night ventilation may decrease the cooling needs up to 40% (Santamouris and Asimakopoulos, 1996).

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 as we move toward the goal of cost-effective solar buildings with net-zero annual energy consumption (IEA SHC Task 40 / ECBCS Annex 52).

Expected advances over the next 5, 10, and 15 years are summarized in Table 3.11.

Table 3.11: Possible scenarios for evolution of passive solar technologies over 15 years

Technology	5 years	10 years	15 years
Glazings and Fenestration Systems	Double low-e argon glazings become dominant in mild-moderate and cold climates Triple-glazed windows start becoming more common in cold climates Window areas on equatorial facades start approaching 30%–50% of façade area	New technologies such as electrochromic coatings and transparent photovoltaics begin to be widely introduced in window products	Widespread and systematic design of fenestration systems as the basis for achieving energy-positive buildings
Daylighting and Solar-Gain Control Systems	Motorized shading and its automatic control begins to be introduced on a broad scale in office buildings and solar homes New louver and glazing designs to optimize daylight transmission at specific solar-angle ranges	Active solar-gain control begins to become coordinated with HVAC and lighting control widely	Daylighting and solar-gain control systems become highly marketable building features as essentials of a high-quality indoor environment, particularly systems that are highly tunable to occupant needs and preferences
Building-Integrated Thermal Storage	Thermal mass that can be used in both passive and active mode (e.g., with	Control strategy (e.g., night setback of room temperature and	

	hollow cores) begins to become more common Phase-change materials in plaster becomes more common in cold climates	predictive control) are considered at the design stage when thermal mass is sized	
Integration of Passive Solar Technologies with Whole-Building Systems	Integrated thermal-daylighting design of office buildings Design of buildings both for optimizing direct gains in winter and reducing cooling loads in summer through natural or hybrid ventilation Use of cool roof coatings to reduce cooling loads	Integrated thermal-structural design of buildings (e.g., concrete buildings) becomes widely influenced by passive solar design and night cooling	Passive design becomes fully integrated with the energy design, architectural design, and operation of the building; architecture and engineering programs evolve to reflect this change

3.7.2 Active Solar Heat and Cooling

The vision of the 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 (PVT) 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. 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.

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, 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.

Currently, about 9% of the total heating needs in Europe are covered by block and district heating systems. This share is much higher in a number of countries, especially Eastern Europe and Scandinavia. The prevalence of Scandinavian countries is surprising, because solar radiation is lower in this region than in Southern Europe. Within district heating systems, solar thermal energy can be produced on a large scale and with particularly low specific costs, even at high latitudes, such as in Sweden and Denmark. Only a very minor share (less than 1%) of the solar thermal market in Europe is linked to district heating systems, but these systems make the most of large-scale solar heating plants.

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.

3.7.3.1 Solar PV cells

In the Strategic Research Agenda for Photovoltaic Solar Energy Technology (EU PV Technology Platform, 2007), future technologies are categorized into Emerging and Novel technologies. “Emerging” technologies have passed a proof-of-concept phase or can be considered as mid-term options for the two established solar cell technologies—crystalline Si and thin-film solar cells. These emerging concepts are based on extremely low-cost materials and processes, and include technologies such as dye-sensitized solar cells and organic solar cells. The main development challenge for organic cells is achieving a sufficiently high (intrinsic and extrinsic) stability in combination with a reasonable efficiency—where “sufficient” varies with the application. Therefore, the application of organic cells for power generation may be reached in the longer term, whereas commodity applications and niche markets are expected in the early stage. “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 technologies include various applications of hybrid cells, quantum dots (QDs), and plasmonic solar cells. In this subsection, only the “Novel” solar cells are surveyed as a future technology.

3.7.3.1.1 Hybrid solar cells

These cells combine nanostructures of both organic and inorganic materials, resulting in the unique properties of inorganic semiconductor nanoparticles with organic/polymeric materials (Arici et al., 2003). In addition, low-cost synthesis, processability, and versatile manufacturing of thin-film devices make them attractive (Sariciftci et al., 1992; Yu et al., 1995]. Inorganic semiconductor nanoparticles may also have high absorption coefficients and particle-size-induced tunability of the optical bandgap. Photovoltaic devices of 7- to 60-nm elongated CdSe nanocrystals and regioregular poly(3-hexylthiophene) (P3HT) composite have been reported (Huynh et al., 2002) with a power conversion efficiency of 1.7% under simulated AM1.5 illumination.

3.7.3.1.2 Quantum dots

These solar cells have the potential to increase the maximum attainable thermodynamic conversion efficiency of solar photon conversion by up to about 66%. This boost is due to quantum mechanical effects in nanometer-size semiconductors, where strong correlation between electron-hole pairs is more significant than in bulk semiconductors. QD solar cells include several possibilities, such as multiple-exciton generation and intermediate-band solar cells. Metal chalcogenide semiconductors such as CdS (Huynh et al., 1999; Wijayantha et al., 2004; Baker and Kamat, 2009), CdSe (Chen et al., 2006), PbS (Robel et al., 2006; Plass et al., 2002), and PbSe (Hoyer and Koenenkamp, 1995) have received considerable attention for QD application. When the sizes of these materials are decreased down to the QD region, the quantum confinement effect makes it possible to generate multiple electron-hole pairs per photon through the impact ionization effect (Schaller and Klimov, 2004). The intermediate-band solar cell (Luque 1997) uses two photon absorptions—one of which is expected to be low-energy photons that allow electrons confined in the mini-band formed in the coupled QDs to escape into the mobile states, resulting in the use of a wide range of the solar spectrum and thus, high efficiency. InGaAs quantum dots embedded in a GaAs matrix have given evidence of lower-energy absorption (Okada, 2008). Although the expected efficiency is very high (more than 40%), the current efficiency status is lower than for conventional solar cells, and it will take time for the higher efficiencies of these new concepts to be realized.

3.7.3.1.3 Plasmonic solar cells

A surface plasmon can be described as a combination of the collective oscillations of electrons in the conduction band of metals and electromagnetic fields. They occur at the interfaces between metals and a dielectric. When a surface plasmon is excited, electromagnetic fields of light are enhanced. Surface plasmons have been proposed as a means to increase the photoconversion efficiency in solar cells by: (1) shifting energy in the incoming spectrum toward the wavelength region where the collection efficiency is maximal, or (2) increasing the absorbance by enhancing the local field intensity. This technology could be beneficial for organic solar cells and dye-sensitized solar cells, where the light absorption predominantly occurs in a very thin layer in the interfacial region.

3.7.3.2 PV system technologies

A PV system is composed of the PV module, as well as the balance of system, which includes storage, system utilization, and the energy network. The system must be reliable, cost effective, attractive, and mesh with the electric grid in the future (EU PV Technology Platform, 2007; New Energy and Industrial Technology Development Organization, 2009; U.S. Photovoltaic Industry Roadmap Steering Committee, 2001; U.S. Department of Energy, 2008; Kroposki, 2008; Navigant Consulting Inc., 2006).

Table **3.12** summarizes the PV system development needed over the next 20 years.

At the component level, a major objective of balance-of-system (BOS) 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, 2009). In the long term, VLS-PV will play an important role in the worldwide energy network (Water and Climate Security, 2007).

Table 3.12: Development of PV system technologies over the next 20 years.

Technology	5 years	10 years	Over 20 years
Components and System Use	Increased inverter reliability and lifetime to achieve (over 20 years) Low-cost electronic components through the application on new designs strategies and new semiconductors (e.g., SiC, GaN). Low-cost support structures, cabling, and electrical connections for grid-connected PV systems. PV inverters optimized for new PV module technologies. Standardizing system components to facilitate economies of scale in manufacture and simplify replacement. Component development for minimizing system losses (e.g., modules with tolerance to partial shading, modules for operation at high DC voltage). Low-cost control and monitoring of system output, including using appropriate measurement protocols. Tools for early fault detection. Prefabricated ready-to-install units, particularly for large grid-connected systems	Increased inverter reliability and lifetime to achieve (over 30 years) New concept such as AC PV modules with integrated inverters that can be produced in very high numbers at low cost, advanced modules for BIPV applications, and multi-functional, self-cleaning, construction elements, new design solutions. Strategies for centralized system monitoring (e.g., Web-based). Updating fault detection tools for advanced system designs. Development of new function for stability and control of electrical grids at high PV penetrations. Billing and metering schemes for PV in off-grid PV systems.	Modules with integrated storage, providing extended service lifetimes (over 40 years).

	Adaptation of battery management systems for new generations of batteries, and highly reliable, low-maintenance components for off-grid systems.		
Network & Storage	Computer programmers to forecast output, and validation of forecast algorithms. Assessment of long-term average local radiation potentials and forecasts of solar irradiation. Assessment of value of PV electricity, including for meeting peak demand, and as an uninterruptible power supply when combined with a storage device.	PV system output energy forecasting method for future energy network. Interaction of PV with other decentralized generation. Development of power electronics and control strategies for improving the quality of grid electricity at high PV penetration. Management of island micrograms with high share of PV generators. Development of efficient incentive management for PV systems.	Development of technologies for high-capacity storage (>1 MWh) and alternative storage technologies. Development of technologies for very-large-scale system.
Standards and Quality Assurance Socio-Economic Aspects and Enabling Research	Performance, energy rating, qualification and safety standards for PV modules, PV building elements, concentrator systems incl. trackers and PV inverters/AC modules. In-line process and production control techniques and procedures. Guidelines for specifications and quality assurance of materials, wafers and cells, modules, components for concentrator systems and BOS components.	Guidelines for production equipment. Develop further in-line process and production control techniques and procedures. Improve certification schemes, in particular for system Recycling processes (new components) and economic and logistical aspects of PV module and component reuse and recycling. Public awareness and information dissemination	

	Recycling processes.	schemes relating to large-scale deployment of PV technology	

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, 2003) have concluded that cost reductions will come from technology improvement, economies of scale, and mass production. Other needed innovations related to systems, power cycles, and collectors are discussed below.

3.7.4.1 Beam-Down solar concentration system

The Solar Concentration Off-Tower (SCOT), also called the Reflective Tower or Beam-Down optical configuration, was first proposed by WIS (Israel). A hyperboloid reflector is installed at the tower top, redirecting the concentrated solar radiation toward a lower focal region near ground level. The Beam-Down concept is attractive because the heavy receiver may be placed on or near the ground; furthermore, the heating medium does not need to be pumped to the top of the tower.

However, the Beam-Down system has some technological difficulties, such as the mechanical integrity of the central reflector against the wind force, and a wider focus due to the dilution of the beam concentration at the receiver aperture. To solve these problems, multi-ring reflector technology has been proposed.

Some temperature ejection system is needed for the central reflector, because the reflector is irradiated by middle-level flux (100 kW/m^2) of a slightly concentrated solar beam from the heliostat field. A heat-resistant-type reflector should be developed.

3.7.4.2 Power cycles

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. Although CSP works with turbine cycles of 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, 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 (see Sec. 3.9.4).

3.7.4.3 Collectors

The objective for collectors 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 DLR et al. (2005). Table 3.13 summarizes key developments for CSP technologies needed over the next 20 years.

Table 3.13: Development of CSP technologies over the next 20 years.

Technology	5 years	10 years	20 years
Trough	Continued rollout of existing trough technology providing much of the critical mass for the CSP industry. Improved selective surfaces. Improved heat-transfer fluids. Storage enables peak and intermediate-load dispatchability.	Very-large-capacity plants become the norm. Fluids and processes developed to reduce need for heat exchangers and multiple tank storage. Longer-term storage becomes cheaper and mandatory. High-temperature selective surfaces suitable for operation in air.	Opportunities for continued improvements in trough efficiency are minimal and cost reductions are mainly through economies of scale and mass production. The scale of the CSP industry affords development of improved steam turbines specifically for solar operation.
Linear Fresnel	First commercial plants in operation.	Larger plants under deployment.	

	Applied engineering to reduce costs. Improved inverted cavity designs developed.	Mass production of Fresnel reflector segments begins to occur and costs fall. Advanced secondary reflectors in receivers allow higher operating temperatures.	
Central Receiver	Higher-temperature steam operation in commercial plants. Larger plants installed and operational. Investigation of optimal heliostat size revisited as higher temperatures sought. Commercial-scale molten-salt towers demonstrated. Tower Brayton and tower thermochemical systems demonstrated.	Multiple solar towers now in operation based on steam or molten salt, with storage. Move to commercial-scale tower Brayton on back of high-temperature receiver development. Use of towers for first commercial-scale thermochemical systems.	Anticipate tower installation rate now outstripping troughs as benefits of higher temperatures realised.
Dish	Dish/Stirling reliability questions overcome as hours continue to be logged on multiple dish installations. First commercial-scale dish/Stirling farms. Demonstration of dish Brayton and dish thermochemical. Larger dishes deployed and economics better understood.	Commercial farms of dish-powered heat engines now under deployment.	

3.7.5 Solar Fuels Conversion

Solar-driven fuel processing methods include thermal decomposition, thermochemical, photochemical, electrochemical (solar electrolysis using PV or CSP), biochemical, and hybrid reactions.

Solar electrolysis using PV or CSP is nearly feasible commercially, but production costs are still 1.5 to 2 times oil at US$100/bbl. For solar electrolysis, the photoelectrochemical (PEC) cell is the future technology innovation. The solar thermochemical cycles of a metal-oxide-based cycle, the hybrid-sulfur cycle, and the solar electrolysis of water are the promising processes for future “clean” hydrogen mass production. Other candidates as future technology innovation for solar fuel conversion are producing biofuels from modified photosynthetic microorganisms, and developing 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 technological advanced multi-electron redox catalysts coupled to photochemical elements.

3.7.5.1 Solar thermochemical cycles of metal-oxide-based cycle

A number of solar reactors applicable to solar thermochemical cycles of a metal-oxide-based cycle have been developed, including:

- Solar reactor by HYDROSOL I and II EU projects,
- Solar reactor for ZnO/Zn process,
- Tokyo Tech rotary-type solar reactor, and
- Counter-Rotating-Ring Receiver/Reactor/Recuperator (CR5).

3.7.5.2 Solar thermochemical cycle of hybrid-sulfur cycle

The hybrid-sulfur cycle is a two-step water-splitting process. It uses an electrochemical, instead of a thermochemical, reaction for one of the two steps (hybrid thermochemical cycle). 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 reaction 2.

3.7.5.3 Solar-powered production of molecular hydrogen from water

Electrochemical water splitting powered by conventional electricity or PV arrays produces molecular hydrogen at the cathode, while organic-compound oxidation under mild conditions occurs at the anode in competition with the production of oxygen.

3.7.5.4 Hydrogen production from water using a photoelectrochemical cell

The radiation needs to be converted into a suitable form of energy. Solar radiation can be converted into chemical energy such as H_2 by a photoelectrochemical cell. A PEC cell is fabricated using an electrode absorbing the solar light, two catalytic films, and a membrane separating H_2 and O_2.

3.7.5.5 Biomimetic photosynthetic technologies

SOLAR-H2 integrates two frontline research topics: artificial photosynthesis in man-made biomimetic systems, and photobiological H_2 production in living organisms. H_2 production by these methods on a relevant scale is still distant, but has vast potential. The scientific risk is high and the research is very demanding. Thus, the overall objective is to explore, integrate, and provide the basic science needed to develop these novel routes and advance them toward new horizons.

3.7.6 Other Potential Future Applications

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.

3.8 Cost Trends

This section provides cost trends for the five direct solar technology areas.

3.8.1 Passive Solar Technologies

The discussion in this subsection is covered under the areas of heating and daylighting.

3.8.1.1 Heating

High-performance building envelopes entail greater up-front construction costs, but lower energy-related costs during the lifetime of the building (Danny, 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 3.33 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 3.33, 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.

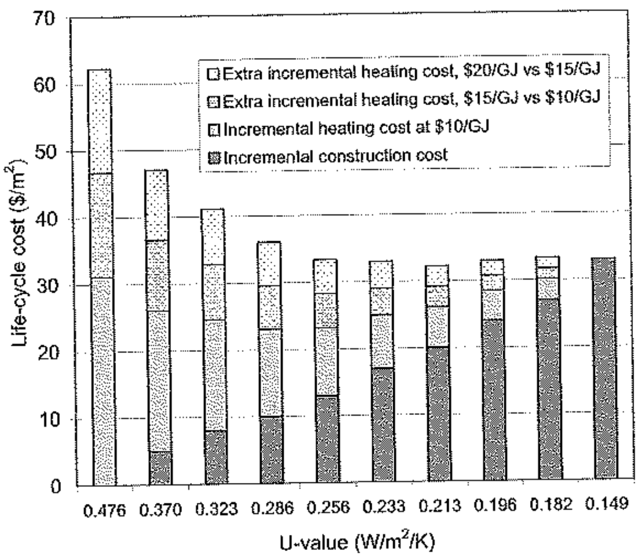


Figure 3.33: Comparison of incremental life-cycle costs of walls with increasing amounts of insulation.

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 3.33 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 3.34 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.

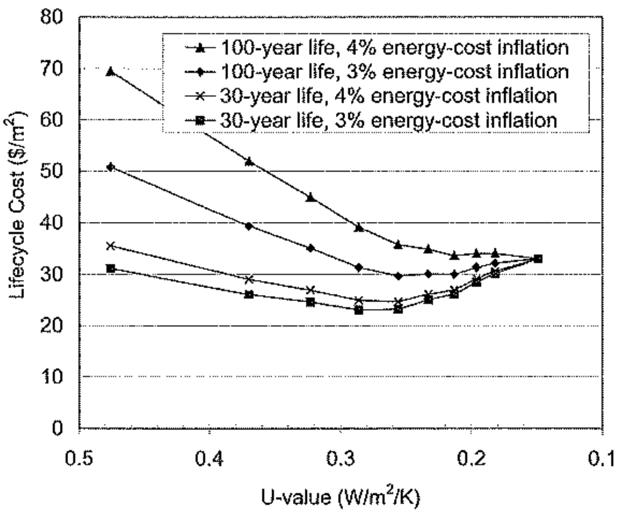


Figure 3.34: Comparison of incremental life-cycle costs of walls with increasing amounts of insulation for 30- and 100-year life spans.

The main conclusion of these figures is that it is justified to require insulation levels substantially in excess of the level that is calculated to minimize life-cycle cost (Danny, 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.

For example, Davis Energy Group was challenged as part of the Pacific Gas and Electric's Advanced Customer Technology Test to improve an initial design for a house that already met California's strict Title 24 energy code. A long list of small improvements—including efficient appliances, thicker insulation, and better windows—eliminated any need for the $2,050 furnace and its associated ducts and equipment. The designers had set up a package of potential energy-savings measures that were not cost effective from just their energy savings, even though they each reduced cooling loads. These measures included superwindows to block summer heat and ceramic tile to store "coolth" in the house for use during daily heat peaks. Seven such measures cost $2,600; but from a whole system perspective, they eliminated the last $1,500 worth of air conditioner and $800 of its future upkeep costs, which almost fully made up for the cost of the measures. This example emphasizes the point that even though individual efficiency measures may have large costs, counting their energy and capital-cost savings can turn them into attractive investments. The Davis Energy Group house proved very comfortable, even in a severe hot spell (Rocky Mountain Institute, 2004).

3.8.1.2 Daylighting

The economic benefit of daylighting 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 (Danny, 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 Heat 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 3.14 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 3.14: Cost per kWh for solar thermal, gas, and electricity - today and 2030.

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 (Figure 3.35).

Although important cost reductions in solar thermal energy can be achieved through R&D and economies of scale,

Table 3.14 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.

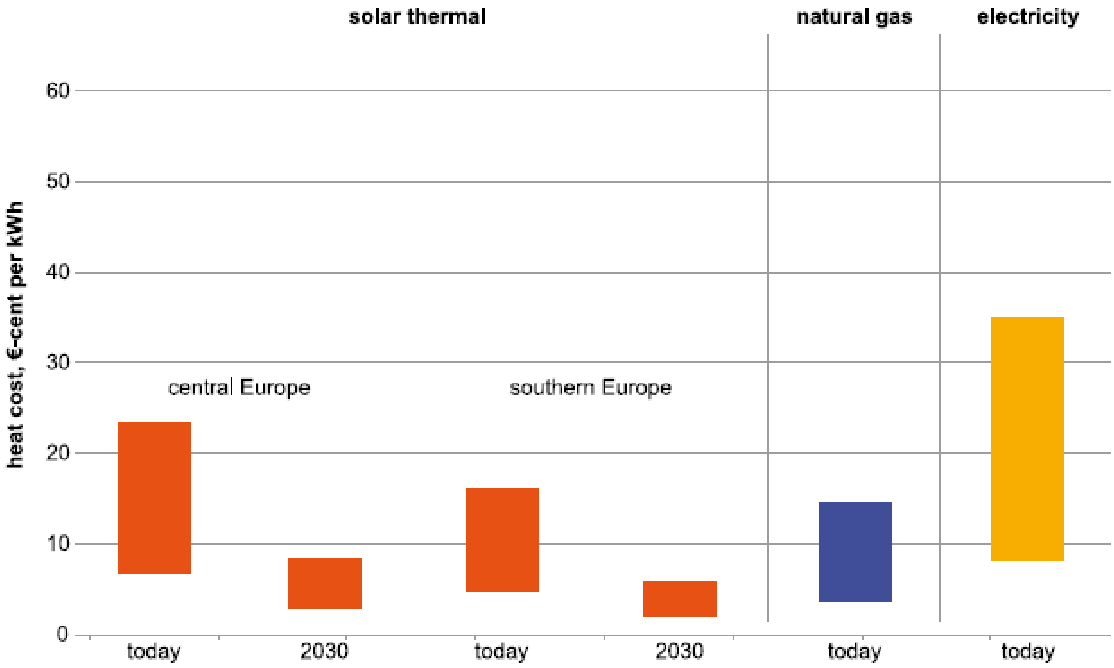


Figure 3.35: Range of costs for solar and other technologies—today and 2030 (ESTIF, 2009).

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. 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 3.36).

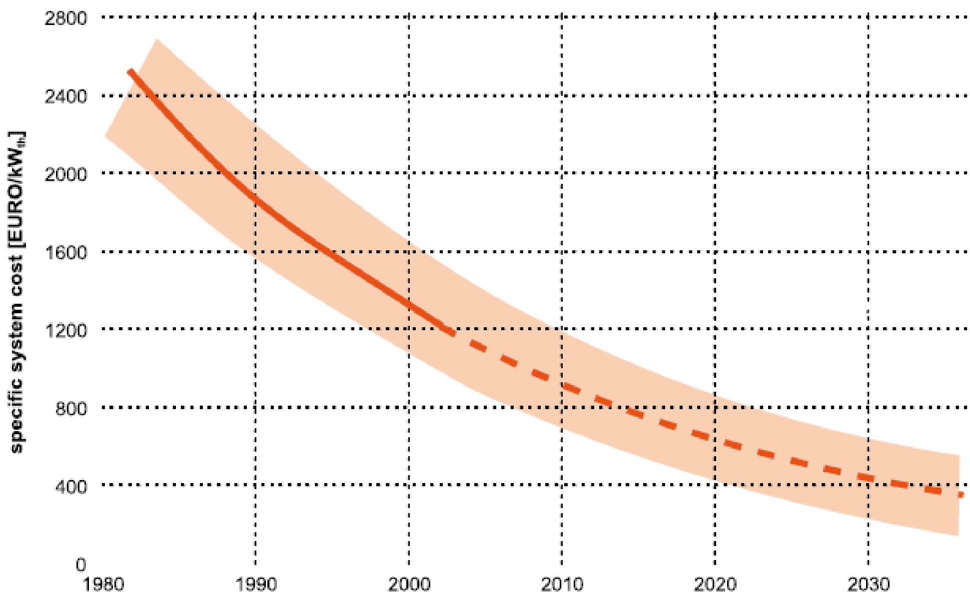


Figure 3.36: Costs of small solar thermal systems, past and projected to 2030 (Institut für Thermodynamik und Wärmetechnik (ITW), University of Stuttgart).

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 €/m^2
- Flat-plate or stationary compound parabolic collectors, 200 to 500 €/m^2
- Evacuated-tube collectors, 450 to 1,200 €/m^2

Table **3.15** gives illustrative costs of solar thermal energy, and

Table **3.16** summarizes cost and performance data for a variety of solar thermal systems in Germany.

Table 3.15: Illustrative costs of solar thermal energy.

System cost ($/m² or €/m²)	System efficiency	Cost of thermal energy (cents or eurocents/kWh)								
		1100kWh/m²/year			1650kWh/m²/year			2200kWh/m²/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 3.16: System costs, cost of heat, solar utilization, and solar fraction for solar thermal DHW or space heating systems in Germany.

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 (Danny, 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 2008, the average global price of PV modules used for power applications (modules > 75 W) dropped from 9.32 to 3.65 USD/W (2008 USD). The PV module learning curve in Figure 3.37 indicates a progress ratio of 80%, and consequently, a learning rate of 20%, which means that the price is reduced by 20% for each doubling of cumulative sales (Surek, 2005).

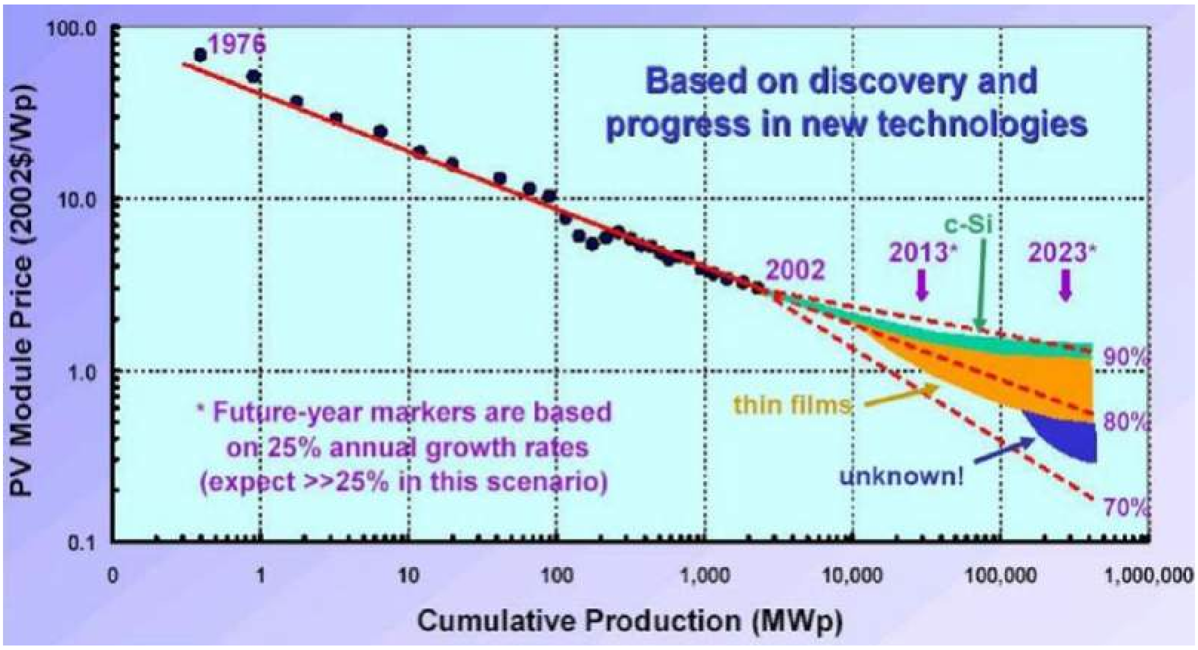


Figure 3.37: Learning curve for PV modules (Surek, 2005).

Figure 3.38 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.

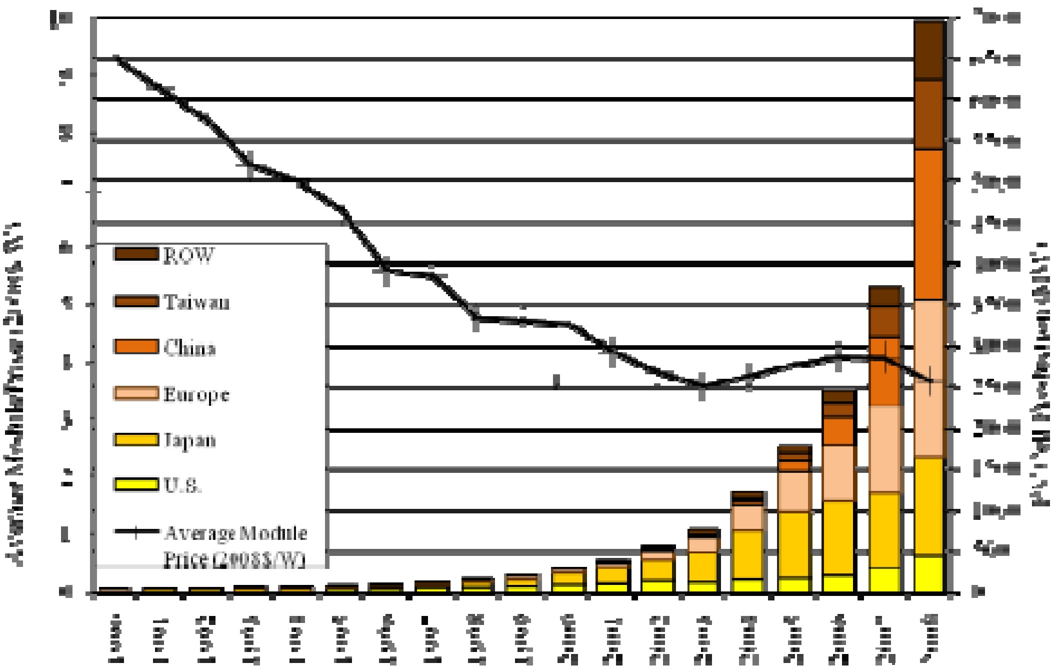


Figure 3.38: PV module prices have fallen as PV cell production has increased (Navigant Consulting Inc. 2008, PV News 1993, 2001, 2006, 2008, 2009). Production data: Prometheus Institute and Greentech Media, PV News:. Module price data: Navigant Consulting, April 2008.

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 3.17). Both thin-film and crystalline silicon technologies have numerous pathways for realizing continued technological innovation and cost

Table 3.17: Module manufacturing costs and price forecast per peak watt in 2008 US$ (Greentech, 2009).

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

reductions. In addition, third-generation technologies could come into the market in the longer term at even lower cost/price levels.

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 3.39 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.

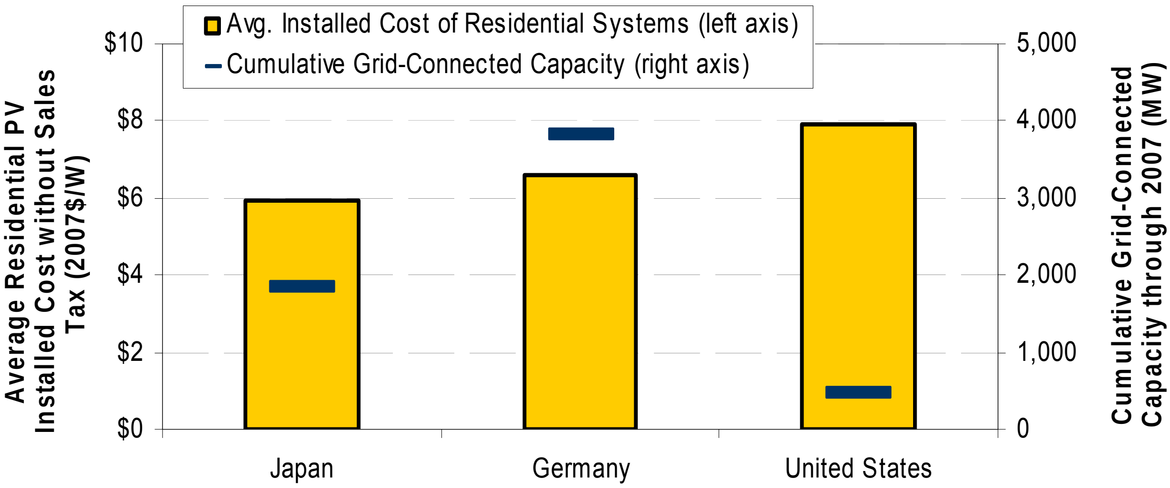


Figure 3.39: Average installed cost of residential PV systems completed in 2007, in Japan, Germany, and the USA (Wiser et al., 2009).

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 fourth-quarter 2009 average PV system price in Germany dropped to 3,125 €/kWp (2005 US $: 3,618 $/kWp) (Bundesverband Solarwirtschaft, 2009). In 2009, thin-film projects were realized as low as 2.72 $/Wp (2005 US $; 3 $/Wp in 2009 $) (New Energy Finance, 2009). The resulting levelized cost of energy (LCOE) varied between 0.145 and 0.363 $/Wp (0.16 and 0.40 $/Wp in 2009 $).

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 PVPS, 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 GEF, 2006) suggested four phases in cost reduction for CSP technology and that cost competitiveness with fossil fuel could be reached by 2025.

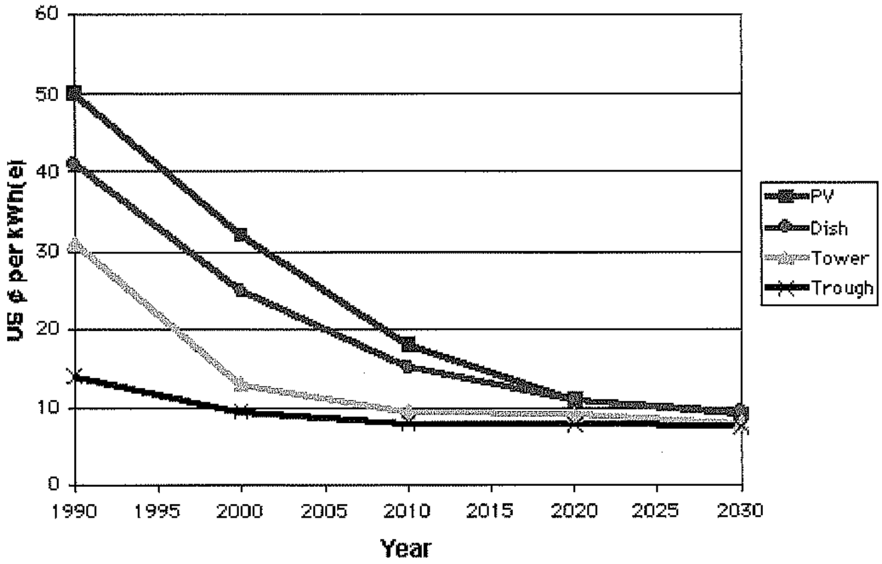


Figure 3.40: Energy cost (in U.S. cents per kWh) for PV and three CSP technologies from 1990 to 2030.

Currently, the average cost for installing a CSP plant is roughly 4 million USD/MW. For example, the total investment for the 354-MW Solar Electric Generating Station plant in California (installed from 1985 to 1991) was 1.25 billion USD (nominal, not adjusted for inflation). For the 64-MW Nevada Solar One plant installed in 2007, construction and associated costs amounted to 260 million USD.

Project costs in Europe are around 4.62 $/W (2005 $) (4.0 2008 €/W), but can reach 16.16 $/W (2005 $) (14 €/W; 2008 €) depending on the total storage capacity and the type of fossil back-up. Average LCOE values in 2009 were 0.254 to 0.346 $/W (0.22 to 0.30 €/kWh) (New Energy Finance 2009).

The U.S. DOE CSP initiative that funds R&D projects with U.S. companies is focusing on thermal storage, trough component manufacturing, and advanced CSP systems and components (US Department of Energy, 2008). The projects are expected to reduce today's 0.12 to 0.14 USD/kWh 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.

3.8.5 Solar Fuels Conversion

A long-sought goal of energy research has been to find a method to produce hydrogen economically by splitting water using sunlight as the source of energy. Approaches to carry out this kind of solar fuels conversion range from well-established chemical engineering practices with near-term predictable costs, to long-term basic photochemical processes, the details of which are still speculative. Thus, the goal remains elusive because near-term systems tend to have high costs, while the costs of advanced long-term systems are not well defined.

Molecules are more convenient to transport over long distances than electrons, and a smooth transition to a carbon-neutral transport sector without the need to change the existing infrastructure is most easily achieved. In this sense, solar hybrid fuels such as methanol, DME, and synthetic oil are commercially feasible compared to solar hydrogen.

3.8.5.1 Solar hybrid fuels

The production cost for solar hybrid fuels and solar hydrogen by solar electrolysis are nearly commercially feasible. However, implementing these processes on a large scale generally involves significant capital and energy costs. The combination of capital costs to provide concentrated solar energy and the elaborate and expensive plants required to carry out the chemical processes puts a heavy financial burden on this approach. Alternately, if sunlight is used in non-concentrated systems, the cost per unit area of the converter must be very low to make a viable system. However, when the solar chemical process is applied without solar concentration, each reaction would be controlled and operated in a vast area. In the solar hybrid fuel production, both systems are applied where solar light is concentrated or non-concentrated.

3.8.5.2 PV-solar electrolysis

The rejection of hydrogen as a solution to global warming by becoming the medium of wind and solar was made when gasoline was priced at 1 USD/gallon. From wind energy, H2 by the electrolysis of water and steam would now cost less than 3 USD for an amount equivalent in energy to that in a gallon of gasoline ("equivalent"). From PV, H_2 would be dropping in price from 8 to 5 USD/equivalent as the efficiency of PV increases toward 20%. Solar thermal would produce hydrogen for about half the price of PV.

3.8.5.3 Solar thermochemical cycles

Hydrogen is acclaimed to be an energy carrier of the future. Currently, it is mainly produced by fossil fuels, which release climate-changing emissions. Thermochemical cycles, such as the hybrid-sulfur cycle and a metal-oxide-based cycle, along with electrolysis of water are the most-promising processes for "clean" hydrogen mass production for the future. In a comparison study, both thermochemical cycles were operated by CSP for multistage water splitting. The electricity required for the electrolysis was produced by a parabolic trough power plant. For each process investment, operating and hydrogen production costs were calculated on a 50-MW_{th} scale. The study points out the 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 were obtained that range from 3.9 to 5.6 €/kg for the hybrid-sulfur cycle, 3.5 to 12.8 €/kg for the metal-oxide-based cycle, and 2.1 to 6.8 €/kg for electrolysis.

3.9 Potential Deployment

In this section, various future deployment scenarios through 2050 are compared with each other. However, most scenarios do not have a holistic approach to include all renewable and non-renewable energy sources in the scenario. Therefore, the estimated investment needs to realize the various scenarios differ significantly per kWh generated, depending on the development and/or integration burden into the existing energy supply system.

The potential of direct solar energy is often underestimated. This is because of the wide range of technologies and various applications of direct solar energy, and because 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). Because renewable energy sources (except biomass) do not require a combustion power plant, the IEA method simply accounts the electricity as primary energy. The only exceptions are geothermal and nuclear power stations, where the following conventions are used:

The primary energy equivalent of nuclear energy is calculated from the gross generation by assuming a 33% conversion efficiency, i.e., 1 TWh = (0.086 ÷ 0.33) Mtoe (million tonnes of oil equivalent). In the case of electricity produced from geothermal heat, if the actual geothermal efficiency is not known, then the primary equivalent is calculated assuming an efficiency of 10%, so 1 TWh = (0.086 ÷ 0.1) Mtoe.

On the other hand, the BP method counts the "equivalent primary energy" of fossil fuels needed to generate electricity. BP uses a correction factor of 2.6, which is equivalent to the average energy loss in a power plant.

The IEA method appears to be more commonly used in the scenario literature. But authors often do not explain which method is used, which causes confusion in comparing different scenarios and distorts the numbers. In addition, some scenarios do not differentiate between the different solar energy applications and list everything under solar, such as the "Shell energy scenarios to 2050" (Shell, 2008).

Another issue is how distributed stand-alone generation of solar electricity and low-temperature solar heat are accounted for. 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 already 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 issue that remains unresolved is what statistical number to use for the primary energy part of heat—either the total produced or the actual used.

Currently, the main market drivers are the various national support programmes for solar-powered electricity systems or low-temperature solar heat installations. These programmes 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.

The investment needs are taken from the IEA *Energy Technology Perspectives* 2008 (IEA, 2008). The reference scenario reflects the developments that will occur with the energy and climate policies that have been implemented in 2008; the ACT scenario considers global stabilization of CO_2 emissions by 2050; and the BLUE scenario considers a global 50% reduction of CO_2 by 2050. RDD&D stands for research, development, demonstration, and deployment.

3.9.1 Policies to Achieve Goals

[AUTHORS: This text is still being developed.]

3.9.2 Trends in Low-Temperature Solar Thermal

Investment needs are listed below, followed by descriptions of the trend of solar thermal's potential within different timeframes (Table 3.18). 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 IEA (2008) estimates the following investment needs in its Energy Technology Perspectives.

- ACT scenario: RDD&D and investment costs between 2005 and 2030: $ 255–280 billion and commercial investment costs between 2035 and 2050: $ 305–340 billion.
- BLUE scenario: RDD&D and investment costs between 2005 and 2020: $ 255–280 billion and commercial investment costs between 2035 and 2050: $ 645–680 billion.

Table 3.18: Evolution of the cumulative low-temperature solar capacities until 2050 (Greenpeace 2008, IEA 2008 scenarios). Note: [1]Calculated from heat supply in PJ/a and 850 full-load hours annually.

Name of Scenario And Year	2000	2010	2020	2030	2050
	Cumulative Installations in GW_{th}				
Greenpeace[1] (reference scenario 2008)		112	360	640	1,200
Greenpeace ([r]evolution scenario 2008)		300	2,160	5,630	13,680
IEA Reference Scenario (2008)					650
IEA ACT Map (2008)			650		1,500
IEA Blue Map (2008)			650		3,000
Shell (Scramble)			330	4,250	15,360
Shell (Blueprints)	0	163	1,150	3,600	12,090

In its Strategic Research Agenda (ESTTP, 2008), the European Solar Thermal Technology Platform formulated the following medium-long-term solar thermal potential. As considered by ESTIF, solar thermal could 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.

Overcoming a series of technological barriers will make it possible to achieve a wide market introduction at competitive costs of advanced solar thermal applications such as the following:

- Active Solar Building, covering at least 100% of their thermal energy with solar, and in some cases, providing heat to neighbours
- High solar-fraction space heating for building renovations
- Wide use of solar for space cooling
- Wide use of solar for heat-intensive services and industrial process heat, including desalination and water treatment.

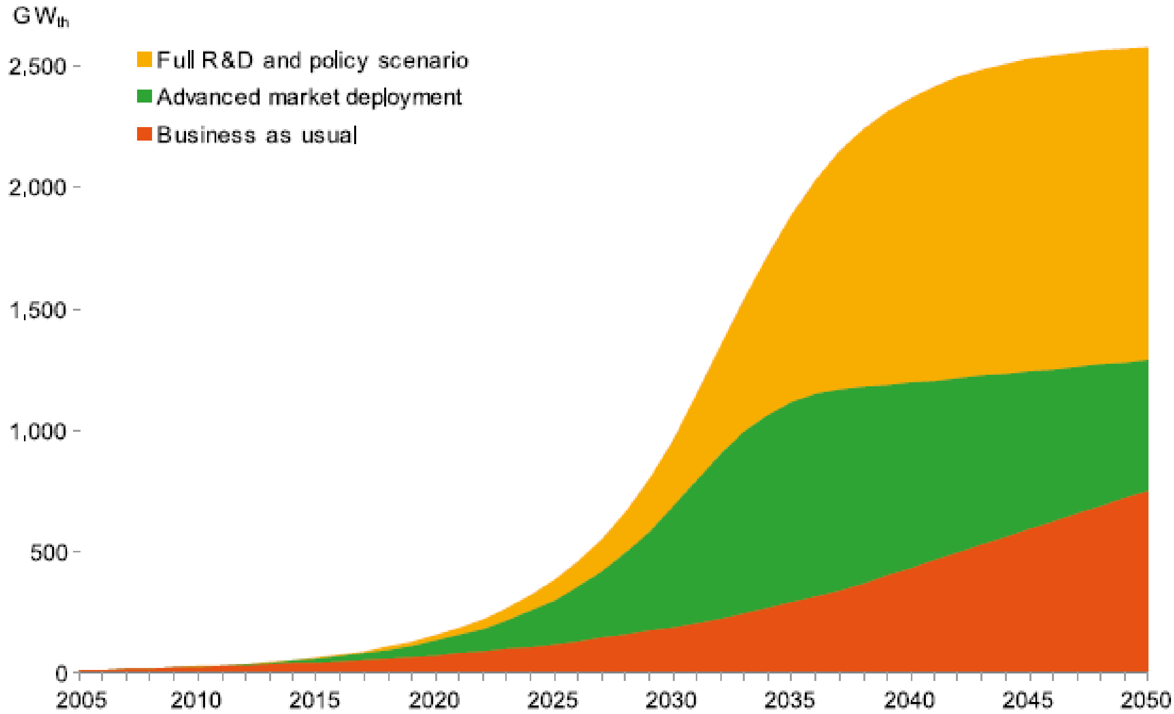


Figure 3.41: Growth in solar thermal energy use in different scenarios (ESTIF, 2009).

These are the key elements of the ESTTP Vision, Deployment Roadmap, and Strategic Research Agenda. Figure 3.41 shows the ESTIF scenarios.

Based on political support mechanisms, technical developments based on increased R&D and on independent report calculations of the ESTTP show realistic growths rates of 20% in the solar thermal market. These growth rates would lead to an installed capacity of 970 GW_{th} by 2030 in the EU. Based on the EU-25 heat demand of the year 2004 (ESTIF, 2009), these solar thermal collectors could supply about 8% of the total heating demand. Combined energy-conservation measures and increased efficiency in the building sector (i.e., 40% decrease in heat demand compared to 2004) would enable solar thermal systems to supply about 20% of the overall heat demand in EU-27 by 2030.

The long-term potential (2050) of solar thermal is to provide for about 50% of the EU´s heat demand. To achieve this goal, an installed capacity of 2576 GW_{th}, or 8 m² per inhabitant, would be necessary.

3.9.3 Trends in Photovoltaics

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. However, the market barriers and deployment options differ quite significantly depending on the kind of application. Table 3.19 and Table 3.20 show scenarios developed for PV electrical capacities and generated electricity.

Table 3.19: Evolution of the cumulative solar PV electrical capacities (GW) until 2050 (Greenpeace 2008 and IEA 2008 scenarios).

Name of Scenario	2000	2010	2020	2030	2050
and Year	Cumulative Installations in GW				
Greenpeace (reference scenario 2008)	1.00	10	50	86	153
Greenpeace ([r]evolution scenario 2008)	1.00	21	270	920	2,900
Greenpeace (advanced scenario 2008)	1.00	21	290	1,500	3,800
IEA Reference Scenario (2008)	1.00	10	30	< 60	non-competitive
IEA ACT Map (2008)	1.00	22	80	130	600
IEA Blue Map (2008)	1.00	27	130	230	1,150

Table 3.20: Evolution of the solar PV electricity until 2050 (Greenpeace 2008 and IEA 2008 scenarios).

Name of Scenario	2000	2010	2020	2030	2050
and Year	Electricity in TWh				
Greenpeace (reference scenario 2008)	1.40	13	68	120	213
Greenpeace ([r]evolution scenario 2008)	1.40	26	386	1,351	4,349
Greenpeace (advanced scenario 2008)	1.40	26	406	2,100	5,320
IEA Reference Scenario (2008)	1.40	14	42	120	170
IEA ACT Map (2008)	1.40	31	110	250	1410
IEA Blue Map (2008)	1.40	38	180	440	2,670
Shell* (Scramble)	n.a.	n.a.	170	2,170	7,830
Shell (Blueprints)	n.a.	83	580	1,830	6,170

3.9.3.1 Off-Grid (Rural Electrification)

According to the World Bank, 1.6 billion people worldwide have no access to electricity in their homes, which represents more than one-quarter of the world's population (The World Bank, 2006). Four out of five people without electricity live in rural areas of the developing world, especially in peripheral urban and isolated rural areas. The lack of electricity deprives people of basic necessities such as refrigeration, lighting, and communication and, consequently, it hampers development.

Reaching the unelectrified rural population is often only possible through distributed energy systems, due to low potential electricity demand and economic development in these areas, and sometimes, for political reasons, grid extension is not a feasible option.

The use of PV systems to generate electricity for mini-grids or off-grid with solar home systems (SHSs) is an excellent option for improving this situation. A World Bank analysis (The World Bank IEG, 2008) of selected countries showed that the use of electricity from SHSs for lighting purposes is, by far, more cost effective than lighting with kerosene lamps or extending the grid.

Nevertheless, people implementing rural electrification often give greater priority to projects with minimized initial costs to maximise the number of beneficiaries; but they do not take into account the total cost over the lifetime of a generation system. The cost distribution of high initial-investment costs for PV electricity systems and almost no operational costs is therefore a disadvantage and requires special financing mechanisms that are still not common practice. To unlock the large potential of PV deployment, Martinot et al. (2002) suggested the following successful policies and regulatory frameworks to support renewable energies:

- Policies that promote production-based incentives, rather than investment-based incentives, are more likely to spur the best industry performance and sustainability.
- Power-sector regulatory policies for renewable energy should support independent power producer/power purchase agreement (IPP/PPA) frameworks that provide incentives and long-term stable tariffs for private power producers.
- Regulators need skills to understand the complex array of policy, regulatory, technical, financing, and organizational factors that influence whether renewable energy producers are viable.
- Financing for renewable power projects is crucial, but elusive.

In addition to the current market development programmes in the grid-connected markets, the European Photovoltaic Technology Platform developed a "Renewable Energy Purchase Agreement Tariff" to expand the potential rural electrification PV markets to overcome the financing barriers (Moner-Girona, 2008).

However, it should be mentioned that an analysis in the field of rural PV electrification shows poor-quality installations and equipment. This fact has contributed to the spread of a false concept in some areas that PV systems “do not work.” In this way, the success of implementing and popularizing SHS in developing countries needs more than policies and financial support. In particular, it also needs an institutional on-site framework that allows the following conditions to be met: commercial availability, ease in getting replacement parts, existence of local technical capacity to install, and maintenance and collection of monthly fee.

3.9.3.2 Grid-connected

[AUTHORS: This text is still being developed.]

3.9.3.3 Investment Needs

The IEA estimates the following investment needs in its *Energy Technology Perspectives*:

- ACT scenario: RDD&D and investment costs between 2005 and 2035: $ 180–222 billion and commercial investment costs between 2035 and 2050: $ 495–550 billion.
- BLUE scenario: RDD&D and investment costs between 2005 and 2030: $ 185–222 billion and commercial investment costs between 2035 and 2050: $ 980–1,040 billion.

3.9.4 Trends in Concentrating Solar Power

Trends and potential for CSP capacities are shown in Table 3.21 and Table 3.22. The deployment of CSP technology is limited by the regional availability of good-quality sunlight with high direct-normal irradiance of 2,000 kWh/m2 or more in the Earth's "Sun Belt." Despite this requirement, space is not a constraint for deploying this technology. However, the availability of water is a critical issue that must be addressed for large-scale CSP deployment because CSP plants require a continuous water supply for their steam generation, cooling, and cleaning of the solar mirrors. To address water limitations and environmental regulations, air cooling or a combination of wet/dry hybrid cooling can be used. However, dry cooling performs least efficiently during the summer months, when solar energy is most abundant and the plants should have the greatest output to meet the higher electricity demand (WorleyParsons 2008). [TSU: Redundancy with section 3.6.1.5, p.66, lines 38-44]

Air cooling and wet/dry hybrid cooling systems offer highly viable alternatives to wet cooling and can eliminate up to 90% of the water usage (US Department of Energy, 2009). The penalty in electricity costs for steam-generating CSP plants range between 2% and 10%, depending on the actual geographical plant location, electricity pricing, and effective water costs (Richter et al., 2009). The penalty for linear Fresnel designs has not yet been analyzed, but it is expected to be somewhat higher than for troughs because of the lower operating temperature. Conversely, power towers should have a lower cost penalty because of their higher operating temperature.

Given their size of typically 50 to 300 MW, CSP plants need to be linked to the transmission network. Therefore, developing the grid infrastructure is critical to the widespread implementation of CSP. According to a study by the German Aerospace Centre (DLR, 2006), about 10% of the generated electricity will be lost by high-voltage direct-current transmission from the Middle East-North Africa (MENA) countries to Europe over a distance of 3000 km. In 2050, twenty power lines with 5,000-MW capacity each could provide about 15% of the European electricity demand. The total investment for a power transport capacity of 700 TWh/year was calculated at € 350 billion for the CSP plants and € 45 million for the transmission lines.

Table 3.21: Evolution of the cumulative CSP capacities until 2050 (Greenpeace 2008, IEA 2008 scenarios).

Name of Scenario and Year	2000	2010	2020	2030	2050
	Cumulative Installations in GW				
Greenpeace (reference scenario 2008)	0.35	2	8	12	17
Greenpeace ([r]evolution scenario 2008)	0.35	5	83	199	801
Greenpeace (advanced scenario 2008)	0.35	5	100	315	2,100
IEA Reference Scenario (2008)	0.35	n.a.	n.a.	< 10	competitive
IEA ACT Map (2008)	0.35	n.a.	n.a.	250	380
IEA Blue Map (2008)	0.35	n.a.	n.a.	250	630

Table 3.22: Evolution of the electricity generated by CSP until 2050 (Greenpeace 2008, IEA 2008 scenarios). Note: [1]50% of total solar energy is heat, 20% electricity from CSP and 30% electricity from PV.

Name of Scenario and Year	2000	2010	2020	2030	2050
	Electricity in TWh				
Greenpeace (reference scenario 2008)	0.63	5	26	54	95
Greenpeace ([r]evolution scenario 2008)	0.63	9	2,670	1,172	5,255
Greenpeace (advanced scenario 2008)	0.63	9	320	1,860	12,770
IEA Reference Scenario (2008)	n.a.	n.a.	n.a.	< 15	25
IEA ACT Map (2008)	n.a.	n.a.	n.a.	625	890
IEA Blue Map (2008)	n.a.	n.a.	n.a.	810	2,080
Shell[1] (Scramble)	n.a.	n.a.	110	1,450	5,220
Shell (Blueprints)	n.a.	56	390	1,220	4,110

The IEA estimates the following investment needs in its Energy Technology Perspectives:

- ACT scenario: RDD&D and investment costs between 2005 and 2030: $ 265–315 billion and commercial investment costs between 2035 and 2050: $ 190–215 billion.
- BLUE scenario: RDD&D and investment costs between 2005 and 2030: $ 260–300 billion and commercial investment costs between 2035 and 2050: $ 290–330 billion.

3.9.5 Trends in Solar Fuels

To some extent, solar fuels are a natural progression from CSP used for electricity generation. The processes required to produce solar fuels are high temperature above 600°C and with many of the processes well above 1,000°C. Thus, towers and dishes are the preferred concentrator technologies for solar fuels. As towers increase their operating temperature for conventional CSP steam-generation systems up toward temperatures of 600°C for supercritical steam, the lessons and experience gained 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 transport fuels or in industrial processes. Figure 3.42 illustrates possible pathways for solar fuel production.

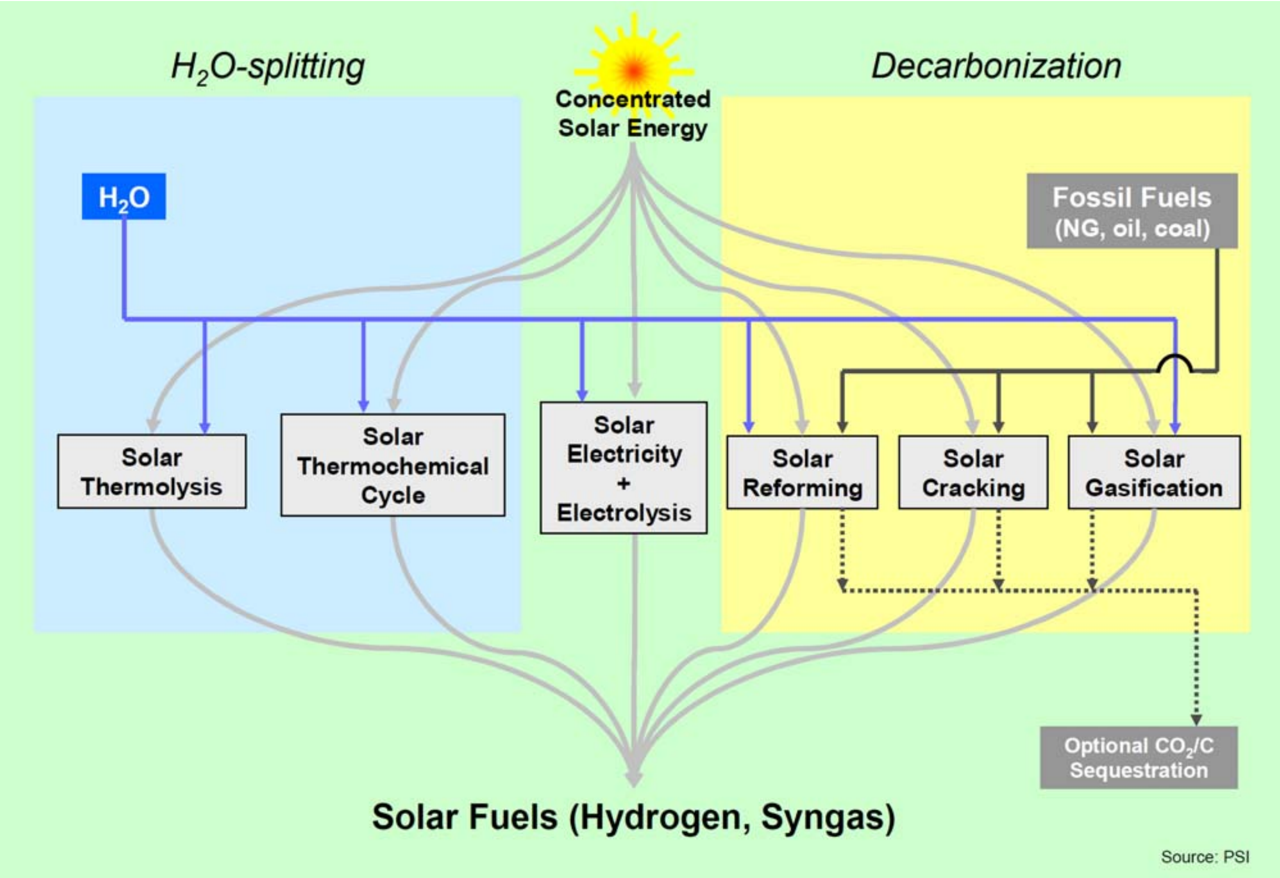


Figure 3.42: Thermochemical routes for solar hydrogen production, indicating the chemical source of H_2: H_2O for solar thermolysis and solar thermochemical cycles; fossil or biomass fuels for solar cracking, and a combination of fossil/biomass fuels and H_2O for solar reforming and solar gasification. For solar decarbonization processes, optional CO_2/C sequestration is considered. All of those routes involve energy-consuming (endothermic) reactions that use concentrated solar radiation as the energy source of high-temperature process heat.

There has been considerable discussion on the merits of hydrogen as a future fuel. Regardless of whether it is hydrogen itself or in the form of some other hydrogen carrier such as methanol in the meantime, hydrogen is attracting enormous funding due to its long-term potential.

Both the U.S. Department of Energy and the European Commission have a clear vision of the hydrogen economy, with firm targets for hydrogen production costs. The U.S. target for 2017 is 3 US$/gge (gasoline gallon equivalent; 1 gge is about 1 kg H_2), and the EU target for 2020 is 3.50 €/kg H_2. The economics of large-scale solar hydrogen production has been assessed in numerous studies, which indicate that the solar thermochemical production of hydrogen can be competitive compared with the electrolysis of water using solar-generated electricity. It can become competitive with conventional fossil-fuel-based processes at current fuel prices, especially if credits for CO_2 mitigation and pollution avoidance are applied (SolarPACES, 2009).

As part of the transitional path, solar thermochemical processes are today demonstrating the production of solar reforming of natural gas to provide a cleaner version of the more conventional gas-to-liquids processes (GTL) (Stein, 2009). The global market for GTL (non-solar) is growing at an annual rate of 13.0% (Gainer, 2009), and the GTL products price is 20 to 25$/bbl (crude oil price; 19$/bbl) (Abdul Rahman, 2008). Thus, conventional GTL is nearing competitiveness with oil in some circumstances. A cost study on solar reforming of natural gas to produce solar H_2 showed future costs of 4.5 to 4.7 cents/kWh, which is about 20% more expensive than conventionally produced hydrogen (Moller, 2006). This indicates that the cost of large-scale solar GTL products are within the competitive range once carbon costs are considered.

3.9.6 Long-Term Deployment in the Context of Carbon Mitigation

Figure 3.43 shows the solar PV energy contribution to global supply in carbon stabilization scenarios from a review of literature in primary energy units (EJ).

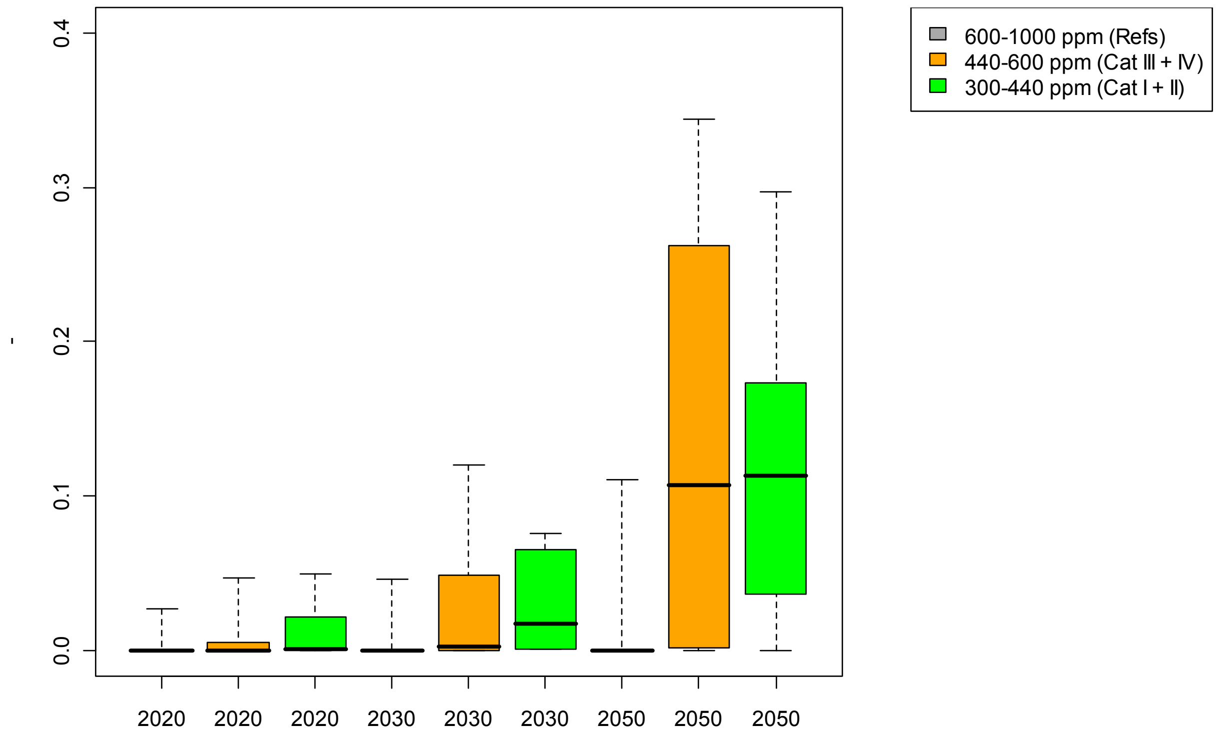


Figure **3.44** shows the same data as a proportion of the total electricity supply. Finally, Figure 3.45 shows the solar thermal energy (CSP) contribution to global supply in carbon stabilization scenarios from a review of literature in primary energy units (EJ).

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 a 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 bigger contribution for CSP (about 65%).

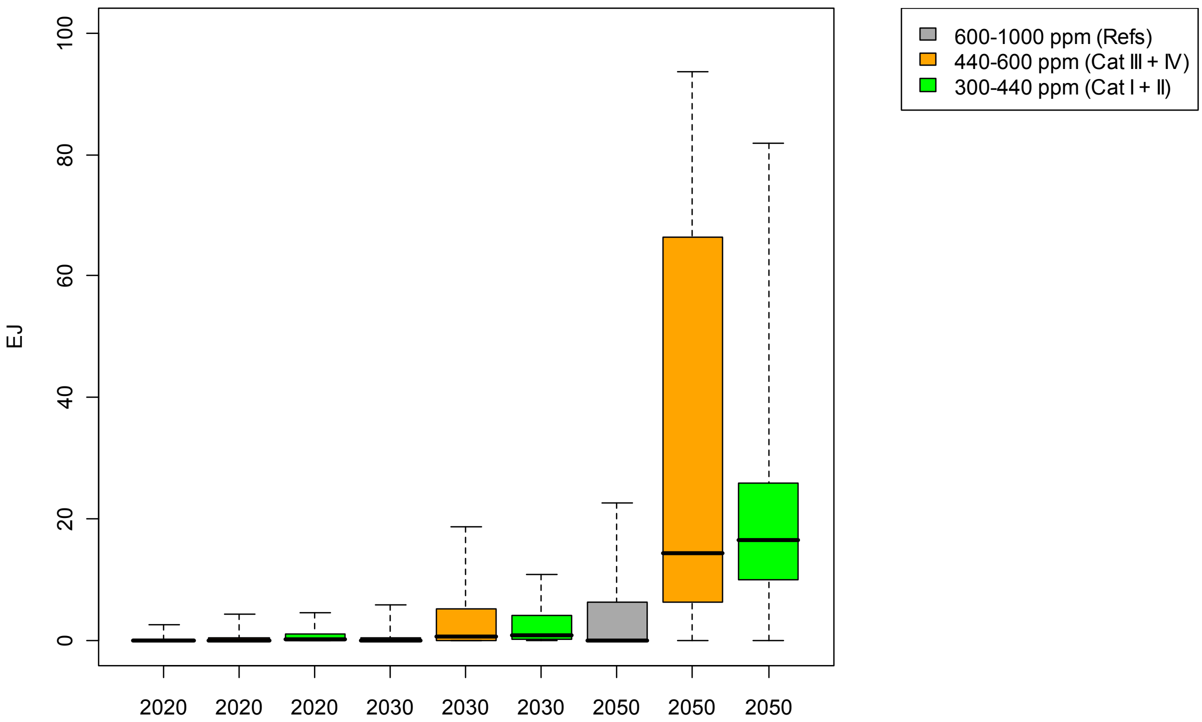


Figure 3.43: Global supply of solar PV energy in carbon stabilization scenarios.

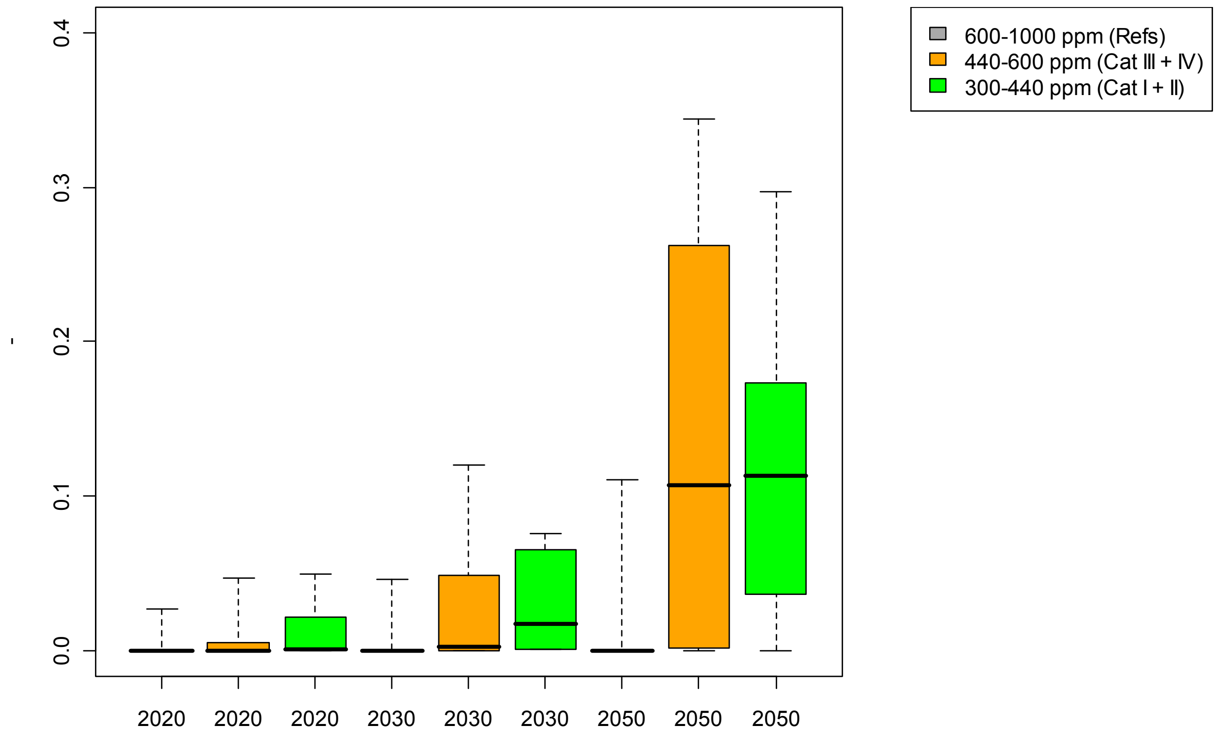


Figure 3.44: Solar PV electricity share in total global electricity supply. [TSU: Title on y-axis missing]

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 considered are decreased, the solar contribution grows spectacularly. In fact, Figure 3.43 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 to 600 and 300 to 440 ppm-CO_2 stabilization ranges, while only 2 EJ (~ 0% of global electricity supply) in the 600 to 1000 ppm-CO_2 stabilization range. The contribution of solar PV found in 2020 and 2030 is very low in all scenarios, being always lower than 7 EJ.

It should be highlighted the huge variation among the studies used in Figure 3.43. These variations are probably due to the different approaches used to generate these scenarios, but also to the difficulties found by the modelling tools used in these studies to address the technical and economic viability of solar energy. This variation is especially big in the solar PV contribution in 2050 for the 440 to 600 ppm-CO_2 stabilization scenario, which ranges from 7 to 70 EJ, depending on the study considered. In the most-stringent 300 to 440 ppm-CO_2 stabilization scenario, the solar PV supply in 2050 varies from 10 to 23 EJ equivalent to 5 to 18% of global electricity supply.

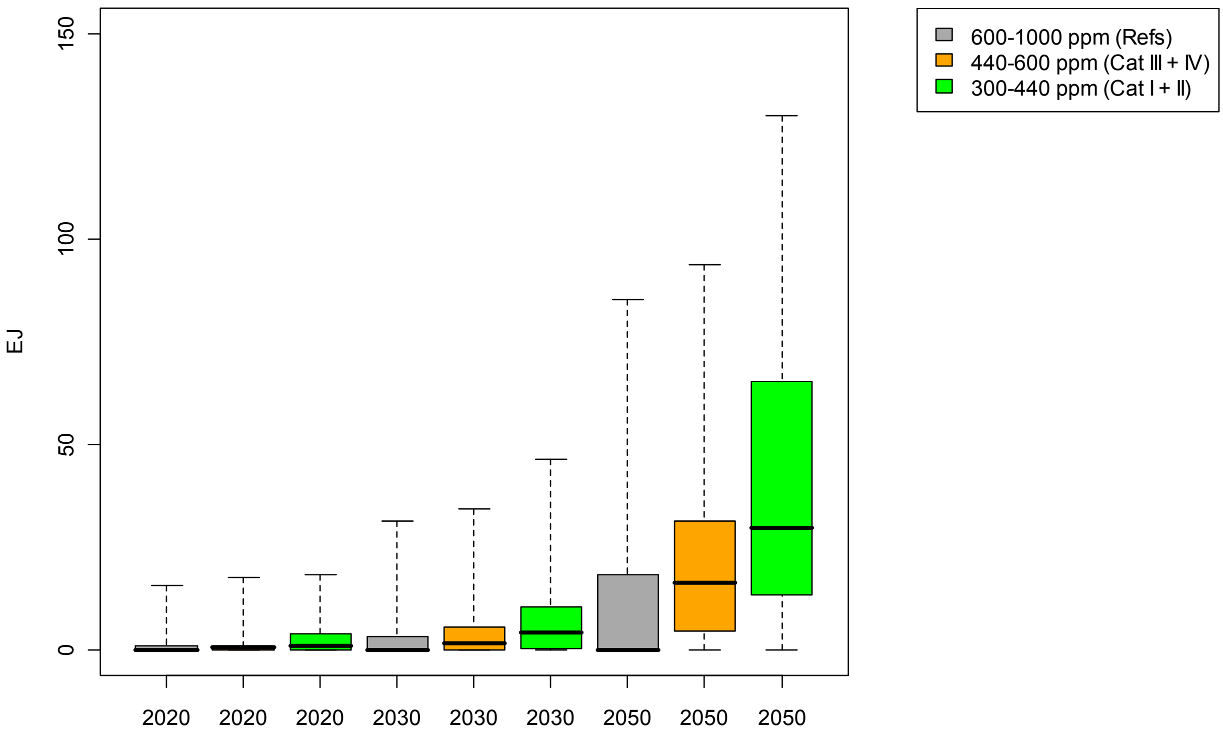


Figure 3.45: Global supply of solar thermal energy (CSP) in carbon stabilization scenarios.

When considering the potential contribution of thermal solar energy in the global electricity supply with different stabilization ranges, the growth with time seems to have a better slope, showing already 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 an extremely low contribution if the 600 to 1000 ppm-CO_2 stabilization scenario is considered, but the contribution is already around 20 EJ with the 440 to 600 ppm-CO_2 stabilization, and 35 EJ with the most-stringent scenario.

Once more, the variation among the studies included in Figure 3.45 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 70 EJ.

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 4

Geothermal Energy

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Length

Chapter 4 has been allocated a maximum of 34 (with a mean of 27) pages in the SRREN. The actual chapter length (excluding references & cover page) of the original version (prior to TSU commenting and formatting) was 38 pages, a total of 4 pages over the maximum (11 over the mean, respectively).

Expert reviewers are kindly asked to indicate where the Chapter could be shortened by 7-14 pages in terms of text and/or figures and tables to reach the mean length.

References

References of figures/tables are often missing. References from the text that are found missing in the reference list have been highlighted in yellow. In the same manner, references found in the reference list but missing from the text have also been highlighted.

Metrics

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

Figures

Pictures and figures will be replaced by equivalents with higher resolution where necessary.

Chapter 4: Geothermal energy

CONTENTS

EXECUTIVE SUMMARY

Geothermal energy is literally the heat of the Earth's interior. This heat can be tapped mainly through wells in the form of naturally formed geothermal fluids (geothermal reservoirs) or fluids artificially introduced from the surface (EGS: Enhanced Geothermal Systems). Once at surface, both types of fluids can be indirectly used to generate electric energy in a power unit, or in a direct way in several applications requiring heat, as heating and cooling for buildings, district heating, fish ponds, balneology, greenhouses, industrial and agricultural production and mineral drying, as well as space heating and cooling with geothermal heat pumps (GHP).

Geothermal is a renewable energy (RE) source since the tapped heat is continuously renovated by natural processes of the Earth's interior, and the extracted geothermal fluids are replenished by natural recharge and by reinjection of the exhausted fluids, providing a sustainable development. Given its locations and conditions, it is not expected that geothermal resources can be impacted by climate change.

Geothermal technologies are mature with established markets around the world. Geothermal-electric generation accounts for one century of commercial experience with more than 10 gigawatts of installed capacity in 24 countries providing up to 15% of their electricity demand in some of them; in all those countries, geothermal resources are used for base-load generation with an average capacity factor of 77%. Geothermal direct applications can be traced since the Palaeolithic, and currently there are almost 30 thermal gigawatts operating in 70 countries. Nevertheless, the geothermal technical potential is estimated to be 1000 gigawatts for electricity and 50,000 thermal gigawatts for direct uses, with an economic deployment of 160 gigawatts (electrical) and 815 gigawatts (thermal) by 2050. This could provide around 3% of the worldwide demand of electricity by this year, with some countries obtaining almost 100% of their own electrical needs from geothermal energy.

Direct CO_2 emissions average 120 g/kWh$_e$ for currently operating conventional geothermal-electric power plants and less than 1 g/kWh$_e$ for binary cycle plants. Corresponding figures for direct use applications are even lower. The life-cycle assessment CO_2-equivalent is 25-80 g/kWh$_e$ for binary plants and 4-60 g/kWh$_{th}$ 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.

Even geothermal-electric projects have relatively high up-front capital costs, varying currently between 2,000 and 10,000 US$ (2005) per megawatt [TSU: given capital cost values are per kilowatt], the levelized costs (LCOE) of geothermal electricity are competitive in the electric markets, being calculated to be 49-75 US$ (2005) per megawatt-hour (MWh) and around 176 US$/MWh for future EGS projects. These costs are expected to lower to 44-63 US$/MWh (and 137 US$/MWh for EGS) by 2050. Costs of geothermal direct uses are also competitive (1,100 to 2,700 US$ per installed thermal kilowatt).

In despite of the present competitiveness of geothermal resources for electric and heating uses, policy support for research and development is required for all geothermal technologies, and especially for EGS, including subsidies, guarantees and tax write-off to cover the risks of initial deep drilling. Feed-in tariffs with confirmed geothermal prices, and direct subsidies for district and building heating can also be useful.

Geothermal energy is independent of the climate and has an inherent storage capacity that makes it especially suitable for supplying base-load power in an economical way, and can thus serve as a partner with energy sources which are only available intermittently, contributing to significantly mitigate climate change. This is the challenge. This is the opportunity. [TSU: language]

4.1 Introduction

Geothermal resources essentially consist of the thermal energy stored at depth within the earth in both rock and trapped steam or liquid water. Exploitable 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 mantle hot spot anomalies. Intermediate (100-180°C) to 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 to these temperature-defined categories, 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 also 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 aquifer systems contain deeply circulating fluids in porous media or fracture zones, but lack a specific heat source. They are further sub-divided into systems at hydrostatic pressure and systems at pressure higher than hydrostatic (geo-pressured). 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. Temperature: H: High (>180°C), I: Intermediate (100-180°C), L: Low (ambient to 100°C). EGS: Enhanced (or Engineered) Geothermal Systems. GHP: Geothermal Heat Pumps.

Type	Natural fluids	Subtype	Temperature Range	Utilisation	
				Current	Potential
Hydrothermal	Yes	Continental	H, I & L	Power, direct uses	
		Submarine	H	None	Power, direct
Conductive	No	Shallow (<400 m)	L	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

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 penetrating 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.

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 pressure, chemical or thermal stimulation methods, they form a potential Enhanced or Engineered Geothermal System (EGS) resource that can be used for power generation and/or direct applications. EGS resources (including Hot Dry Rock: HDR) occur in any geothermal environment, 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 for oil and gas (~10 km depth). Stacked geothermal sub-types (plays) are common. Naturally fractured and water-saturated hot rocks are EGS targets below high temperature (>180°C at >2.6 km) hot sedimentary aquifer targets in the Australian Cooper Basin (Goldstein, 2010).

Direct uses of geothermal energy started at least since the Middle Palaeolithic when hot springs were used for ritual or routine bath (Cataldi, 1999), but industrial utilisation begun 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, at many places geothermal energy has provided safe, reliable, environmentally sustainable, renewable energy in the form of electric power and direct heating services on both large and small scales. 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, geothermal (ground-source) heat pumps 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 energy savings in most countries of the world.

Today's hydrothermal technologies have demonstrated very high average capacity factors (up to 90%) in electric power generation with low carbon emissions. 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 geothermal heat pumps 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 GHG emissions and 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.

4.2 Resource potential

4.2.1 Global technical resource potential

The global technical geothermal potential was estimated at 50 EJ according to Table 4.7, chapter 4 (Energy Supply) of the IPCC Fourth Assessment Report (AR4). This is now considered a conservative estimate. Also, in Table 4.2 of the same AR4, it was estimated an available energy resource for geothermal (including potential reserves) of 5000 EJ/year (Sims et al., 2007).

The total energy contained in the Earth is of the order of 12.6 x 10^{12} EJ and that of the crust of the order of 5.4 x 10^{9} EJ to depths of up to 50 km (Dickson and Fanelli, 2003 and 2004). 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 land and 0.1 W/m^2 through the ocean floor. The result is a global average temperature gradient of 25-30°C/km and a total terrestrial heat flow rate of 44 TWt (1400 EJ/year).

Within a 10 km depth under the continents (reachable with current drilling technology) the stored thermal energy is of the order of 40 x 10^{7} EJ (EPRI, 1978). Within 5 km depth the energy was estimated to be 14 x 10^{7} EJ (WEC, 1994). In addition to the stored energy, the average thermal energy recharge rate from below 5 km depth (ignoring volcanic eruptions) is about 315 EJ/year (Stefansson, 2005). Based on those considerations, the overall **theoretical potential** for geothermal resources can be estimated to be almost 42 x 10^{6} EJ (EPRI, 1978; Table 4.2).

More recent assessments reinforce these expectations. In a MIT-led assessment, the US stored geothermal energy was estimated to be 14 x 10^{6} EJ with a technically extractable capacity of about 1200 GWe to depths of 10 km (see Tables 3.2 and 3.3 in Tester et al., 2006).The US Geological Survey (2008) estimated mean electric power generation potential from identified and undiscovered EGS resources in the western US alone is 518 GWe. Also for Australia, Budd et al. (2008) estimated that recovery of just 1% of the geothermal energy stored from 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.

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 utilization at a given site. To calculate an effective technical potential it is 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 the heat nearer to the surface, thus giving rise to convecting hydrothermal resources where drilling at up to 4 km depth can access fluids at temperatures of 180°C to more than 350°C.

A statistical analysis (Goldstein, 2010) of stored geothermal energy to depths of 5 km (WEC, 1994) and 10 km (ESPRI, 1978) assumes 0.5% and 20% as the minimum and maximum recovery factors, respectively. This assessment concludes the global technical recoverable continental geothermal energy resource is in the order of 9 x 10^{6} EJ to 5 km and 27 x 10^{6} EJ to 10 km, with a 7% (statistical mean) recovery of stored heat. Both estimates are conservative in the context of sustainable level for development (42 x 10^{6} EJ, EPRI, 1978; Table 4.2).

From the distribution of geothermal resources over different temperature regimes, Stefansson (2005) estimated the low temperature potential (for direct use or binary-cycle electricity) to be 153 EJ/year (5 TWt). The combined high and low temperature technical potential (about 800 EJ/year) is approximately the same order of magnitude as the natural heat recharge of the underground resources.

For hydrothermal submarine resources, an estimation of 130 GWe off-shore technical potential has been made (Hiriart et al., 2010). This is based on the 3900 km of ocean ridges already confirmed as having hydrothermal vents and with the assumption that only 1% could be developed for electricity production with a recovery factor of 4%.

Stefansson (2005) concluded that the most likely value for the technical potential of known, onshore, hydrothermal resources capable of use for electricity generation (T>130°C) is 209 (±27) GWe. This value is supported by a statistical correlation between the numbers of active land-based volcanoes (1322 in total) and identified geothermal resources in well-explored regions. However, theoretical considerations based on well-explored regions of the USA and Iceland reveal that the magnitude of hidden hydrothermal resources is expected to be 5-10 times larger than this estimate of identified resources (Bertani, 2009).

The global geothermal **technical potential** can be estimated to be almost 30 EJ/y for electricity generation and almost 631 EJ/y for direct utilisation (Bertani, 2009). Technical potential for geothermal-electricity, including EGS, is equivalent to 1000 GWe (1 TWe) of installed capacity assuming an average capacity factor of 0.95, and to 8,322 TWh/y of electric generation. The technical potential for geothermal direct uses is equivalent to 50,000 GWt (50 TWt) of installed capacity, assuming an average capacity factor of 0.40 (Table 4.2 and Fig. 4.1).

A comparison of estimates of global geothermal economic potential published by different authors (Bertani, 2003) reveals that the projections are very scattered, due to differences in assumptions and uncertainties in energy recovery factors, economic viability and assumed rates of learning in all areas (exploration, drilling, stimulation, and energy conversion) as deployment proceeds. Nevertheless, a thorough review concludes that geothermal electricity **economic potential** (by **2050**) from identified geothermal reservoirs is realistically estimated to range between a minimum of 35 GWe, a median of 70 GWe, and a maximum of 160 GWe (Figure 4.1), depending on assumptions regarding technology improvement, development incentives or constraints that may be in effect over the next 40 years (Bertani, 2009; Fridleifsson et al., 2009; Rybach, 2010; Mongillo, 2009; Mongillo et al., 2010). The median value represents an annual compounding growth rate of 5% over 40 years and is considered to be economically realisable using present day technology. The maximum value (more than twice the median) represents an annual growth rate of 7% and is also economically realisable, but includes the assessed benefits of future financial incentives, and enhanced technologies such as permeability stimulation and deeper drilling.

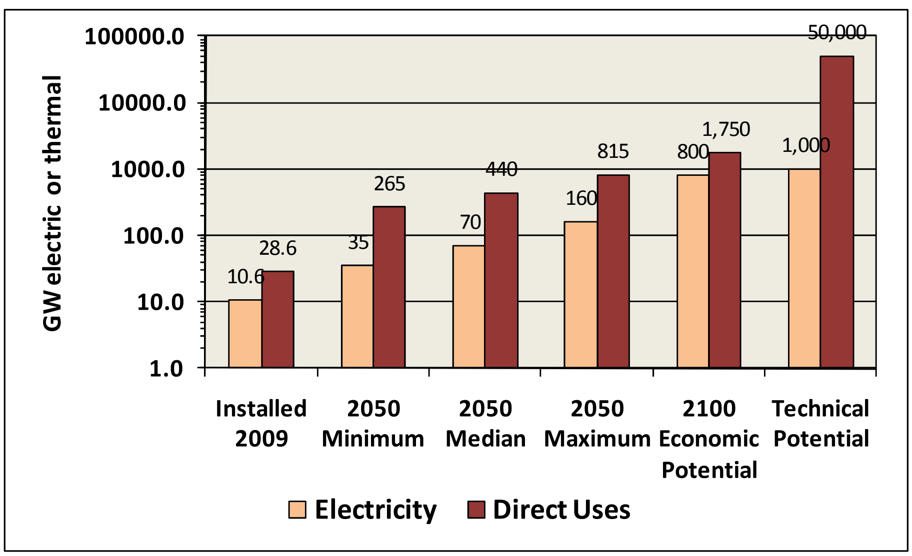

Figure 4.1. Estimated global geothermal electricity and direct use economic potentials by 2050 and beyond, with assumptions of status-quo growth rates (minimum), present technology (median) and technology improvement (maximum). Data for 2009 direct uses correspond to 2005 (to be updated [by AUTHORS]). Technical resource potentials (including inferred but unidentified resources) are also shown (Adapted from Fridleifsson et al., 2008, and Stefansson, 2005).

The geothermal-electric **economic potential** by **2100** was also estimated to be around 24 EJ/y, equivalent to 800 GWe of installed capacity using the same capacity factor of 0.95.

On the basis of the estimates shown in Figure 4.1, it is considered plausible to produce up to 8.3% of the total world electricity by 2100 with onshore geothermal resources (including EGS), serving ~17% of the world population (Bertani, 2009). More than thirty countries (located mostly in Africa, Central/South America, the Pacific and South-East Asia) could potentially obtain 100% of their electricity from a combination of base-load geothermal and variable-load hydro and wind resources.

The next issue is to consider the prospective contribution of EGS to the technical and economical potential more carefully. Recognizing that there is very limited operating experience with EGS at a commercial scale, any estimate is by nature speculative. Nonetheless, one should keep in mind that many characteristics and deployment requirements of EGS systems bear similarity to commercial hydrothermal systems. And, if geothermal is to have a large scale impact in off-setting global carbon dioxide emissions in the future, utilization of the EGS resource will be necessary.

A statistical analysis by Goldstein et al. (2009) yields a mean forecast for global EGS deployment of 444 GWe (worldwide) by 2050 without any consideration of commercial risks or technical uncertainties. Accounting for these factors, the authors give a more realistic range of 90 to 130 GWe by 2050, from which it was estimated that EGS could represent around the half of the maximum of 160 GWe projected by this year (Fig. 4.1). Industrial and governmental co-funding of EGS development aims to make financial investment more attractive based on an increased probability of EGS project success. With this co-funding and appropriate mitigation policy instruments, high grade, hot rock resources are expected to become competitive, as early as 2015.

Regarding geothermal **direct uses**, the **economic potential** by **2100** is estimated to be 22 EJ/y, equivalent to 1750 GWt of installed capacity with an average capacity factor of 0.40. The **economic potential** by **2050** is estimated to be between a minimum of 265 GWt, a median of 440 GWt, and a maximum of 815 GWt (Figure 4.1), depending on similar assumptions to those made for estimating the electric potential (Fridleifsson et al., 2008; Rybach, 2010; Mongillo, 2009; Mongillo et al., 2010).

Potential for increased direct use is very large. Recent likely-case scenario estimates of future direct use indicate that by 2050 the total use could increase to 815 GWt, with a GHP (Geothermal Heat Pumps) contribution of some 740 GWt (90%) (Table 4.9). The dominance and expected significant growth in GHP use arises from their ability to be used for heating, cooling and domestic hot-water applications anywhere on the earth’s surface (Lund et al., 2003; Curtis et al., 2005; Rybach, 2008).

4.2.2 Regional resource potential

The assessed geothermal theoretical, technical and economic potentials (the latter by 2100), are presented on a regional basis in Table 4.2. The original regional assessment for the theoretical potential was conducted by EPRI in 1978 (EPRI, 1978), with a very detailed estimation of the heat stored inside the first 3 km under the continents, taking into account the average geothermal gradient and the presence of either a diffuse geothermal anomaly or an high enthalpy region, due to the location nearby the plate boundaries. Data from theoretical and technical potentials are taken and adapted from Bertani (2009), regrouping countries and regions into the 10 IEA regions. The economic potential by 2100 is an original estimation.

Table 4.2. Geothermal potentials for the IEA regions (Theoretical and technical potentials adapted from Bertani, 2009).

IEA REGION	Theoretical Potential	Technical Potential		Economic Potential (2100)	
		EJ/year		EJ/year	
	10^6 EJ	Direct uses	Electricity	Direct uses	Electricity
1. OECD North America	9.402	141.060	8.384	5.046	6.441
2. Latin America	5.509	81.409	6.896	0.631	0.749
3. OECD Europe	2.019	30.711	1.110	6.307	4.494
4. Africa	6.083	93.145	2.390	2.018	1.947
5. Transition Economies	6.930	106.732	1.710	0.631	0.599
6. Middle East	1.355	20.711	0.580	0.505	0.449
7. Developing Asia	3.732	55.379	4.300	1.261	4.494
8. India	0.938	14.528	0.100	0.631	0.899
9. China	3.288	48.842	3.720	2.523	2.397
10. OECD Pacific	2.487	38.203	0.770	2.523	1.498
TOTAL	**41.743**	**630.720**	**29.960**	**22.075**	**23.967**
Equivalent installed capacity (in GWt or GWe)*		**50,000**	**1,000**	**1,750**	**800**

*Equivalence considers 0.95 and 0.40 as average capacity factors for electricity and direct uses, respectively.

4.2.3 Sustainable development and the possible impact of climate change on resource potential

Geothermal energy is a renewable resource, yet it is clearly different from solar, wind, and biomass. As thermal energy is extracted from the active reservoir, it creates locally cooler regions. In more practical terms, commercial geothermal projects are operated at production rates that cause local declines in hydraulic pressure and/or in temperature over the economic lifetime of the installed facilities. These cooler and lower pressure zones 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). Detailed modelling studies (Pritchett, 1998) 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.

With proper well placement and reservoir management, 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 re-establishing the pre-production state 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 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, 2008). After production stops, begins recharge driven by pressure and temperature gradients. The recovery typically shows an asymptotic behaviour, fastest at first then slowing down subsequently. Practical replenishment will generally occur on time scales of the same order as the lifetime of the geothermal production systems (Axelsson et al., 2005).

Good examples of sustainable uses of high- and low-temperature geothermal fields are given in recent international sustainability workshop proceedings (Axelsson and Bromley, 2008).

Since geothermal resources are located underground or undersea, they are not dependent on climate conditions. Therefore, climate change is not expected to have any relevant impact on the resource potential from a worldwide nor a regional perspective. However, the GHP efficiency could be affected by changes in surface temperature, and a future scarcity of water may force geothermal power plants to switch to air-cooled systems.

4.3 Technology and applications (electricity, heating, cooling)

4.3.1 Geothermal energy utilisation

Geothermal energy is used in two ways – as a heat supply for conversion to electricity and for direct heating or cooling without conversion. Geothermal resources can be divided into three main groups, depending on temperature and their relation to magmatic activity:

a) High-temperature (>180°C). These systems are mostly related to geologically recent volcanism and are mainly used for conventional power production. Some non-volcanic, high temperature areas are being appraised for power production from EGS.

b) Intermediate temperature (100°C-180°C). These are found all over the world in deep sedimentary basins, in hot rocks below sedimentary basins and in areas indirectly related to volcanism or tectonic fracturing and are often used for combined heat and power applications.

c) Low temperature (ambient to 100°C). These systems typically have little direct relation to volcanism, and are used mainly for direct heat and heat pump applications.

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. Some 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. In addition many reservoirs are utilised by extracting heat from thermal water of a producer well and generating power in a binary cycle. The cooled water is re-injected into the reservoir after passing the heat exchanger.

Geothermal technologies belong to category 1 (technologically mature with established markets in at least several countries) according to the 2004 Renewables Conference held in Bonn. 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, some exploration activities (including geological, geochemical and geophysical surveys) have to be developed to locate and assess them. The objectives of geothermal exploration activities 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. The major focus is the underground temperature distribution and the Earth’s stress field in order to identify potential fluid bearing structures. Exploration of a prospective geothermal reservoir involves estimating its lateral extent and depth with geophysical methods, such as seismic, magneto-telluric and resistivity surveys, and drilling exploration wells. Thermograms recorded in available shallow water-wells (50-200 m) could be also useful to reveal geothermal anomalies and constructing terrestrial temperature maps (Zui, 2004, 2010).

Today, geothermal wells are drilled over a range of depths to about 5 km using conventional rotary 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 drilling-pad, heading in different directions to access large resource volumes, and target permeable structures. Current geothermal drilling methods are presented in more detail in the chapter 6 of Tester et al. (2006).

4.3.3 Reservoir engineering

The most sophisticated 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 (Pruess, 2009), and optimum plant size selected.

Injection management is an important aspect of geothermal development. Because most geothermal reservoirs are fracture-dominated, the system "plumbing" is poorly known at early times, and the placement of injection wells cannot be optimized until the field has been stressed by production, and flow paths and thermal responses identified. 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, geothermal reservoir evolution can be modelled and pro-actively managed. Hence, it is prudent to monitor and analyse the chemistry and thermodynamics 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.

4.3.4 Surface equipment and power plants

Surface equipment generally has to handle steam, water and/or both (two) phases. Systems with direct use of steam consist of pipelines, water-steam separators, vaporisers, de-misters, and different types of turbines. Binary cycles require heat exchangers. Steam turbines are driven by convective flow to a low pressure exhaust or a vacuum. In a condensing turbine (Figure 4.2), vacuum conditions are usually maintained by direct condenser. Depending on humidity and temperature, a significant proportion of the steam condensate is thereby lost to the atmosphere as vapour. The unit sizes are commonly 20-110 MWe (DiPippo, 2009). 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. Back-pressure turbines are also steam turbines that exhaust to the atmosphere, omitting the condenser and the cooling tower, and are frequently used as small plants supplied by isolated wells for distributed local (rural) power supplies. 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.

Binary cycle plants of Organic Rankine Cycle (ORC) type (see Figure 4.3) typically utilise lower temperature geothermal fluids (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.

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 (200-260°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.

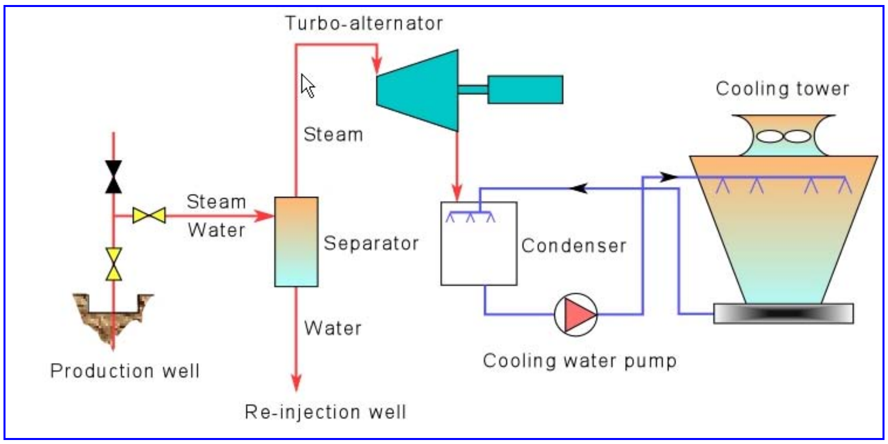

Figure 4.2. Schematic diagram of a geothermal condensing steam power plant. [TSU: Please add source.]

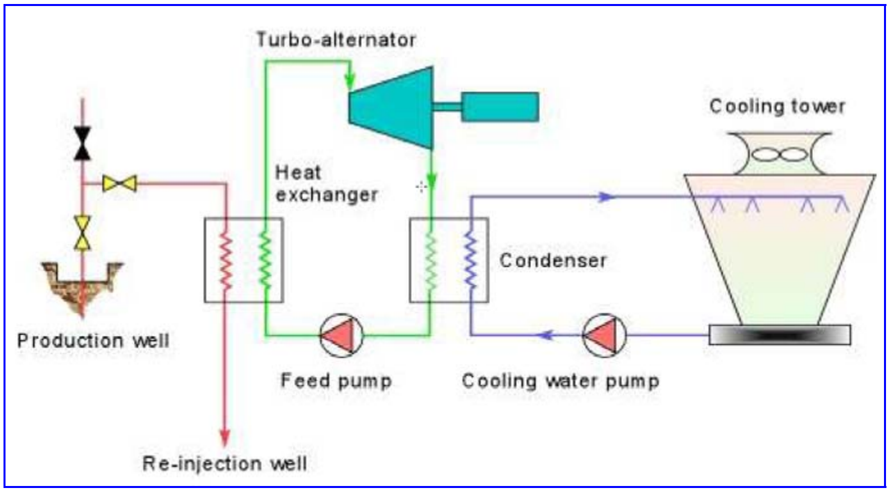

Figure 4.3. Schematic diagram of a geothermal binary cycle power plant. [TSU: Please add source.]

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 new 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 district heating and/or for power generation.

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).

Conforming research priorities for EGS and magmatic resources as determined in Australia (DRET, 2008), the USA (DOE, 2008), the EU (ENGINE, 2008) and the International Partnership for Geothermal Technologies (IPGT, 2008) are summarised in Table 4.3. Successful deployment of the associated services and equipment will be also relevant to many conventional geothermal projects.

Table 4.3. Priorities for geothermal research –focusing on potential of magmatic and EGS resources. (Adapted from Goldstein et al., 2008). HTHP: high temperature and high pressure.

Complementary research & share knowledge	Education / training
Standard geothermal resource & reserve definitions	Improved HTHP hard rock drill equipment
Predictive reservoir performance modelling	Improved HTHP multiple zone isolation
Predictive stress field characterisation	Reliable HTHP slim-hole submersible pumps
Mitigate induced seismicity / subsidence	Improve resilience of casings to HTHP corrosion
Condensers for high ambient-surface temperatures	Optimum HTHP fracture stimulation methods
Use of CO_2 as a working fluid for heat exchangers	HTHP logging tools and monitoring sensors
Improve power plant design	HTHP flow survey tools
Technologies & methods to minimise water use	HTHP 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 is others, such as ‘Rainbow’, with an estimated output of 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 could 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). An external coiled heat exchanger could be placed over the top of the hot water vent at one end, while at the other end another coiled heat exchanger with hyperbolic cooling tower could be installed in the cold water of the surrounding sea. The operation would be similar to other binary cycle power plants using evaporator and condenser heat exchangers. This cycle has an internal efficiency of the order of 80%, resulting from losses of the turbine, pumps and generator (Hiriart et al., 2010). Overall efficiency for a submarine vent 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 and off-to-onshore grid-connection costs and the potential impact on unique marine life around hydrothermal vents.

4.3.7 Direct use

Direct use provides heating and cooling for buildings including district heating, fish ponds, greenhouses and swimming pools, and industrial and process heat for agricultural products and mineral drying. In addition, ambient temperature shallow ground and groundwater are used for space heating and cooling with geothermal heat pumps.

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 re-injection wells. Closed loop systems are more flexible than open loop systems, but in both cases a fossil fuel backup boiler (as shown in Figure 4.4) may be provided to meet peak demand, to reduce the overall investment, and to conserve the geothermal resource.

In Iceland, the geothermal water is piped up to 25 km from the geothermal fields to the 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.

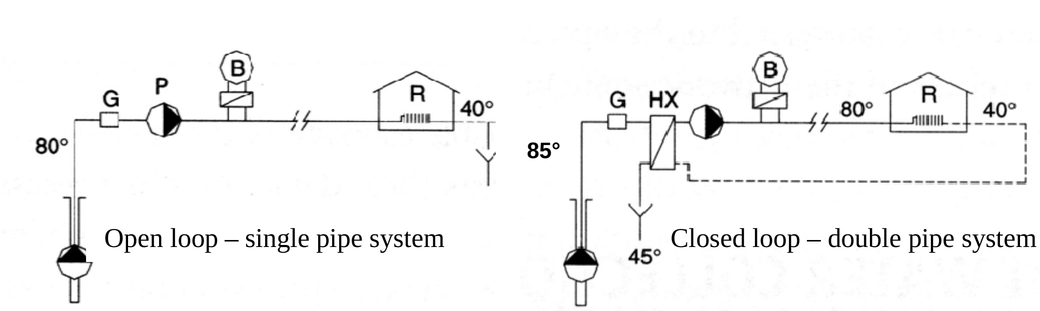

Figure 4.4. Two main types of district heating systems (Dickson and Fanelli, 2003). G=gas separator, P=pump, B=backup boiler, R=radiation heating, HX=heat exchanger.

4.3.8 Geothermal heat pumps

Geothermal Heat Pumps (GHP) are one of the fastest growing applications of renewable energy in the world today (Rybach, 2005). 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 available 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.

There are two main types of geothermal heat pumps (Figure 4.5, modified from Lund et al., 2003). 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 to surface.

In essence heat pumps are nothing more than refrigeration units that are reversed. In the heating mode the efficiency is described by the coefficient of performance (COP) which is the heat output divided by the electrical energy input. Typically this value lies between 3 and 4 (Rybach, 2005).

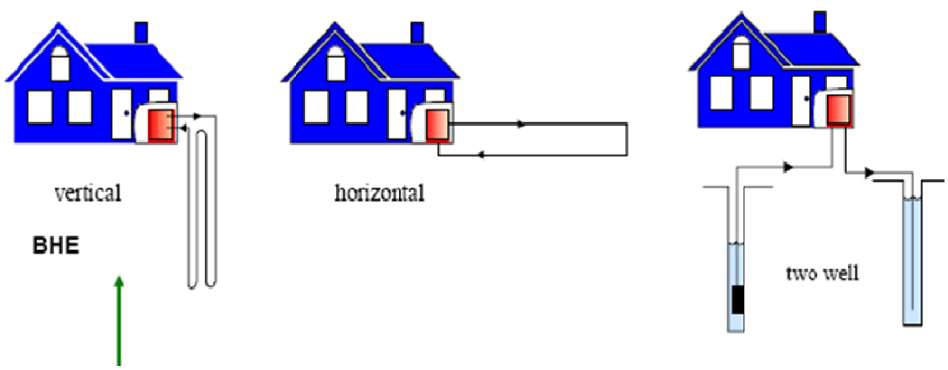

Figure 4.5. Closed loop and open loop heat pump systems. Green arrow indicates the most common system, with borehole heat exchangers (BHE). The heat pump is shown in red. [TSU: Please add source.]

4.4 Global and regional status of market and industry development

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: websites as footnotes?]. For convenience, the global geothermal market can be subdivided into conventional resource development for electricity, non-conventional development (EGS), and direct heat utilisation.

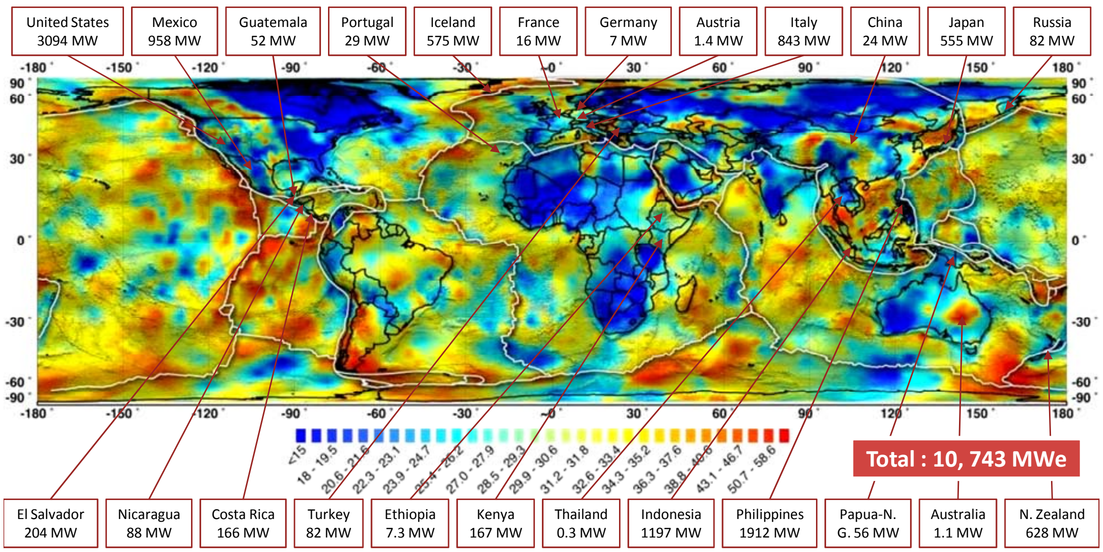

Figure 4.6. Geothermal-electric installed capacity by country in 2009 (Credits: [by AUTHORS]). Figure shows worldwide heat flow ranks in color (units? [by AUTHORS]) and tectonic plates boundaries (To be completed [by AUTHORS]). [TSU: Please add source.]

4.4.1 Status of geothermal electricity from conventional geothermal resources

In 2009, electricity was being produced from conventional high temperature geothermal resources in 24 countries (Fig. 4.6). Many developing countries are amongst the top 15 in geothermal electricity production, but many more have untapped resources inferred from their favourable locations with respect to active volcanism and fractured crustal rock, for example, Chile and Peru.

The worldwide use of geothermal energy for power generation (predominantly from conventional hydrothermal resources) was 67 TWh/year in 2008. The installed capacity by the middle of 2009 was 10.7 GWe (Fig. 4.6), and has been growing at 4.4% annually since 2004 (Gawell and Greenberg, 2007; Fridleifsson and Ragnarsson, 2007). This is higher than the 1999-2004 average annual growth rate of 3% (Bertani, 2005, 2009) (Fig. 4.7).

Evolution of geothermal installed capacity, annual generation and capacity factor since 1995 are provided in Table 4.4, along with projections to year 2100.

Table 4.4. World installed capacity, electricity production and capacity factor of geothermal power plants 1995-2005 and forecasts for 2010-2100 (with data from Fridleifsson et al., 2008, and Bertani, 2009).

Year	Installed Capacity (GWe) Actual or mean forecast	Electricity Production (GWh/yr) 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	11	74,669	77
2020	25	178,000	81
2030	50	372,000	85
2040	100	780,000	89
2050	160	1,261,000	90
2100	800	6,700,000	96

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. Electricity has been generated commercially by geothermal steam since 1904 (Figure 4.7).

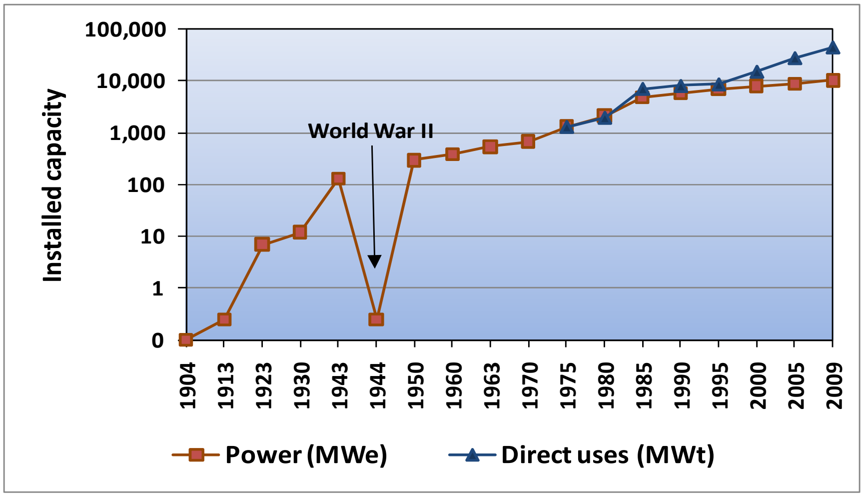

Figure 4.7. Historic development of geothermal installed capacity (power and direct uses) worldwide. For direct uses there are no reliable data before 1975. [TSU: Please add source.]

The US is currently the world's top geothermal market. 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 (Stephure, 2009). US geothermal activity is concentrated in a few western states, which are home to vast reserves of US hydrothermal resources, particularly in California and Nevada, but only a small fraction of the geothermal potential has been developed so far. By September 2009, an industry advocacy group, the Geothermal Energy Association (GEA) had identified around 132 new geothermal-electric projects in different stages of development in the US. These projects represented between 4249 and 6443 MWe of new geothermal power plant capacity under development in 14 states of the country (Jennejohn, 2009).

Outside of the US, over 29% of the global installed geothermal capacity resides in the Philippines and Indonesia (Fig. 4.8). Indonesia is expected to evolve as the larger geothermal growth market in the longer term due to its better resource potential and growing power appetite (Stephure, 2009).

Outside of the US and Southeast Asia, the markets of Japan, Iceland, Italy, and Mexico account for over 65 percent of remaining [TSU: % of remaining unclear] global installed geothermal capacity. Although these markets have seen relatively limited growth over the past few years, greater urgency to advance low-carbon base-load power generation is helping re-start new capacity growth in these markets. Moreover, attention is turning to new markets like Chile, Germany, Australia, and East Africa, and other not so new as Turkey, Nicaragua and Russia (Fig. 4.8).

The majority of existing geothermal assets are owned by large incumbent state-owned utilities and large 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 roughly 90% of the entire installed global market.

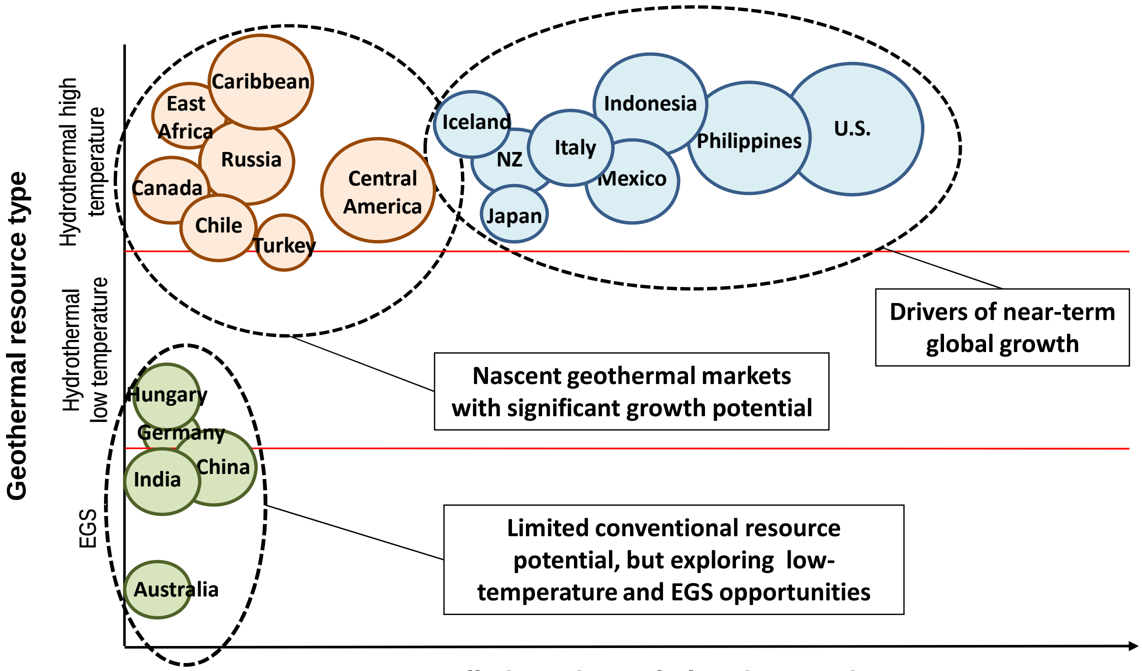

Figure 4.8. Global geothermal country rankings by installed capacity and resource type. (Bubble size approximately reflects MWe resource potential) (Emerging Energy Research, 2009.)

Today the geothermal-electric capacity represents only 0.22% of the total worldwide electric capacity (about 5,000 GWe [TSU: 5 GWe, consitency with table 4.4? (2005: 8.9 GWe, 2010: 11 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 (Fridleifsson, 2007).

4.4.2 Status of Enhanced Geothermal Systems

There are several places where targeted EGS demonstration is underway. Australia can claim large-scale activity, since by 2010 eighteen stock market-registered enterprises held Australian geothermal licences. A real boom can be observed, with 48 companies in 391 leases (a total of 362,000 km^2 in six states), US$ 248 million invested to year-end 2008 and more than US$ 1000 million forecast to year-end 2014. This is underpinned with government grants to co-fund drilling, geophysical surveys and research totalling US$ 267 million (to year end 2009) (Goldstein et al., 2010). Project developers plan to establish the first power plants (with a few MWe capacity) in 2010 (Beardsmore, 2007).

The EU project “EGS Pilot Plant” in Soultz-sous-Forêts, France (started in 1987), has recently commissioned the first power plant (1.5 MWe) to utilise the enhanced fracture permeability at 200°C (low fracture permeability was enhanced). In Landau, Germany, the first EGS-plant with 2.5 to 2.9 MWe went into operation in fall 2007 (Baumgärtner et al., 2007). Another approach is made for deep sediments in the in situ geothermal laboratory in Groß Schönebeck using two research wells (Huenges et al., 2009). One of the main future demonstration goals in EGS will be to see whether and how the power plant size could be up-scaled to several tens of MWe by improved reservoir engineering measures.

The US in its recent clean energy initiatives has included significant EGS research, development, and demonstration components as part of a revived national geothermal program.

Although EGS power plants, once operational, can be expected to have great environmental benefits, their potential future impact and environmental benefits such as avoiding additional CO_2 emissions, cannot yet be satisfactorily quantified. [TSU: Relation to market and industry development?]

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 are: space heating of buildings (52%, of which 32% [TSU: percentage points?] is from heat pumps), bathing and balneology (30%), horticulture (greenhouses and soil heating) (8%), industrial process heat (4%), aquaculture (fish farming) (4%) and snow melting (1%) (Lund et al., 2009 [TSU: list of references contains two publications of Lund et al., 2009]).

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 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 as 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 28.6 GWt [by AUTHORS] (Fig. 4.1), with a total thermal energy usage of about 72.6 TWh/y (0.261 EJ/y) [by AUTHORS] (Lund et al., 2005). Out of that total, geothermal heat pumps (GHP) contributed more than half (15.7 GWt) [by AUTHORS], with approximately 1.6 million geothermal heat pumps (GHP) operating in more than 30 countries (IEA-GIA AP, 2008). GHP represents one of the more expanding markets of renewable energy in the world, and due to its rapidly growing development, statistical data can provide only snapshots of the current situation (Data for 2005; to be updated by 2009 later) [by AUTHORS].

4.4.4 Impact of policies

[TSU: cross-reference to chapters 1 and 11?]

Main present barriers in the geothermal market and industry, according to the taxonomy of barriers used in this report [TSU: replace by cross-reference to chapter 1.4 instead?], can be described as follows.

I1 (Clarity in concepts [knowledge, understanding]) [TSU: see above]. Support is needed for programmes to standardise geothermal technologies for a reliable and efficient use independent of site, to educate and enhance the public knowledge, understanding and acceptance of geothermal energy use, and to conduct research towards the avoidance or mitigation of potential induced hazards and adverse effects.

I2 (RE know-how systems) [TSU: see above]. The development of all geothermal technologies relies on the availability of skilled installation and service companies with 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. For enhanced global development, such services need to be better distributed worldwide.

T3 (Transport and accessibility) [TSU: see above]. Distributions of potential geothermal resources vary from being nearly site-independent (for ground heat pump technologies and Enhanced Geothermal Systems) to site-specific (for hydrothermal sources). The distance between electricity markets or centres of heat demand and geothermal resources, as well as the availability of a transmission capacity, is sometimes a significant factor in the economics of power generation and direct use.

E2 (Cost structure and accounting) & E3 (Project appraisal and financing) [TSU: see above]. Reducing costs and increasing the efficiency of supplying geothermal energy will enhance its market competitiveness. Policies set to drive uptake of geothermal energy should take local demand factors into account. Small heat customers can be satisfied with the deployment of GHP technologies, with relatively small budgets. Hence, in many countries, the deployment of GHP technologies can be a suitable base-line for development targets. District heating systems can be operated with less auxiliary energy (for pumps) than GHPs, and have potential to provide greater mitigation of CO_2 emissions. However, district heating systems and industrial heat use applications require larger scale investments. Hence, production from hydrothermal resources to supply district heating systems and industrial heat uses can be sensibly and efficiently supported in some markets. Heat from deeper geothermal wells is better suited to larger heat and electricity demands. The development of geothermal energy from deeper resources requires yet larger scale investment in advance of deployment.

P3 (Energy subsidy, taxing, other support policies) [TSU: see above]. Policy support for research and development is required for all geothermal technologies, but especially for EGS –as the US Department of Energy currently does in the US. Public investment in geothermal research drilling programs should lead to a significant acceleration of EGS development. Specific incentives for geothermal development 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). However, since feed-in tariffs for direct heating are difficult to arrange, direct subsidies for building heating and for district heating systems may be more successful. Subsidy support for refurbishment of existing buildings with GHP is also convenient.

P4 (Regulations and rules impeding RE) [TSU: see above]. The success of geothermal development in a country is linked to government policies and initiatives. It would be recommendable these policies take into account that geothermal energy is independent of weather conditions and has an inherent storage capability which makes it especially suitable for supplying base-load power in an economical way, and it can thus serve as a partner with energy sources which are only available intermittently. 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 can also increase investors certainty for market access by moulding rules to foster fast and affordable connection of RE to power grids. Many countries are yet to reform market rules (public benefit tests) for electricity markets in alignment with mandated trajectories for increased use of renewable energy and emissions reductions. 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 the development of geothermal resources worldwide is their positive attributes and limited environmental impacts. Sound practices protect and enhance natural thermal features that are valued by the community, minimise any adverse effects from disposal of geothermal fluids and gases, deal with possible induced seismicity and ground subsidence, optimize water and land use, and improve long-term sustainability of geothermal production for generations to come. 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

[TSU: references missing.]

Geothermal systems are natural phenomena, and typically discharge gases mixed with steam from surface features such as fumaroles, and minerals mixed with water from hot springs. Apart from CO_2, geothermal fluids can, depending on the site, contain a variety of other gases, such as hydrogen sulphide, nitrogen, and smaller proportions of ammonia, mercury, radon and boron. Sometimes very small amounts of methane are present, but in geothermal applications its effect is negligible relative to CO_2. The amounts depend on the geological and hydrological conditions of different geothermal fields.

Measured direct CO_2 emission from the operation of conventional power plants in **high-temperature** hydrothermal fields 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, hydrogen sulphide is usually not sufficiently concentrated to be harmful after venting to the atmosphere and dispersal. Despite this, removal of hydrogen sulphide released from geothermal power plants is a requirement in the US, Italy and Mexico. Elsewhere, H_2S monitoring is often used to provide assurance that concentrations after venting and atmospheric dispersal are not harmful.

Direct CO_2 emission from **low-temperature** (<100°C) geothermal fluid is negligible or in the order of 0-1 g/kWh$_e$ depending on the carbonate content of the water. When extracted geothermal fluid is passed through a heat exchanger and then completely re-injected (such as in a closed-loop pumped EGS system, among others), CO_2 emissions are nil to negligible. Geothermal heat pumps also reduce the direct CO_2 emission by at least 50% compared to other heating or cooling systems. Other gas emissions from low-temperature geothermal resources are normally much less than the emissions from the high-temperature fields conventionally used for electricity production.

Enhanced Geothermal Systems in the future are likely to be designed as closed-loop circulation systems, with zero direct emissions.

Direct emissions of CO_2 from geothermal **direct uses (heating)** are also negligible. In Reykjavik (Iceland), the CO_2 content of thermal groundwater used for district heating (0.05 mg/kWh) 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 re-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 re-injected into the reservoir and thus never release CO_2 into the environment. A similar closed loop arrangement with zero emissions generally applies to pumped EGS or hybrid projects.

Most of the chemicals in geothermal fluids are concentrated in the water phase. Boron and arsenic are the components most likely to be harmful to ecosystems if released in relatively large quantities to natural waterways. Therefore, the water is routinely re-injected into wells and thus not released into the environment. However, after separation and condensation, surplus steam condensate may be suitable for stock drinking water or irrigation purposes instead of injection. The most likely contaminates to be aware of will be boron, dissolved hydrogen sulphide, sulphuric acid, and added biocides (to treat the cooling tower) or sodium hydroxide (to raise the pH). In some situations (e.g. 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 merits.

4.5.2 Life-cycle assessment

As it is known, life-cycle assessment (LCA) analyses the whole life cycle of a product "from cradle to grave". For geothermal power plants all environmental impacts directly and indirectly related to the construction, operation and deconstruction of the plant need to be considered in LCA, especially referring to intermediate and low temperature geothermal plants due to the large effort to lock up the reservoir relative to the usable energy.

Even though published results vary depending on assumptions made, for most existing geothermal plants the global warming potential is small. 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. (2009) 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 63 g/kWh. They also presented other LCA indicators, which are compared to those of the reference mix in Table 4.5, where it can be observed that the geothermal CO_2-equivalent is between 4 and 1% from the reference mix, such as for the finite energy resources. At a site with above-average geological conditions, CO_2-equivalent and the demand of finite energy resources can reach below 1% of the environmental impacts of the reference mix.

Table 4.5. Environmental impact indicators for a reference electricity mix and for typical geothermal binary power plants (Prepared with data from Frick et al., 2009).

LCA indicator	Reference electricity mix	Binary geothermal plants (1.75 MWe)
Finite energy resources	8.9 MJ/kWh	0.35-0.96 MJ/kWh
CO_2-equivalent	566 g/kWh	23-66 g/kWh
SO_2-equivalent	1.083 g/kWh	0.183-0.517 g/kWh
PO_4-equivalent	60 mg/kWh	24-70 mg/kWh

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. [TSU: SO2: sulphur dioxide, PO4: phosphate.]

For typical geothermal binary power plants, the power related SO_2-equivalent is between 17 to 54% and the power related PO_4-equivalent between 40 to 117% regarding the environmental impacts of the electricity mix. The lower values thereby refer to the plants providing power and heat. At a site with above-average geological conditions, SO_2- and PO_4-equivalent are at least reduced to below 22% of the electricity mix impacts. In general terms, geothermal power plants can be rated as environmentally benign based on that comparison.

Regarding geothermal direct uses, Kaltschmitt (2000) published figures of 4-16 tonnes CO_2-equivalent /TJ for low-temperature district heating systems, and data for heat pumps of 50-56 tonnes CO_2-equivalent/TJ based on life cycle assessments.

The life cycle of geothermal intermediate to low temperature developments is characterised by large initial material and energy inputs due to the construction of the wells, power plant, and pipelines, which need to be optimised to maximize net-energy output and minimize emissions. For hybrid electricity/district heating applications, the more heat can be used directly the better the environmental benefits.

The main conclusion of those LCA is that the use of geothermal energy for the provision of electricity and heat using intermediate and low temperature geothermal resources is environmentally advantageous. The net energy supplied more than offsets the environmental impacts of human, energy and material inputs.

4.5.3 Potential hazards of induced micro-seismicity and others

Local hazards arising from natural phenomena, such as micro-earthquakes, hydrothermal steam eruptions or ground subsidence may be influenced by the operation of a geothermal field, to the extent that 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. [TSU: length of sentence] A geological risk assessment is needed to help avoid or mitigate these hazards.

With respect to induced seismicity, detectable events by humans from felt ground vibrations or noise have been an environmental and social issue associated with some EGS demonstration projects, particularly in heavily populated areas (e.g. Soultz in France, Basel in Switzerland and Landau in Germany). The EU-project GEISER (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs) recently started in order to better understand and mitigate induced seismicity hazards in the development of geothermal reservoirs (GEISER, 2010). 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).

Best practice, risk-management protocols for induced seismicity implemented by regulators in South Australia are described in Malavazos and Morelli (2008).

Over its 100 year history, no commercially operating plant has been stopped due to induced seismicity. 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 recirculation, 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.

There have been some hydrothermal steam eruptions triggered 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 preventing subsidence in the Imperial Valley (US) where maintaining levels to allow for irrigation drainage is important.

4.5.4 Benefits and impacts

Conventional high temperature geothermal power projects effectively contribute to mitigate GHG emissions. 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 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. 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) (Chevron, 2007). [TSU: relevance in this context?]

One 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). Other good examples are at Galanta in Slovakia (Galantaterm, 2007), Pannonian Basin in Hungary (Lund et al., 2005; Arpasi, 2005), and Paris Basin in France (Laplaige et al., 2005).

In many cases, local deployment opportunities are created from geothermal development, which can be particularly 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. These same regions may be populated by indigenous people with a relatively poor standard of living and limited land ownership rights. Because drilling and plant construction must be done at the site of a geothermal resource, local workforce development can lead to a permanent employment for many. Leading geothermal companies and government agencies have approached this social issue by improving local security, building roads, schools, medical facilities and other community assets, which are in some cases funded by contributions from profits obtained from operating the power plant. In some dry climate settings (e.g. Kenya) free water is provided, in others (e.g. Philippines) free electricity for local residents. Loan funds may be established to help small local businesses.

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. This creates a conflict for obtaining permits to undertake drilling and development activities, and even for access to subsurface resources by directional drilling from outside such parks. 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.

Another measure of optimum land use that is relevant in some settings is the ‘footprint’ occupied by geothermal installations. Taking into account surface installations (drilling pads, roads, pipelines, fluid separators and power-stations), the typical footprint for conventional geothermal is about 900 m^2/GWh/year (for 30 years), or 160 m^2/GWh/year excluding wells (Table 4.6). According to Kagel et al. (2005) and Tester et al. (2006), low-temperature geothermal plants are related to a land use between 1400 to 2300 m^2/MWe or a cumulative basis between 150 and 300 m^2/GWh per year (Table 4.6). The subsurface resource that is accessed by directional or vertical geothermal boreholes typically occupies an area equivalent to about 10 MWe/km^2 (Sanyal, 2005). 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 and forestry at Mokai and Rotokawa in New Zealand, and a game reserve at Olkaria, Kenya).

Table 4.6. Comparison of 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 (2), pipes, etc.)	7460	900
49-MWe geothermal FC-RC plant (1) (excluding wells)	2290	290
20-MWe geothermal binary plant (excluding wells)	1415	170

Reference? Notes (1) and (2)? [by AUTHORS] FC: Flash cycle, RC: Rankine cycle.

4.6 Prospects for technology improvement, innovation, and integration

4.6.1 Technological and process challenges

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.

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. Most of these methods will also 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. Improvement and innovation in technologies and methods for the characterisation of deep geothermal reservoirs in ways that enable reliably predictive extrapolations from known to unexplored geothermal resources at specific sites.
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 4.3).
3. Improvement of methods to hydraulically stimulate reservoir connectivity between injection and production wells to emulate 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. 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.
6. 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 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.

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 elevation (and pixel size) appropriate to the features being imaged. Ground-based verification, soil sampling and heat flow measurements should follow. Recent advances in remote sensing and airborne electromagnetic methods have yet to be tested in the geothermal environment.

Research centres are now working towards an integrated approach for the comprehensive characterisation of EGS sites in a variety of geological settings. R&D will need to focus on achieving a better understanding of how cracks form and propagate in different stress regimes and rock types. New tools need to be developed that allow specific zones in a hot borehole to be isolated for both fracture creation and short-circuit repair. This will allow multiple fracture zones to be created from a single borehole, enhance the water circulation rate, and reduce the specific cost of development.

4.6.3 Accessing and engineering the reservoirs

[TSU: references missing.]

4.6.3.1 Drilling technologies

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 plastic 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. Damages can be reduced by using low mud pressures by means of near-balanced drilling (NBD). NBD and borehole stability under changing stress conditions must be well understood and need to be investigated by fracture mechanical experiments and simulations. Further research is required to understand salinity contrast effects, particle induced damage and filtrate induced damage.

The objective of a new-generation of geothermal drilling should be to reduce the cost of geothermal drilling through an integrated effort. Ultimately a larger portion the geothermal resource would be economically accessible, if drilling costs could be substantially reduced by introducing revolutionary methods that use different methods of drilling and completing wells, thermal, particle-assisted abrasive, and chemically-assisted techniques.

Production wells in high-grade fields are commonly 1.5-2.5 km deep with production temperatures of 250-340°C. Yet it is well known from research that much higher temperatures are found in the roots of high-temperature systems. 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., 2007). 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.

4.6.3.2 Reservoir engineering

All tasks related to the engineering of the reservoir require a sophisticated modelling of the reservoir processes and interactions being 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 constitute a major improvement of the EGS concept. New visualisation and measurement methodologies (imaging of borehole, permeability tomography, tracer technology, coiled tubing technology) should become available for the characterisation of the reservoir.

The relation between parameter uncertainty and the predictability of the geothermal reservoir evolution will be investigated with thermo-hydro-mechanical-chemical (THMC) effects included. The availability of fully coupled and efficient THMC codes provides a new basis for developing more reliable models with parameter identification at the reservoir scale based on inverse modelling techniques.

4.6.4 Efficient production of geothermal power, heat and/or cooling

[TSU: references missing.]

Technical equipment needed to provide heat 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 have to be improved, and thermal heat sources must be utilised more efficiently, both at the heat exchanger to a second cycle, 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.

New inexpensive designs of small geothermal power plants using low-temperature reservoirs and able to generate distributed electricity, are likely to appear soon in the market. Those plants should be small, mass manufactured, easy to move from place to place, and easy to operate.

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, and in some cases, gold).

4.7 Cost trends

As other RE technologies, geothermal projects have 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, quality of the geothermal fluids, and so on, but are predictable in comparison with power plants of traditional energy sources which are usually subject to market fluctuations on fuel price. This section describes the capital costs of geothermal-electric projects, the levelized cost of geothermal electricity and the historic and probable future trends, and also presents some costs for direct uses of geothermal energy.

4.7.1 Costs of geothermal-electric projects and factors that affect it

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. Field expansion projects may cost 10-15% lesser than a new (greenfield) project, since investments have already been made in infrastructure and exploration and valuable resource information is available (Stefansson, 2002; Hance, 2005).

The first component (a) includes lease/acquisition, permitting, prospecting and drilling of exploration and test wells. Drilling of this type of wells has a success rate typically about 50-60% (Hance, 2005). 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.

Drilling of production and injection wells (component b) has a success rate of 70 to 90% (Hance, 2005). 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 (Tester et al., 2006).

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).

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). Table 4.7 presents the breakdown of current capital costs (capex) for typical geothermal-electric projects in 2005 US$.

Table 4.7. Breakdown of current capital costs for typical turnkey (installed) geothermal-electric projects (2005 US$)

Type*	Concept	Component				Total
		(a) Exploration & confirmation	(b) Drilling (wells to 1.5-3 km depth)	(c) Surface facilities & infrastructure	(d) Power plant	
1	US$/kWe	475	1275	350	1225	3325
	% capex	14	38	11	37	100
2	US$/kWe	30	1275	350	1225	2880
	% capex	1	44	12	43	100
3	US$/kWe	25	1008	300	1175	2508
	% capex	1	40	12	47	100
4	US$/kWe	24	800	274	1782	2880
	% capex	1	28	10	61	100
5	US$/kWe	205-560	750-1500	205-750	1215-2240	2025-3750
	% capex	10-15	20-40	10-20	40-60	100
6	US$/kWe	275-425	750-1700	425-850	1500-2600	3400-4300
	% capex	8-12	20-40	10-20	40-60	100
7	US$/kWe	530	3350	1350	4720	9950
	% capex	5	34	14	47	100

*Type:

1) Greenfield project, 40-MWe single flash power plant, 200°C, wells to 2 km depth (data from Hance, 2005).

2) Expansion project, 40-MWe single flash power plant, 200°C, wells to 2 km depth. (data from Hance, 2005).

3) Expansion project, 4 x 25 MWe single flash power plant (100 MWe), wells to 2.2 km depth (From actual project installed in 2003).

4) Expansion project, 25-MWe single flash power plant, wells at 1.8 km depth in average (data from actual project currently in construction).

5) Greenfield project, 10-50 MWe condensing power plants (with data from Williamson et al. [TSU: “et al.” added], 2001; Hance, 2005; Petty, 2005; Kagel, 2006; and Chevron, 2009).

6) Greenfield project, 10-20 MWe binary cycle power plants (estimations with data from Hance, 2005; Petty, 2005; Kagel, 2006; and Chevron, 2009).

7) Greenfield project, ~4MWe, binary cycle power plant, low temperature, wells to 2750 m depth (estimations with data from GEOFAR, 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. For example using a single 50-MWe plant instead of multiple 10-MWe plants can decrease power plant costs per kilowatt by roughly 30-35% for binary systems. The installed cost per kilowatt for a 100-MWe flash steam plant can be 15-20% less than that of a 50-MWe plant (Dickson and Fanelli, 2003; Entingh and Mines, 2006).

4.7.2 Levelized cost of geothermal electricity

The levelized cost of geothermal power corresponds to the sum of two major components: levelized cost of capital investment and operation and maintenance costs. The levelized cost of capital investment (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 20-30 years). Operating and maintenance (O&M) costs consist of fixed and variable costs directly related to the electricity production phase. Operation and Maintenance costs include field operation (labour), well work-over, equipment, well operation, and facility maintenance, etc., and are currently ranged between 170 and 210 US$/kWh per year (equivalent to 152 and 187 US$/kWh per year at 2005 US dollar, respectively, according to the Current Consumer Price Index released by the US Bureau Labour Statistics) [TSU: consistent use of tools provided on TSU website to adjust for inflation/deflation?].

For geothermal plants, an additional factor must be added to these O&M costs, which is the cost of reposition or make-up wells, i.e. new wells to replace some of the older whose lifetime is over. Companies usually consider make-up drilling as a capital expense, but must be regarded as 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 typically higher.

In most cases, the LCCI represents a major part (about 65%) of the levelized cost of energy (LCOE) of geothermal projects.

Current LCOE (i.e., including LCCI and O&M costs) in 2005 US$/kWh for some of the typical geothermal-electric plants described in Table 4.7 were calculated according to the methodology described in Chapter 1, using the version 6 of the calculator developed by Verbruggen and Nyboer (2009), and are presented in Figure 4.9. In all cases the project lifetime was calculated to be 30 years and the capacity factor (plant performance) was 77%. For greenfield projects it was estimated that the plant starts to operate between the beginning of the fourth and the sixth year since exploration starts, and for expansion projects the plant is commissioned by the third year.

There are important variations depending on the discount rate used, yet in general terms the LCOE for conventional 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, as clearly indicated by case 3, which is an actual project currently operating in Mexico. The LCOE for case 5, calculated with data from a low-temperature European project presented by GEOFAR (2009), is the highest and may be an appropriate estimate for the theoretical LCOE for EGS projects.

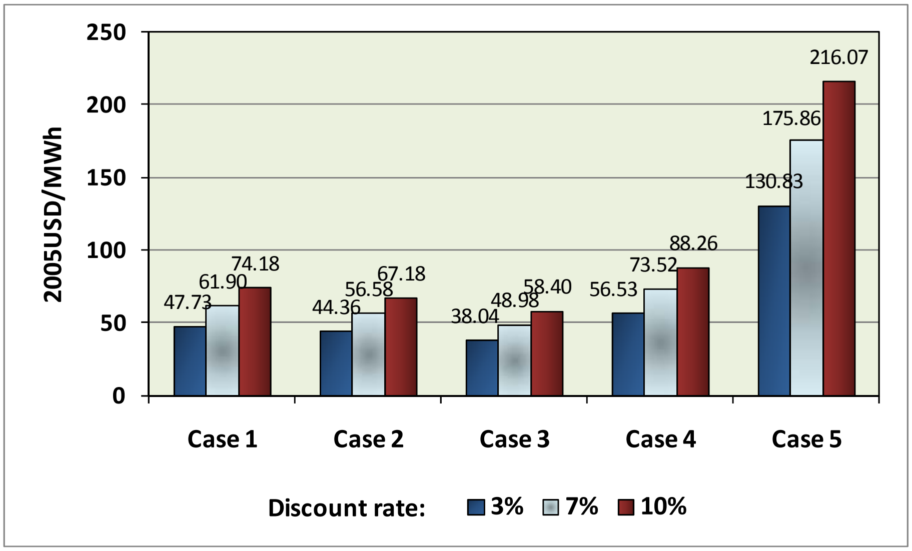

Figure 4.9. LCOE (LCCI plus O&M costs) in 2005 US$ per MWh for typical geothermal-electric plants using three different discount rates (3%, 7% and 10%).

Cases 1, 2 & 3 are the same for Table 4.7.

Case 4: Greenfield project, 20-MW binary cycle plant, wells at 1500 m depth. [TSU: Equivalent to case 6 in table 4.7?]

Case 5: Greenfield project, 4-MW binary cycle plant, well at 2750 m depth. [TSU: Equivalent to case 6 in table 4.7?]

[TSU: detailed data sources missing.]

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 2005-2008 project costs sharply increased due to increases in the cost of commodities such as steel and cement, drilling rig rates and engineering (Fig. 4.10). 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.

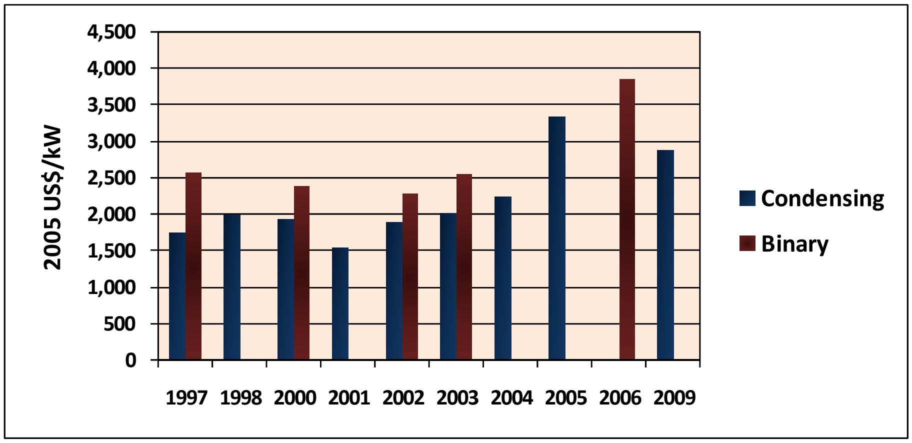

Figure 4.10. Variation in capex cost for condensing and binary geothermal-electric plants (To be completed with more data? [by AUTHORS]). [TSU: detailed data sources missing.]

Regarding the geothermal-electric plants performance, since 1995 the average capacity factor has been continuously increasing, and the average geothermal capacity factor based on 2008 global generation versus installed capacity is around 75%. However, in the past, this value incorporated a wide range of generation issues, including: grid connection failures (e.g. from storm damage), load following on smaller grids, turbine failures (some operating geothermal turbines have exceeded their economic lifetime, so require longer periods of shut-down for maintenance or replacement), and lack of make-up drilling to sustain long-term steam supply (usually due to financial constraints). For new developments, assuming no such grid or load constraints, long-term capacity factors above 95% can be expected (Fridleifsson et al., 2008; Fig. 4.11).

4.7.4 Future costs trends

The future costs for geothermal electricity are hard to predict. This is because future deployment will probably include an increasing percentage of unconventional development types (such as EGS, super-critical temperature and off-shore resources), which are still not commercially proven and presently only limited cost data about them are available. However, considering that the drilling cost represents between 20 and 40% of total capital costs (Table 4.7) and the projected plant performance shown in Fig. 4.11 by 2020, 2030 and 2050, future LCOE for the cases before mentioned were calculated using the same calculator developed by Verbruggen and Nyboer (2009), and are shown in Figure 4.12 considering only a discount rate of 7%, which is the rate decided to be used for all RE future costs trends in this report. [TSU: sentence structure and length]

Some assumptions remained the same: project lifetime is 30 years and the commissioning year for greenfield projects is between fourth and sixth year since exploration starts and for expansion projects is the third year. Figures for 2009 are those already presented in Figure 4.10. For 2020 it was assumed that the drilling cost does not vary since not many differences are expected in the oil industry, yet for 2030 this cost was estimated to be 7% lower and for 2050 15% lower than present costs, in all cases at 2005 US$. These decreasing costs are expected to occur due to better technological practices in the drilling industry and due to a probably higher availability of drilling rigs on that dates. Worldwide average capacity factors for 2020, 2030 and 2050 were assumed to be 81%, 85% and 90%, respectively, according to Figure 4.11. All the remaining aspects and costs were considered not variable, even though improvements in exploration, superficial [TSU: surface?] installations, materials and power plants are likely, which would lead to reduced costs.

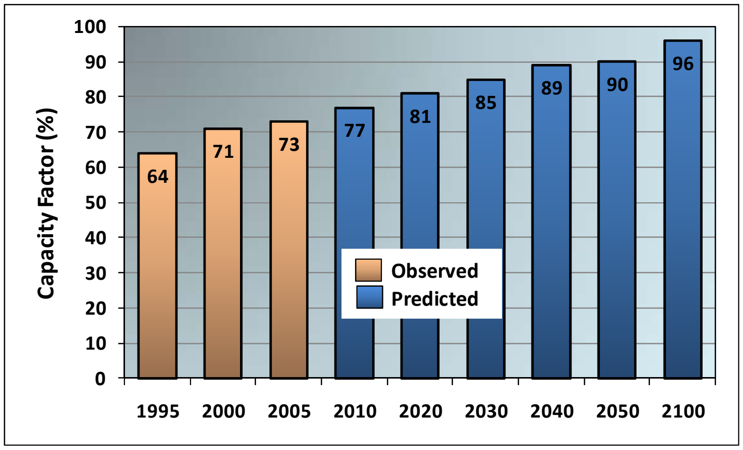

Figure 4.11. Historic and projected average worldwide capacity factor of geothermal plants (with data from Fridleifsson et al., 2008, and Bertani, 2009).

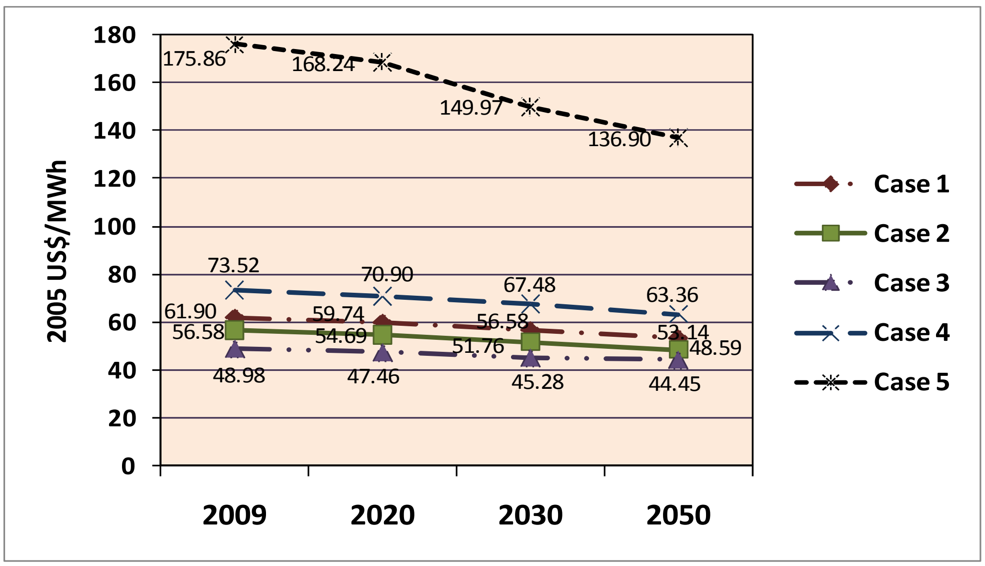

Figure 4.12. Present and projected LCOE in 2005 US$ for typical geothermal-electric plants at discount rate of 7%.

Cases 1, 2 & 3 are the same for Table 4.7.

Case 4: Greenfield project, 20-MW binary cycle plant, wells at 1500 m depth. [TSU: Equivalent to case 6 in table 4.7?]

Case 5: Greenfield project, 4-MW binary cycle plant, well at 2750 m depth. [TSU: Equivalent to case 6 in table 4.7?]

[TSU: Please add detailed data sources.]

4.7.5 Economics of direct uses and geothermal heat pumps

Direct-use projects 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 below 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 Bertani, 2009).

Individual space heating for buildings, depending upon the well depth and temperature of the resource would vary from US$ 9,370 to 23,450 for a 200 m^2 building. With a load factor of 0.30, the capital cost would be 1,595 to 3,940 US$/kWt (Fig. 4.13).

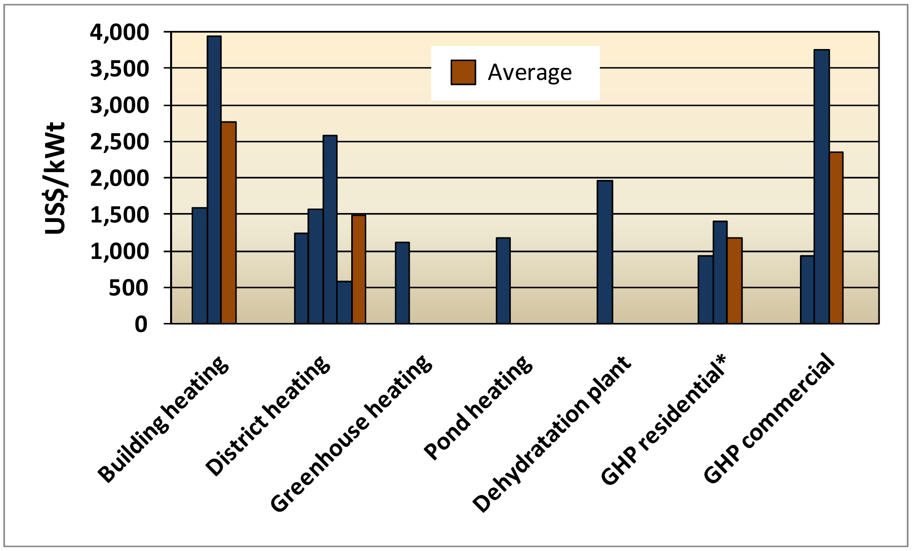

Figure 4.13. Current capital costs in 2005 US dollars per thermal kilowatt for several direct geothermal applications. [TSU: Please add source.]

*Costs for residential Geothermal Heat Pumps do not include the drilling cost.

[TSU: Use of level 4 subheadings for different direct use applications?]

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. The heat is distributed through a network of insulated pipes consisting of delivery and return mains. 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. 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 50% of the load 80 to 90% of the time, thus improving the efficiency and economics of the system (Bloomquist et al., 1987).

A large district heating project in Germany (Reif, 2008), with a well drilled to 3,200 m to provide a capacity of 35 MWt and 66 GWh of heat to customers, costs 1,566 US$/kWt. This cost can be broken down into: 23% drilling, 2% pumps and accessories, 5% geothermal station and equipment, 2% peak-load heating plant (fossil fuel), 42% distribution network, 14% service connection, 12% heat-transfer stations, and 1% land [TSU: ordering by size]. A smaller example in Elko, Nevada, US, built in 1989 with a capacity of 3.8 MWt providing 6.5 GWh/year of heat to customers, costs 1,238 US$/kWt. The breakdown of costs was: 15% resource assessment, 15% drilling of production well (disposal is to a local river), 29% distribution system, 26% retrofitting customer heating systems, and 15% contract services and materials [TSU: ordering by size]. The geothermal station Mszczonow (1.2 MWt), Poland, for space heating, costs the equivalent of 2,578 US$/kWt (Balcer, 2000). Between 30 and 35% of natural gas consumption was saved when the geothermal installation was set in operation, and three conventional gas and coal boilers were stopped. The Klaipeda geothermal heating station (35 MWt), Lithuania, started to operate in 2005, with heat production of 598 x 10^9 J/yr [TSU: GJ] to produce warm water (70-80°C) for district heating. Total capital costs were equivalent to 571 US$/kWt (Radeckas and Lukosevicius, 2000). Based on these examples, total district heating installed costs average 1,488 US$/kWt (Fig. 4.13).

Greenhouses of 2.0 ha size (minimum for a commercial operation) would cost around US$ 281,000, which includes two production wells, one injection well, piping and heat exchanger in addition to the cost of the greenhouse itself of around US$ 2.81 million. With a load factor of 0.50 the annual heating load would be 88 x10^9 J [TSU: GJ]. Annual pumping cost and other O&M would be around 0.02 US$/kWh. The annual savings compared to conventional fuel would be approximately US$ 0.94 million.

Aquaculture ponds and tanks have similar costs, yet vary depending upon if the facilities are under cover, such as in a greenhouse, or outdoors. Typical pond constructs will cost 0.47 US$/$m^2$, thus a commercial operation of 10 to 15 ponds covering 2.0 ha would then cost approximately US$ 9,400. The capital costs of three production wells, two injection wells, piping and heat exchanger would be around US$ 375,000. With a load factor of 0.60, the annual heating requirement would be 263 x 109 J [TSU: 28.667 kJ]. Pumping costs and other O&M for the geothermal system would be around 0.03 US$/kWh. The annual savings in heating cost compared to conventional fuels would be approximately US$ 2.81 million less O&M, resulting in a simple payback of around a year. Covered ponds and tanks would have higher capital cost, but lower heating requirements.

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 [TSU: TJ] to drying 4,500 kg/hour of wet onions over a 250 day period. This plant cost US$ 12.5 million with the geothermal system, including wells adding US$ 3.37 million. The annual operation cost is US$ 5.63 million and annual energy savings of US$ 1.5 million. With annual sales of US% 5.63 million, a positive cash flow is realised in about two years (Lund, 1995).

Geothermal (ground-source) heat pump project costs can 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, have a large influence on the installed cost.

Closed loop systems would cost around 1,400 US$/kWt, whereas open loop systems would be around 938 US$/kWt (without the cost of the well). The highest cost for a vertical closed loop system is drilling the holes of 150 to 300 m deep, running 28 to 47 US$/m. Actual heat pumps unit will be around US$ 2,800.

Commercial and institutional buildings installations are more efficient and thus cost less. Installations of several hundred bore holes for vertical loops are not uncommon and can easily be placed under parking lots, or even under the building itself in piles or caissons as is done in Switzerland. The installed cost can vary over a wide range. Experience in the US for the total cost of the mechanical, electrical and geothermal system is as high as 3,751 US$/kWt, but can be as low as 938 US$/kWt. Operation cost, which is mainly due to the electricity input to the compressor, is around 0.02 to 0.03 US$/kWh. Energy use is around 60 kWh/m^2/year.

4.8 Potential deployment

Overall, the geothermal-electric market appears to be accelerating, as indicated by the trends in both the number of new countries developing geothermal energy and the total of new megawatts of power capacity under development. It is, however, difficult to predict future rates of deployment, because of the numerous variables involved. Using present technology to develop additional hydrothermal resources and given favourable economic drivers, an increase from the current value of 10.7 GWe of installed capacity, up to 70 or 80 GWe could be achievable by 2050. 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 (Fig. 4.1). Some of the new technologies (for example, binary conversion plants, multilateral completions, etc.) have already been proven and are now rapidly deploying, whereas others 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).

Low-temperature power generation with binary plants has opened up the possibilities of producing electricity in countries which do not have high-temperature resources or may have requirements for total re-injection. EGS technologies (deep drilling in lower grade regions, reservoir stimulation and pumping) are being developed to access resources in this setting. Supercritical and off-shore resources are also under investigation. If these technologies can be proven economical at commercial scales, the geothermal market potential could be limited only by demand and not by resource access.

Direct use of geothermal energy for heating is currently commercially competitive, using accessible, high grade hydrothermal resources. A moderate increase is expected in the future development of such hydrothermal resources for direct use, mainly because of dependence on resource proximity and therefore on local economic factors, along with the multiple uses of geothermal resources in combined heat and power plants. In contrast, an exponential increase is expected with the deployment of geothermal heat pumps (GHP) and direct use in lower grade regions, which can be used for heating and/or cooling in most parts of the world. 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.

4.8.1 Regional deployment

[TSU: references missing.]

4.8.1.1 Conventional hydrothermal resources

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 4.1). In such countries, there are significant opportunities for future expansion, particularly if access and technical barriers can be overcome. 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). These require pumped extraction, and are mostly suitable for direct heating, but could also be utilised to generate electricity using binary plant technology. 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. In North America (US and Mexico) the existing installed capacity of almost 4 GWe, mostly from mature developments, is expected to double in the short term (5-7 years). By 2050, a significant proportion of the estimated unidentified resource base in the western US (30 GWe) and Alaska and co-production of energy from hot water discharged by oil wells (5 GWe) is also considered technically feasible now. 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, Japan and Hawaii, 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 to approximately twice the existing capacity over the next 40 years. 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 to replace fossil fuelled heating or power-plants, 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. Indonesia is one of the world's richest countries in geothermal resources and could, by 2050, replace a considerable part of its fossil fuelled electricity production by increasing its geothermal energy capacity by up to 20 times to 20 GWe.

Potential geothermal deployment for electricity (including EGS) and for direct use (including direct heating and cooling and GHP) by regions, are presented in Table 4.8.

Table 4.8. Expected deployment of geothermal energy by region.

REGION	Current (2009)		2020		2030		2050	
	Direct* (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)
1. OECD North America	8.443	4.052	50.0	9.5	120.0	15.0	230.0	42.0
2. Latin America	0.545	0.509	2.0	1.5	5.0	3.0	10.0	7.0
3. OECD Europe	10.959	1.551	62.0	3.0	150.0	5.5	300.0	28.0
4. Africa	1.520	0.174	4.0	0.5	11.0	1.5	18.0	9.5
5. Transition Economies	1.064	0.082	3.0	0.5	5.0	1.0	10.0	5.0
6. Middle East	0.422	0	1.0	0.0	4.0	0.5	7.0	3.5
7. Developing Asia	0.478	3.166	5.0	6.5	10.0	14.0	20.0	31.0
8. India	0.203	0	2.0	0.0	5.0	1.0	10.0	3.0
9. China	3.687	0.024	20.0	1.0	50.0	4.0	125.0	17.0
10. OECD Pacific	1.257	1.184	6.0	2.5	15.0	4.5	85.0	14.0
TOTAL	**28.578**	**10.743**	**155.0**	**25.0**	**375.0**	**50.0**	**815.0**	**160.0**
EJ Equivalent	0.279	0.256	1.589	0.639	3.843	1.34	8.353	4.541

* Data for 2005, which will be updated later. Direct includes direct heating and cooling and Geothermal Heat Pumps. Electric includes Enhanced Geothermal Systems. [TSU: Please add source.]

4.8.1.2 Enhanced Geothermal Systems

Resource grades for EGS vary substantially on a regional basis as well. This will have direct impact on the rate of deployment even after demonstrating EGS technology at commercial scale in the field. In addition, the availability of financing, water, transmission and distribution infrastructure and other factors will play major roles in regional deployment rates. 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, electricity and heating and cooling demand.

Half of the total geothermal electric deployment by 2050 is expected to be contributed by EGS. This ~80 GWe projection depends not only on improvements gained by experience of using existing drilling, reservoir stimulation, and energy conversion technologies used both in hydrothermal and EGS projects, but also on the presence of suitable energy markets, favourable policies, and available attractive financing in all cases. At some level of deployment, given its modular and scalable characteristic, the rate of adoption of EGS is anticipated to accelerate and propagate globally.

4.8.1.3 Direct uses and geothermal heat pumps

The potential deployment in the geothermal direct use market is very large, as space heating 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. The high potential deployment is due in large part to the ability of geothermal ground-source heat pumps to utilise groundwater or ground-coupled heat exchangers anywhere in the world. This use has huge potential for saving energy in buildings which represent over 30% of our primary demand.

Estimation for future development of the worldwide geothermal utilisation market was presented in Table 4.8 on a regional basis, for 2020, 2030 and 2050. Projections were estimated considering a different annual growth for GHP installations and for other direct uses, as shown in Table 4.9.

Table 4.9. Estimation of future deployment of geothermal direct uses, distinguishing Geothermal Heat Pumps (GHP) up to 2100 (Modified from Fridleifsson et al., 2008)

Year	Average annual growth rate from 2005		Installed capacity (GWt)		
	Other direct uses (%)	GHP (%)	Direct Uses	GHP	Total
2005	--	--	12.87	15.72	28.59
2010	~7.0	~20.0	18.00	37.00	55.00
2020	~6.0	~15.0	31.00	124.00	155.00
2030	~5.0	~13.0	45.00	330.00	375.00
2040	~4.4	~11.0	60.00	595.00	655.00
2050	~4.0	~9.0	75.00	740.00	815.00
2100	~2.5	~5.0	150.00	1,600.00	1,750.00

As shown in Table 4.9, estimations show that while only a moderate increase is expected in direct use applications, an exponential increase is foreseen in the heat pump sector. The combined GHP plus other uses deployment expected for 2020, 2030 and 2050 are the same than in Table 4.8, while the total for 2100 corresponds to the economic potential reported in Table 4.2 for geothermal direct uses.

4.8.2 Technological factors influencing deployment

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. The latter requires a better knowledge and measurement of the subsurface stress field. For EGS, additional remaining challenges are: drilling costs for deep wells, reservoir stimulation, management of induced seismicity, demonstration of sustainable production at commercial scale.

Geothermal power generation technologies also have different degrees of maturity. Reducing sub-surface exploration risks will contribute to more efficient and sustainable development. Drilling of high temperature reservoirs requires advanced technologies to prevent reservoir damage by drilling mud. An example is the use of balanced drilling procedures. Improved utilisation efficiency requires better auxiliary energy use and improved performance of surface installations. Better reservoir management, with improved simulation models, 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).

4.8.3 Long-term deployment in the context of carbon mitigation

The expected long-term deployment (2020, 2030 and 2050) based on the before mentioned assumptions, was presented in Table 4.8. The worldwide expected installed capacity by 2020 is 25 GWe for geothermal electric plants and 155 GWt for geothermal direct uses. These figures are equivalent to 0.639 EJ and 1.589 EJ, respectively, for a total primary energy supply (TPES) of 2.228 EJ. Corresponding figures for 2030 are 1.340 EJ and 3.843 EJ, for a geothermal TPES of 5.183 EJ, and for 2050 are 4.541 EJ and 8.353 EJ for a TPES of 12.894 EJ.

All those figures are independent of the rate of carbon mitigation that could be achieved by 2020, 2030 and 2050, since geothermal deployment is not technically affected by that effect – as mentioned earlier in this chapter. However, it is likely that the more restricted the CO_2 emissions will be in the future the higher geothermal deployment will be. A number of different scenarios have been modelled from the integrated assessment models presented in Chapter 10, taking into account the stabilization categories of CO_2 emissions regarded by the IPCC AR4 and grouping them into three: categories I+II (<440 ppm), III+IV (440-600 ppm) and V+VI (>600 ppm).

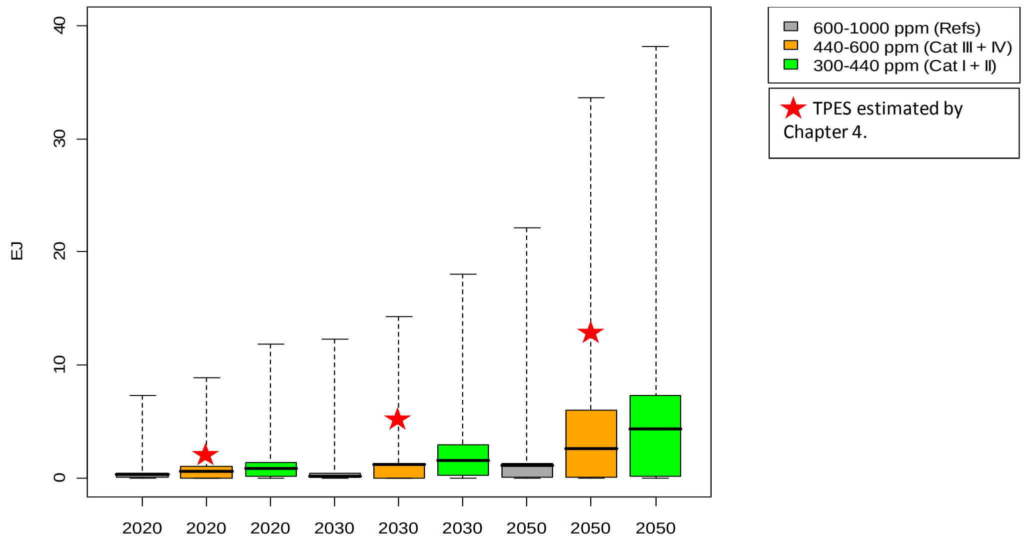

Figure 4.14. Total Primary Energy Supply (TPES) from geothermal resources in the context of carbon mitigation for 2020, 2030 and 2050. Thick black line is the median, the coloured box corresponds to interquantile range 25th-75th percentile, and whiskers correspond to the total range across all scenarios. [TSU: Please add reference to chapter 10.]

Geothermal deployment for each of those category groups are presented in Figure 4.14, where also are plotted the projected deployment estimated in this chapter. [TSU: language] It can be seen that estimations from chapter 4 are within the range of all considered scenarios, yet are higher than the median and are located in the 75%-100% quartile. For instance, by 2020 the median of the scenarios goes from 0.4 EJ for categories V+VI, to 0.61 EJ for categories III+IV and up to 0.81 EJ for categories I+II, while the projected deployment obtained in this Chapter 4 is 2.228 EJ, which is in the last 25% percentile (75-100%) in all cases. A similar condition occurs for 2030 and 2050 (Figure 4.14).

So, it seems to be clear [TSU: language] that the global and regional availability of geothermal resources is enough to meet the results of the modelled scenarios, and also the projected market penetration seems to be reasonable. As a matter of fact, the modelled scenarios would seem to be conservative [TSU: language] compared to the potential deployment estimated in this chapter.

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 5

Hydropower

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(Sub)Section:	All				
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Chapter 5 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 64 pages: a total of 4 pages below the maximum (13 over the mean, respectively). All chapters should aim for the mean number allocated, if any. Expert reviewers are therefore kindly asked to indicate where the Chapter could be shortened by up to 13 pages in terms of text and/or figures and tables to reach the mean length.

References of figures are often missing; references from the text that are found missing in the reference list have been highlighted in yellow. In the same manner, references found in the reference list but missing from the text have also been highlighted.

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 5 : Hydropower

CONTENTS

EXECUTIVE SUMMARY

Hydropower is a renewable energy source where power is derived from the energy of moving water 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 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 resource potential for hydropower could change due to a changing climate. 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 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. Nearly two billion people in rural areas of developing countries do not have electricity. Small 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 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, purpose and size (installed capacity). Size wise categories 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 new 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 what may 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 & upgrading (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 multi-purpose 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. For the time being, 1163 hydropower projects are in the CDM pipeline, represent 26% of CDM applications. However, very few projects have so far received credits.

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

5.1.1 History

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).

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 of hydropower plants involved large dams which submerged land to provide water storage. This has caused great concern for environmental impacts. Historically regional hydropower generation during 1965 to 2007 has been shown in figure 5.1.

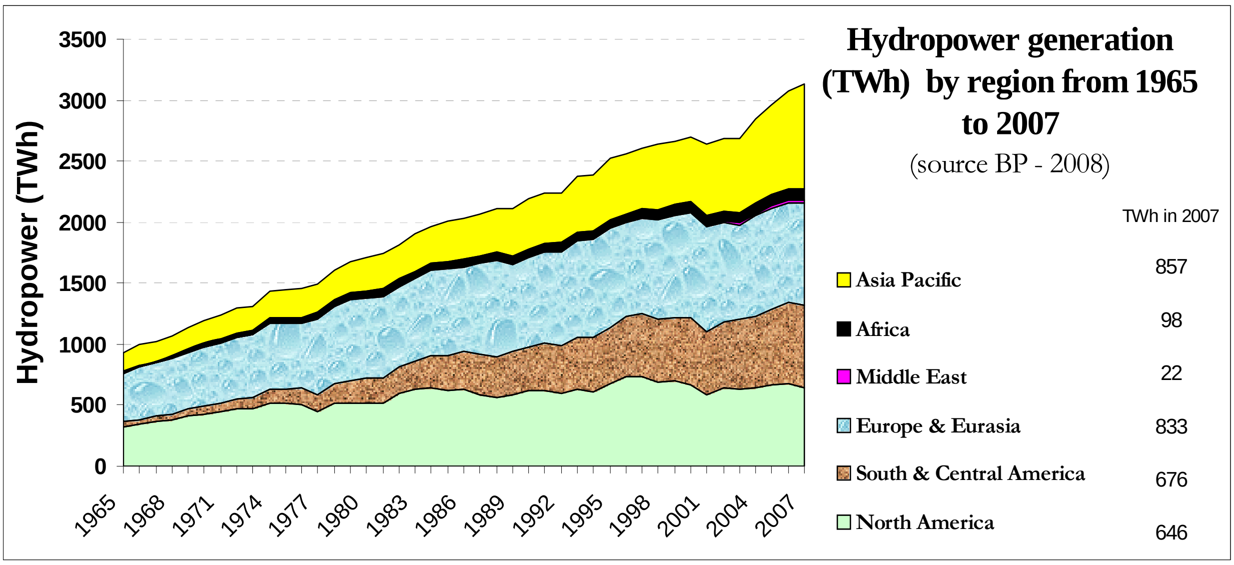


Figure 5.1: Hydropower generation (TWh) by region (BP, 2008).

5.1.2 Classification (size, head, storage capacity and purpose)

Hydropower was the first technology to generate electricity from a renewable source and is presently the only large-scale renewable where the largest plants produce between 80-100 TWh/year (Itaipu-Brazil and Three Gorges-China). Hydropower installations could be seen as a continuum. They are always site-specific and thus designed according to the river system they inhabit. Its great variety in size gives the additional ability to meet 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. Impacts on ecosystems will vary not according to installed effect or whether or not there is a reservoir but will be decided by the design, where various intakes, dams and waterways are situated and how much water flow is used for power generation. The idea of small (SHP) and 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. Based on this it is more fruitful to evaluate hydropower based on its sustainability performance and based on the type of electricity service (intermittent, base or peak load) supplied as opposed to a classification based on technical units with little or no relevance for nature or society.

According to the IEA (2000b), hydropower projects can be classified by a number of ways which are not mutually exclusive:

5.1.2.1 By size (large, medium, small, mini, micro, pico)

The classification according to 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. Based on installed capacity of hydropower projects, classification of hydropower varies from country to country. A general classification may be taken as:

- pico < 0,005 MW
- micro < 0,1 MW
- mini < 1 MW
- small > 1-100 MW
- medium > 100 MW
- large > 500 MW

Chamuera, Rätia, Switzerland (0,55 MW)

Macagua, Venezuela (15,910 MW)

Small hydropower plants have the same components as large ones. Small hydropower has been developed by many countries, especially the developing countries. Compared to large hydropower, it takes less time and efforts to integrate small hydro schemes into local environments. It has 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. Most small hydro power systems do not require the construction of a dam, but are rather run of river schemes.

Small hydro in isolated systems may be also connected to grid, if available at a later date. Such integration with a grid shall improve the total benefits of hydropower projects and quantum shall be as per site-specific conditions. Comparative advantage of the small hydro has already resulted in a large number of these installations all over the world. The success of the small hydro option depends on careful selection and timely completion of the best sites.

The redundancies in terms of stake are reduced. All small hydropower are designed to be failing safe. The local availability of construction materials often helps in implementing the small hydropower project.

5.1.2.2 By head (high or low)

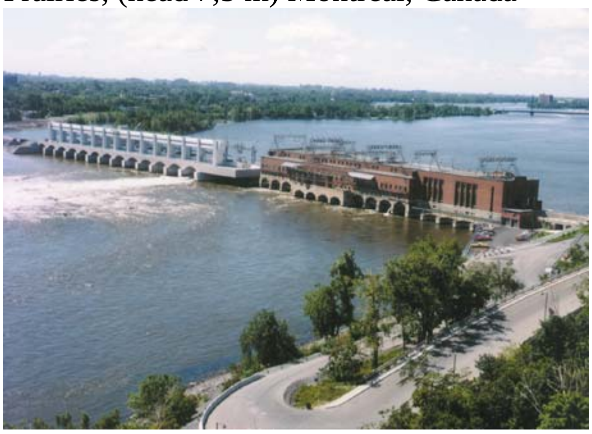
How high the water pressure on the turbines is will be basically determined by the gravity force of the falling water used. The difference between the upper water level and the lower is called head (vertical height of water above the turbine). Consequently, the type of head together with the discharge is a basic parameter for deciding the type of hydraulic turbine to be used. Higher heads involve major civil works whereas low heads involve higher electro-mechanical works. Generally, for high heads Pelton turbines are used, whereas Francis turbines are used to exploit medium heads. For low heads commonly Kaplan and bulb turbines are applied.

Head may be classified as follows:

- High Head 75 m above
- Medium Head 40-75 m
- Low head 3-40 m
- Ultra Low Head < 3 m

High head project Tyssedal Power Plant, Norway (UNESCO Heritage site),

Low head power plant (45MW) Rivières-des-Prairies, (head 7,5 m) Montreal, Canada



5.1.2.3 By purpose (single or multi-purpose)

As hydropower does not consume the water that drives the turbines, this renewable 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 Jacques 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.

Hoover Dam and Lake Mead (USA)

hosts some 12 million visitors each year. The waters of Lake Mead are used to supply 18 million people in cities, towns and Indian communities in the states of Arizona, Nevada and California. In addition, agricultural land totalling 4,000 km2 in USA and 2000 km2 in Mexico is supplied with irrigation water, and the power plant supplies 4 billion kWh/year.

Based on hydrological relation, hydropower plants can moreover be classified into stand-alone hydropower plants and cascade hydropower plants.

5.1.3 Maturity of technology

Hydropower is a proven and well advanced technology based on more than a century of experience. Hydropower schemes are robust, high-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. Hydro 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).

5.2 Resource potential

5.2.1 Worldwide Hydropower Potential

The International Journal of Hydropower & Dams 2005 and 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.

The total worldwide generation potential is 14,368 TWh (IJHD, 2005) with a corresponding estimated total capacity potential of 3,838 MW[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.

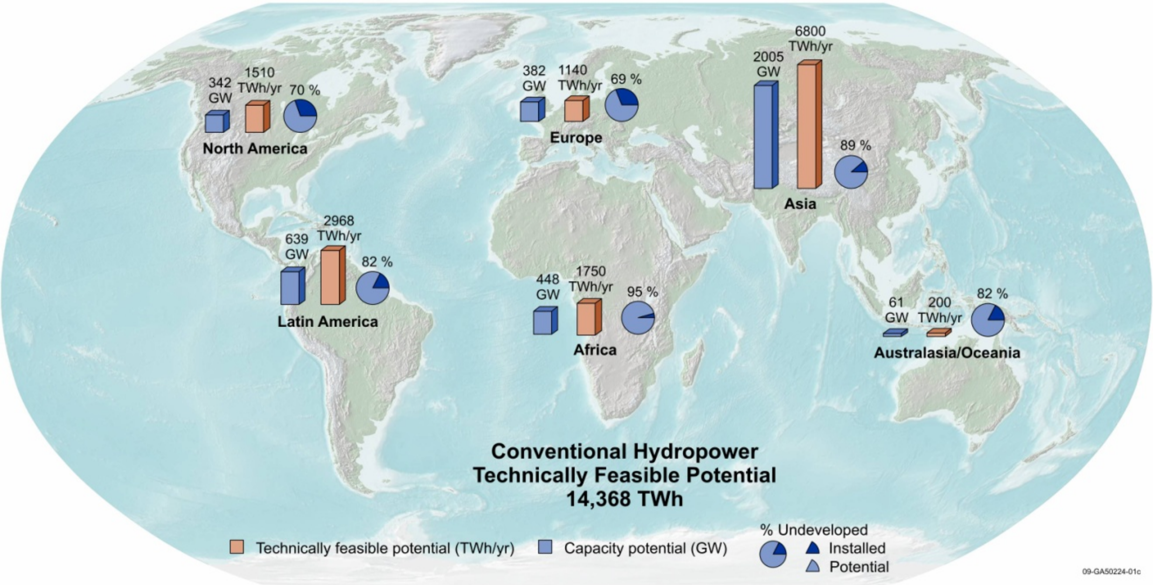


Figure 5.2: Regional hydropower potential in annual generation and capacity with comparison of installed and potential capacities including potential capacity as percent undeveloped (Source: (IJHD, 2005).

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”. Most notably Asia and also Latin America have outstandingly large potentials and along with Australasia/Oceania have very large potential hydropower growth factors (450 to almost 800%). 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 21 times the amount of hydropower currently installed.

An understanding and appreciation of hydropower potential is best obtained by considering current total regional installed capacity and annual generation (2003/2004) (IJHD, 2005) shown in Figure 5.3. The 2005 reported worldwide total installed hydropower capacity is 746 GW producing a total annual generation of 2,794 TWh (IJHD, 2005) Figure 5.3 also includes regional average capacity factors calculated using regional total installed capacity and annual generation [capacity factor = generation/(capacity x 8760hrs)].

[1] Derived value based on regional generation potentials (IJHD, 2005) and average capacity factors shown in Figure 5.3.

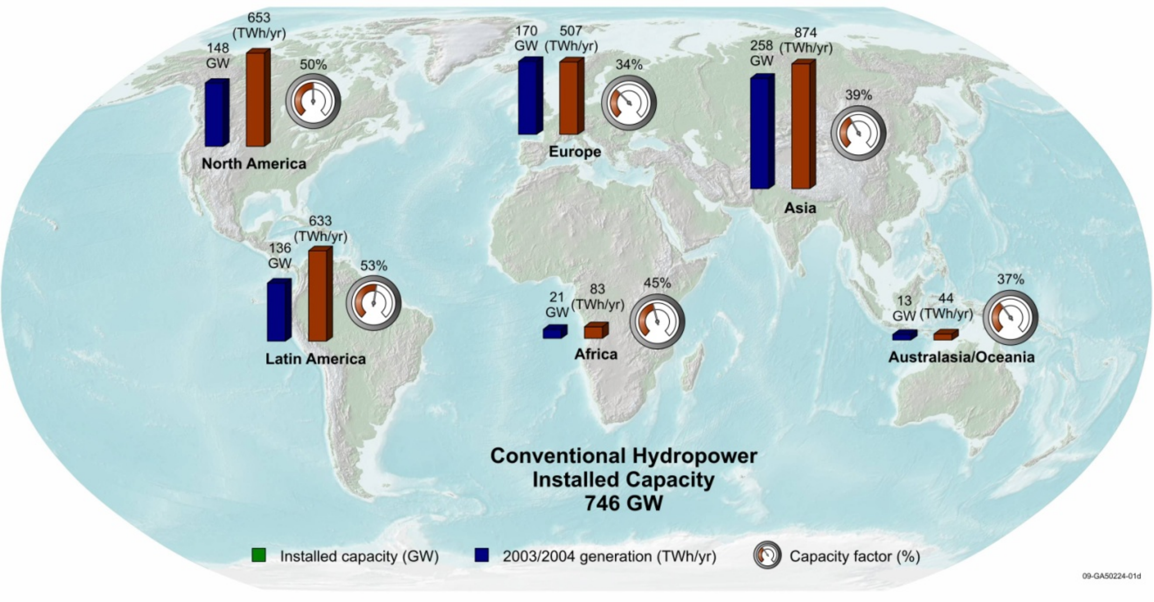


Figure 5.3: Total regional installed capacity, 2003/2004 annual generation, and average capacity factor (Source: (IJHD, 2005). [TSU: colour-coding in figure not consistent]

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. It is also noteworthy that the capacity factors are in the range to be expected although the value for Europe (34%) is surprising low perhaps due to the use of one year of data. If this value along with those for Asia (39%) and Australasia/Oceania (37%) are actually representative, it could indicate 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. The generation potential of in-stream and constructed waterway resources has not been assessed, but they are undoubtedly significant sources of emissions-free energy production based on their large extent.

Worldwide, hydropower has sufficient undeveloped potential to increase its role significantly as a large 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:

1) 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;

2) Changes in extreme events (floods and droughts) may increase the cost and risk for the hydropower projects:

3) 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, increasing flood spill and decreasing generation.

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, 2007c). Here, impacts on water resources were also studied and discussed. Later, a Technical paper on Water was prepared based on the work in WGII and other sources (Bates *et al.*, 2008). The information presented here is mostly based on these sources, but also a few additional papers and reports published in 2008 and 2009 in order to assure that it is as up to date as possible.

5.2.2.1 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 2007c) (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. 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).

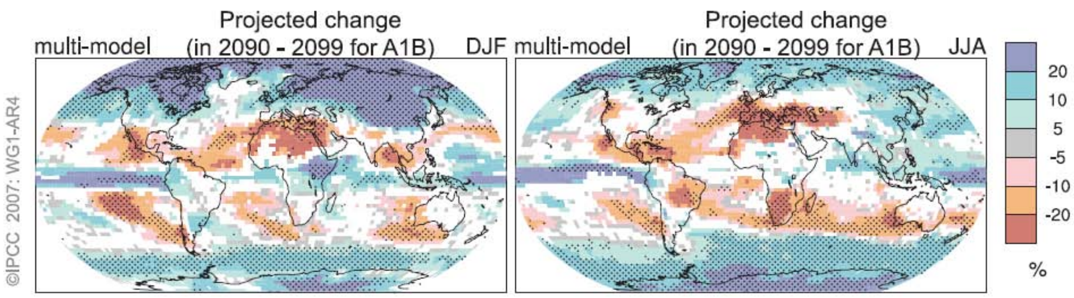


Figure 5.4: Projected multi-model mean changes in global precipitation for the SRES A1B Emission scenario. December to February at left, June to August at right. Changes are plotted only where more than 66% of the models agree on the sign of the change. The stippling indicates areas where more than 90% of the models agree on the sign of the change. [AR4 WG1 TS]

5.2.2.2 Projected changes in river flow

Changes in river flow due to climate change will primarily depend on changes in volume and timing of precipitation and evaporation. 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. A few global-scale studies have used runoff simulated directly by climate models [WGI 10.2.3.2] and hydrological models run off-line. [WGII 3.4] 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).

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).

5.2.2.3 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 WGII. A summary from these findings are given below for each continent, with reference to WGII and relevant chapters:

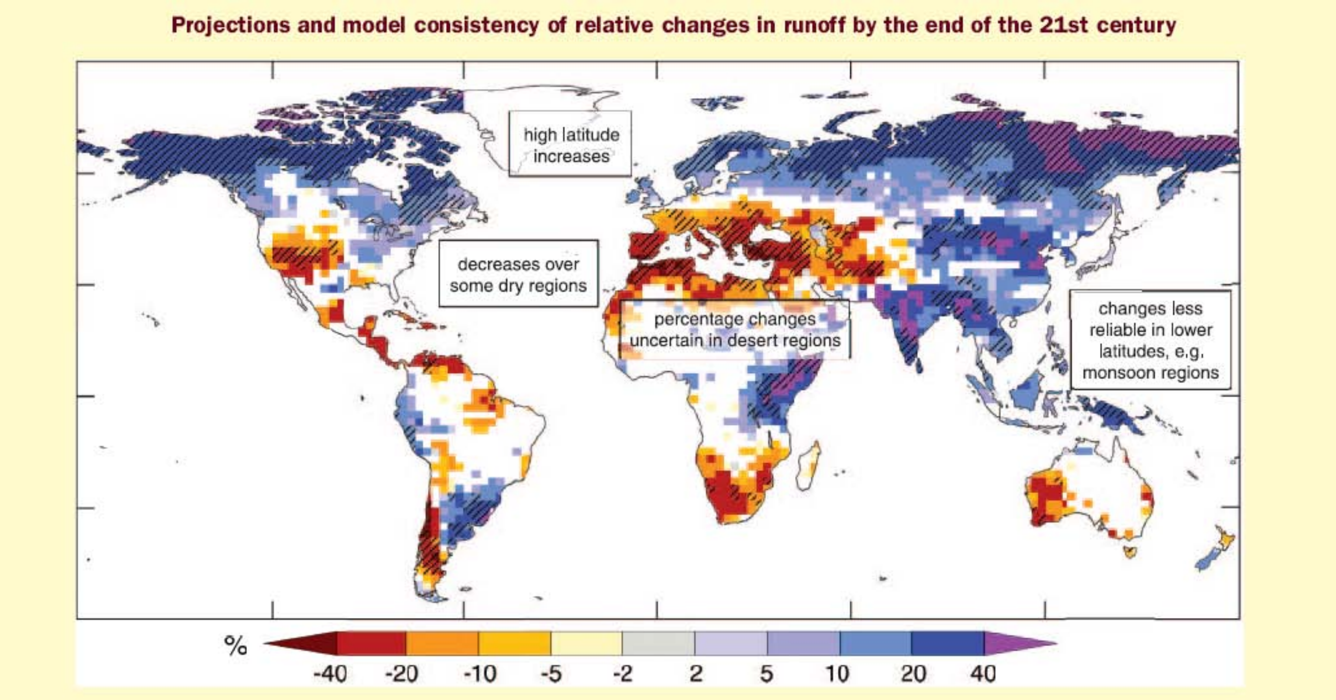


Figure 5.5: Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change (Bates et al., 2008).

5.2.2.3.1 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 [WGII 9.4.2]

5.2.2.3.2 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.

5.2.2.3.3 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. [WGII 12.4.8.1]

5.2.2.3.4 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. In New Zealand, increased westerly wind speed is very likely to enhance wind generation and spillover precipitation into major South Island hydro-catchments, and to increase winter rain in the Waikato catchment (Ministry for the Environment, 2004). Warming is virtually certain to increase melting of snow, the ratio of rainfall to snowfall, and river flows in winter and early spring. This is very likely to assist hydro-electric generation at the time of peak energy demand for heating. [WGII 11.4.10]

5.2.2.3.5 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. [WGII 13.2.2, 13.2.4]

5.2.2.3.6 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. [WGII 4.2] 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). 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. [WGII 3.5, 14.4.8]

5.2.2.3.7 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 were used (USA, Canada, Brazil, India, China and Australia). The changes in hydropower generation for the existing hydropower system (as per 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.

The somewhat surprising result from this study is that only very 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, when averaged over continents or globally.

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 prod. 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**

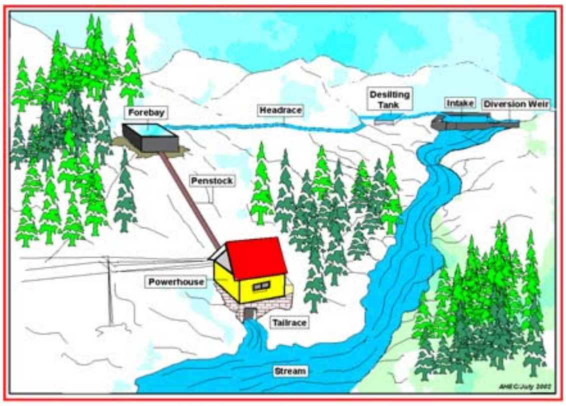
5.3 Technology and applications

5.3.1 Types

HPP are 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. Some RoR HPP also has 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 short in the small tributaries to base-load in large rivers with continuous water flow.

5.3.1.1 Run of River (RoR)

A Run of river hydropower plant 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. Run-of-river hydropower plants 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 hydropower plant situated in small rivers or streams the characteristics of an intermittent source. Installation of small RoR plants 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. In contrast large projects may spend substantial resources on mitigating environmental and social impacts. An example is the Theun Hinboun Expansion Project (280 MW installed effect) now under construction in Laos that has a budget of app. 50 mill USD for mitigating such impacts and for enhancing opportunities (Theun-Hinboun-Project, 2008)

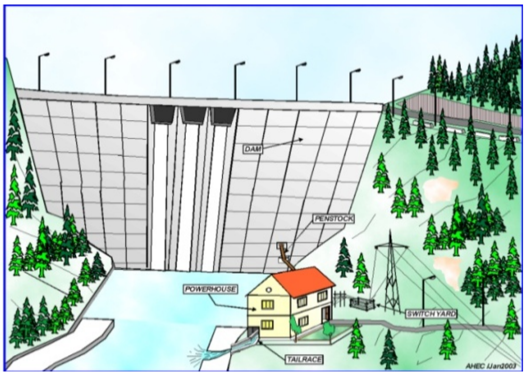


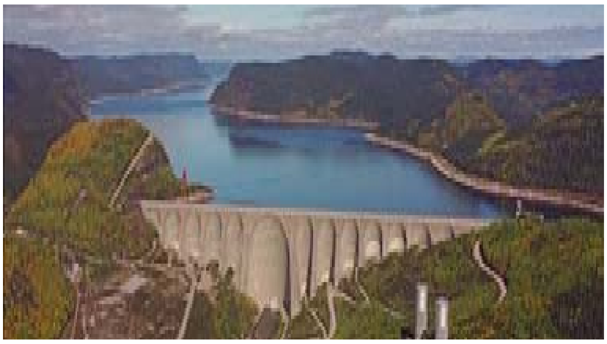
(Shivasamudram, heritage, India)

Figure 5.6: Run of river hydropower plant.

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 landscape.



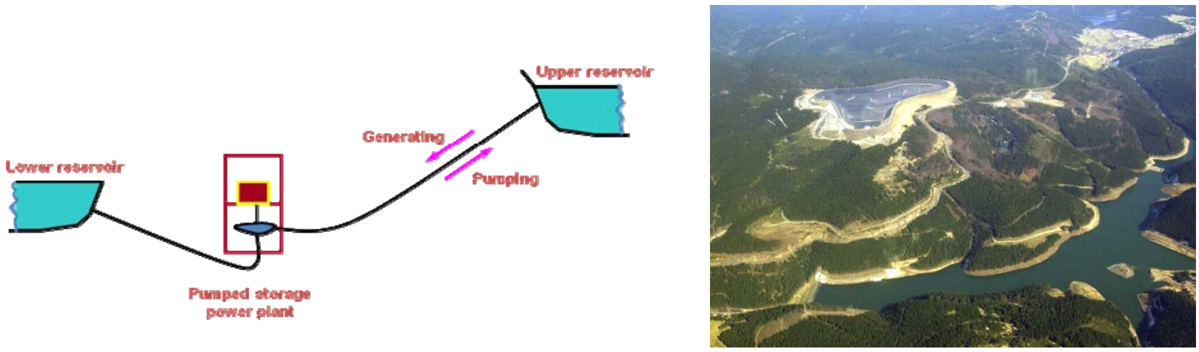


(1,528 MW)Manic-5, Québec, Canada

Figure 5.7: Hydropower plants with reservoir.

5.3.1.3 Pumped-storage

Pumped-storage plants pump water 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. It is considered to be one of the most efficient technologies available for energy storage. Figure 5.8 shows such type of development.



(Goldisthal, Thüringen Germany)

Figure 5.8: Pumped storage project (Source: IEA, 2000b).

5.3.1.4 Instream technology using existing facilities

To optimise existing facilities like weirs, barrages, canals or falls, small turbines can be installed for electricity generation. These are basically functioning like a run-of-river scheme shown in Figure 5.9.

(Narngawal,, India)

Figure 5.9: Typical arrangement of instream technology hydropower projects.

5.3.2 Status and current trends in technology development

5.3.2.1 Efficiency

The potential for energy production in a hydropower plant will be determined by these main parameters given by the hydrology, topography and design of the power plant:

1) The amount of water available, Q_T (Million m^3 of water pr year = Mm^3/year)
2) Water loss due to flood spill, bypass requirements or leakage, Q_L (Mm^3/year)
3) The difference in head between upstream intake and downstream outlet, H_{gr} (m)
4) Hydraulic losses in water transport due to friction and velocity change, H_L (m)
5) 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 , 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. 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. 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.

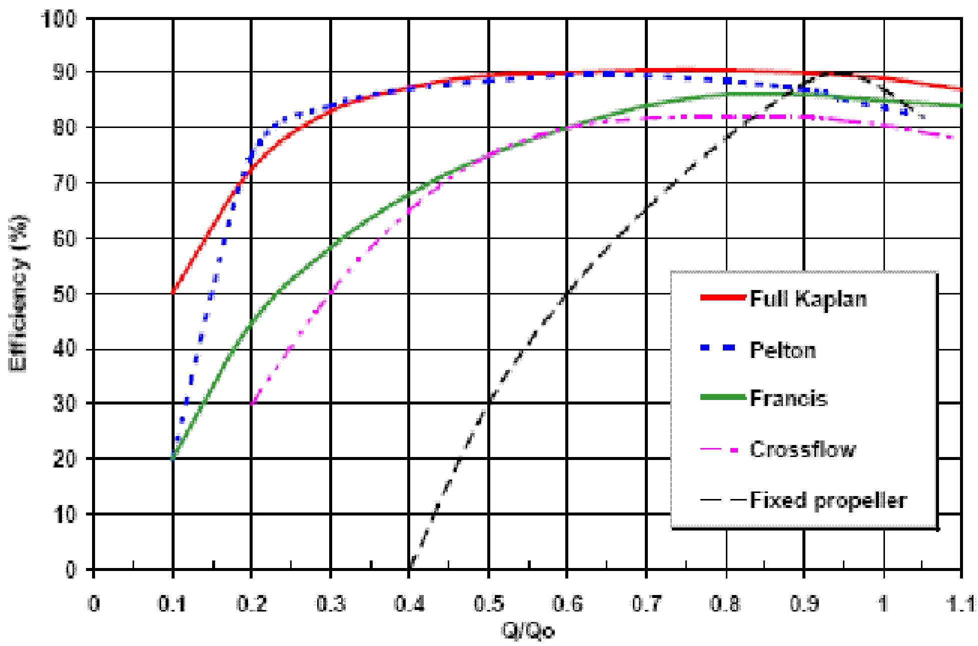


Figure 5.10: Typical efficiency curves for different types of hydropower turbines.

5.3.2.1 Tunneling capacity

5.3.2.1.1 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 especially where the power station is placed underground.

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

5.3.2.1.2 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”) is used to drill a predetermined pattern of holes to a selected depth in the rock face of the proposed tunnel’s path. The drilled holes are then filled with explosives such as dynamite. The charges are then detonated, causing the rock to crack and break apart. The loosened debris or muck is then dislodged and 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. For more details, see below.

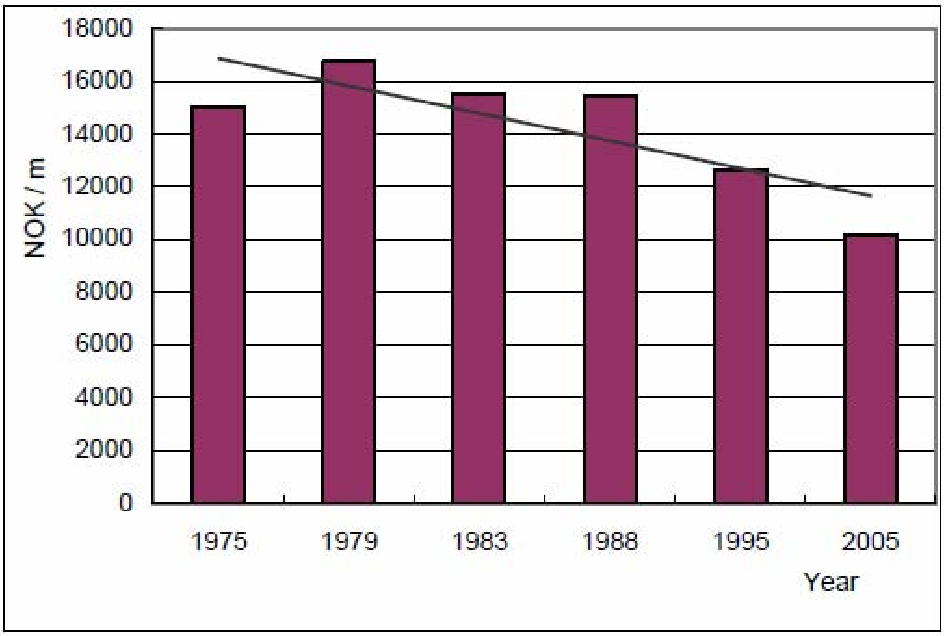


Figure 5.11: Development in tunneling technology - trend of excavation costs for a 60 m2 tunnel, price level 2005, Norwegian Kroner (NOK) pr m. (Zare et al., 2007).

5.3.2.1.3 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.

5.3.2.1.4 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 ads 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 (HARZA,1999) 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.

In every country, the land-used 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. This is a great advantage for the development of hydroelectric projects, since this quantification 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, analyzed and used for useful conclusions. Additionally, it is necessary to establish bathymetric control programs at all reservoirs for hydroelectric generation, which can be easily done by taking measurements every two years. To the previous results must be correlated with studies of basin or sub-basin erosion. Several models are available for these studies, one of which is the GIS (Geographical Information System).

The Revised Universal Soil Loss Equation (*RUSLE*) is a method that is widely utilized to estimate soil erosion from a particular parcel of land. In general the GIS model includes its calibration and using 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 (Patric, 2001). Reservoirs can then be affected significantly by the changes in sediment transport processes.

Reservoir sedimentation problems, due to a high degree of 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 volume increased 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).

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. Sediment deposition in the reservoir can obstruct intakes to block the system from withdrawal of water. Hydropower projects can also suffer from wear of the turbines. The sediment-induced wear of the hydraulic machineries is more serious when the hydropower projects do not have 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 intake and removal of sediment from reservoirs and settling basin 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, remove sediment from the storage reservoirs, design and operate hydraulic machineries of hydropower plant aiming to resist effect of sediment passes through them.

However, it is not easy to apply them 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 the alternative strategies, choices have to be made based on the 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 work remains and need to be done to address sedimentation problems in hydropower projects.

It is important to note that erosion control efforts are not exclusive to hydroelectric projects, but are an important part of national 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 & Uprating (RM&U) of old power stations is cost effective, environment friendly and requires less time for implementation. Capacity additions through RM&U of old power stations is an attractive proposition in the present scenario, when most of the power utilities on account of their financial conditions are not in a position to invest in setting up green field hydro power projects. 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. An example is given in 5.6 (box). The Norwegian Research Council has recently initiated a program looking at so called win-win opportunities where the aim is to increase power production and at the same time improving environmental conditions (T. Forseth 2009).

Normally the life of hydro electric power plant is 30 to 35 years after which it requires renovation. 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 807,000 MW of hydro equipment in operation today will need to be modernised by 2030 (SER2007). Having existing hydropower plants refurbished also result in incremental hydropower, both where present capacity has renovated or where existing infrastructure (like existing barrages, weirs, dams, canal fall structures, water supply schemes) has been reworked, adding new hydropower facilities.

There are 45,000 large dams in the world and the majority do not have a hydro component. A considerable number of these can have hydropower components without disturbing the existing downstream use. 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 timely 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 our 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. The major share of this percentage amount is the result of production in China and Latin America, which grew by 399.5 TWh and 562.2 TWh, respectively (Figure 5.12).

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) of hydroelectric plants (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. In these countries capitalism, although it developed later, seems to have followed in the footsteps of its predecessors [in the developed world], drawing on previously untapped energy to provide clean and safe energy, in sufficient quantities to guarantee the expansion of a solid industrial base (Freitas, 2003).

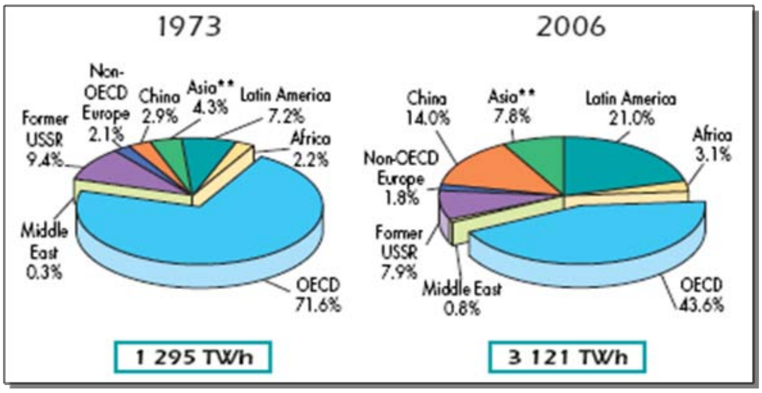


Figure 5.12: 1973 and 2006 regional shares of hydro production* (Source: IEA, 2008)

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 15.2% in China.

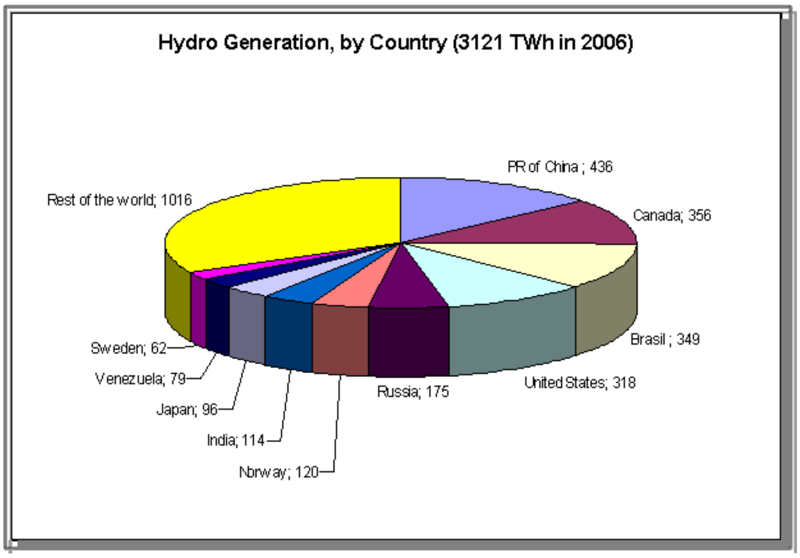


Figure 5.13: Hydro Generation by Country (TWh) (Source: IEA, 2008).

Table 5. 2: Major Countries Producers / Installed Capacity.

Installed Capacity Based on Production	**GW**
China	118
United States	99
Brazil	71
Canada	72
Japan	47
Russia	46
India	32
Norway	28
France	25
Italy	21
Rest of the world	308
World	**867**

2005 data
Sources: United Nations, IEA

Country Based on First 10 Producers	**% of Hydro in Total Domestic Electricity Generation**
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
United States	7.4
Rest of the world**	14.3
World	**16.4**

2006 data
**Excludes countries with no hydro production

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%.

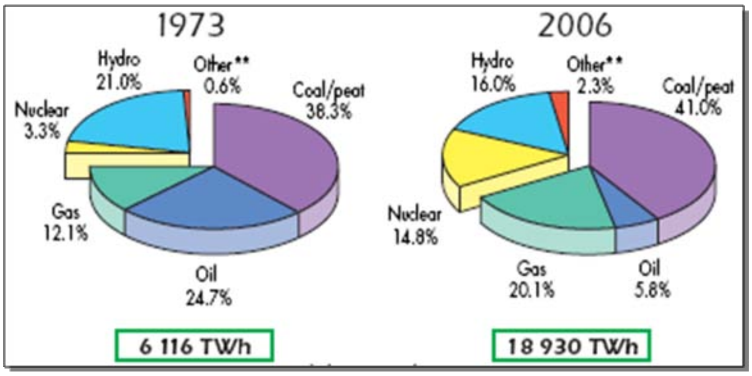


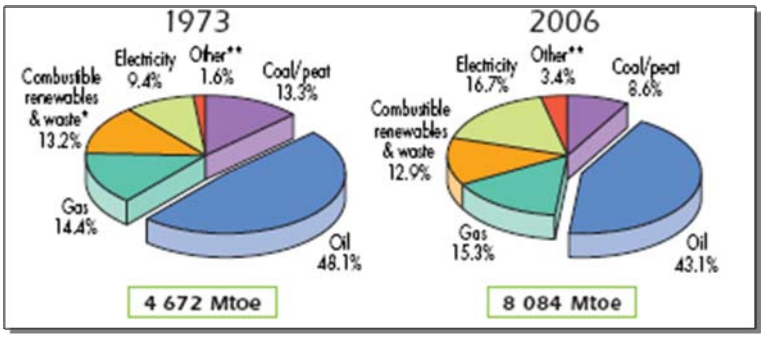
Figure 5.14: 1973 and 2006 fuel share of electricity generation* (Source: IEA, 2008).

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. Russia stands out, in terms of production of electricity from gas, producing 55% in relation to the leader, the United States. The generation of electricity from combustible oil is relatively low-scale when compared with other combustible fuels: accounting for less than one third of the amount generated from the use of gas and around 14% of that generated using coal. In the use of combustible fuel for electricity generation, Japan is prominent, followed by Saudi Arabia. Brazil and Canada, on the other hand, do not appear on the list of the 10 major producers of electricity using these sources (coal combustible oil and gas).

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).

The fact that electricity accounts for the major share of final consumption in 2006 (Figure 5.15) is due to the increase in the final consumption of electricity in China where there was a major acceleration in the generation of electricity, 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 (Source: IEA, 2008).

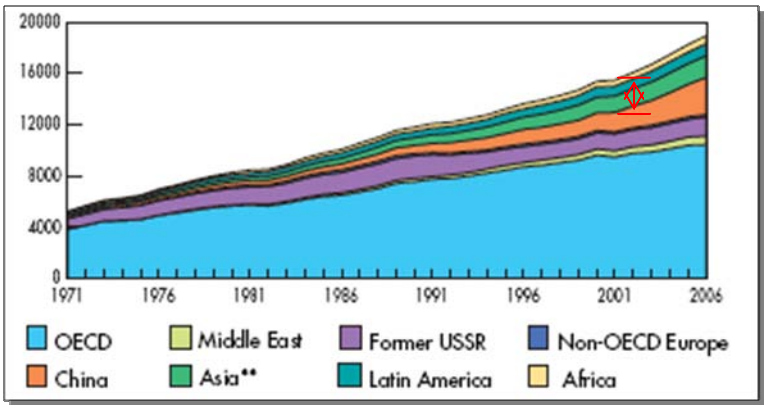


Figure 5.16: Evolution from 1971 to 2006 of world electricity generation* by region (TWh) 'Key World Energy Statistics'. (Source: IEA, 2008).

5.4.3 Industry Status

5.4.3.1 Relevant technical development

With hydropower technology, the challenge is to improve by continuously pushing the envelope in terms of operational range (head and discharge), environmental performance, materials, efficiency and costs. Effort is also being made to develop equipment to operate with even greater flexibility and in more difficult conditions/constraints. Low head and fish friendly turbines are recent technical developments.

Strategic planning and assessment is needed to optimize benefits and minimize impacts. The least-cost option for producers desiring additional capacity is almost always to modernize existing plants, whenever possible. Equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Innovations of Hydro industry are further elaborated subsequently in section 5.7.1.

5.4.4 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. Hydropower can also provide the firming capacity for wind power. By storing potential energy in reservoirs, the inherent intermittent supply from wind power schemes can be supported. Peak power is expensive. 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, these services can even be provided in the pumping mode of reversible turbines.

5.4.5 Carbon credit market

Hydropower projects are one of the main contributors to carbon credits. There are two methodologies approved by UNFCCC that can be used for hydropower projects according to their size: AMS ID for small scale projects (less than 15 MW) and ACM002 for large scale projects (above 15 MW). 1163 hydropower projects in the CDM pipeline represent 26% of the total CDM projects. The CDM Executive board have 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 assumptions and not scientific or professional documentation. The issue of methane production from reservoirs are discussed later in this chapter.

Out of the 1300 projects registered by the CDM Executive Board by January 1st 2009, 287 are hydropower projects (See figure 5.17) [TSU: Reference to Figure 5.17 not clear here; should probably be moved to above paragraph; also numbers given should be checked]. When considering the PDD-predicted volumes of CERs to be delivered, registered hydro projects are expected to generate around 20 million tonnes per year, equivalent to 8% of the total

The majority of hydropower projects in the pipeline are at the validation stage, with 60% at this early stage of the process. A significant portion of these projects are based in China (67%), India (9%) and Brazil (6%). (See Figure 5.18). So far only 12 projects have been rejected by the CDM Executive Board on the grounds of not having additionality criterion.

Large hydro projects are coming more and more through the system. 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 capacities and above Member States must “ensure that relevant international criteria and guidelines, including those contained in the World Commission on Dams Report (see section 5.6.2) 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 5.6.2 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.

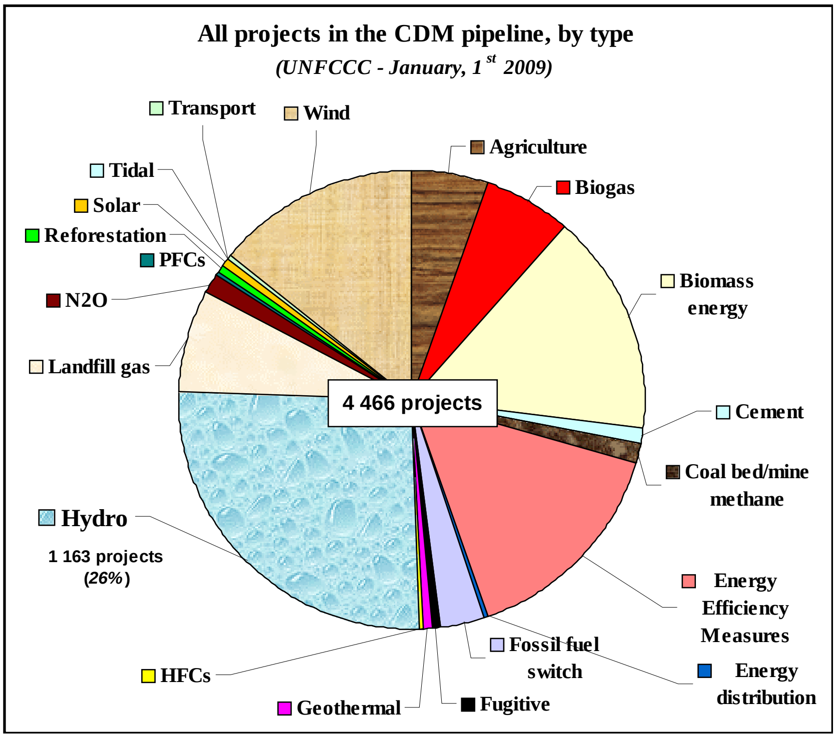


Figure 5.17: Hydro share in the CDM pipeline January, 1st 2009 (Source: UNFCCC): a type analysis.

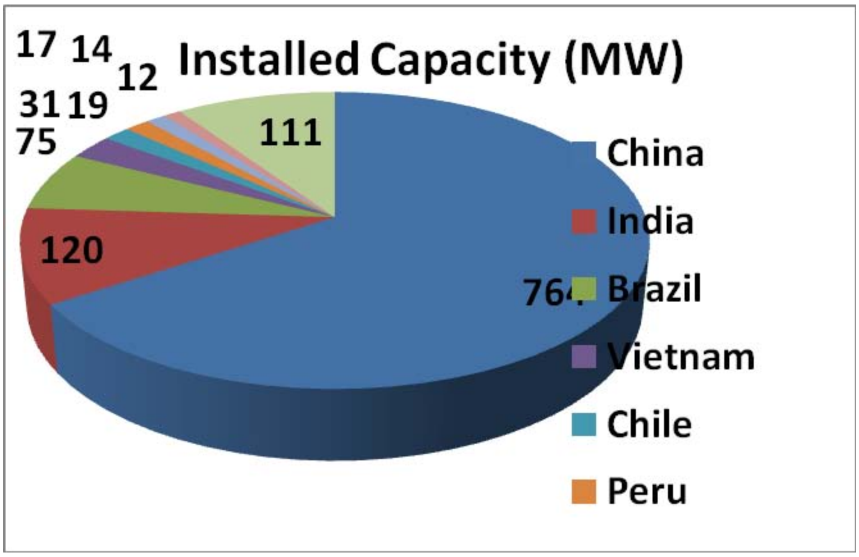


Figure 5.18: Country wise Hydropower projects registered for CDM as on January, 1st 2009 (source UNFCCC).

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).

5.4.6 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 which lead to higher risk premiums for private investors. 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 supply agents 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.

5.4.6.1 Financing

Many economically feasible hydropower projects are financially challenged. High up-front costs are 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 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.

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).

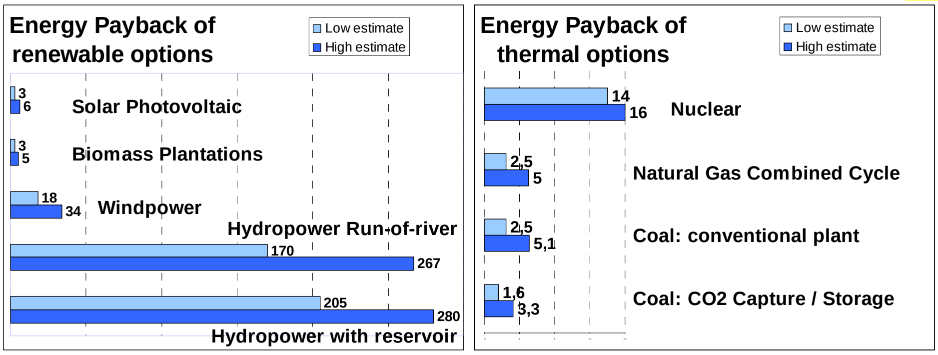


Figure 5.19: Energy Pay back Ratio (Source: Gagnon, 2008).

5.4.6.2 Administrative and Licensing process

The European Union differentiates between small and large hydropower. There are different incentives used for small hydro[2] (feed-in tariffs, green certificates and bonus) depending on the country, but no incentives are used for large 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

[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.

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. Therefore 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

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 'new' 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 wind power, increasing the economic value of the power delivered (US DOE 2003). Likewise, wind energy 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 are extremely quick response to intermittent loads as they can be brought on stream within a short period 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 plants and over 8 hours for steam plants) 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 or individual or group of individuals.

Figure 5.20: 200 kW isolated hydropower plant in Dewata Tea Estate, Indonesia.

On the other hand rural areas may not have grids due to economic reasons and mini grid or isolated systems based hydropower 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 grid often faces the problem of poor plant load factor and making financial return difficult 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.

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 electricity in 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 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** Million	**Urban population** Million	**Population without electricity** Million	**Population with electricity** Million	**Electrification rate** %	**Urban electrification rate** %	**Rural electrification rate** %
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: Energy Outlook 2006

Small 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 hydropower development due to their dispersed location and opportunity advantage.

- Normally small hydro are RoR schemes
- Locally/small factories 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

Development of small hydropower for rural areas involves social, technical and economic aspects. Local management, ownership and community participation, technology transfer and capacity building are the basic issues for success of small hydro plants in rural areas.

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 are usually found during summer daylight hours when air conditioners are running in a warm climate. In northern regions the highest peak hours are usually found in the morning and in the afternoon during the coldest periods in the winter.

Nuclear and fossil fuel plants are not efficient for producing power for the short periods of increased demand during peak periods. Their operational requirements and their long startup times make them more efficient for meeting base load needs only. Since hydroelectric generators can be started or stopped almost instantly, 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 mixing of power sources offers a utility company the flexibility to operate steam plants most efficiently as base plants while meeting peak needs with the help of hydropower. This technique can help ensure reliable supplies and may help 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, hydropower shall be even more important. 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.

Like peaking, pumped storage keeps water in reserve for peak period power demands. Pumped storage is water 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 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 during daily and seasonal peak periods. An advantage of pumped storage is that hydroelectric generating units are able to start up quickly and make rapid adjustments in output. They operate efficiently when used for one hour or several hours.

Intermittent energy sources like solar power and wind power may be tied to pumped storage hydro power systems to be economical and feasible. Hydropower can serve as an instant backup and to meet peak demands. Wind power can be used when the wind is blowing, to reduce demands on hydropower. That would allow dams to save their water for later release to generate power in peak periods.

Hydropower is important from an operational standpoint as it needs no "ramp-up" time, as many combustion technologies do. Hydropower can increase or decrease the amount of power it is supplying to the system almost instantly to meet shifting demand. 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. In addition, hydroelectric pumped storage facilities are the only significant way currently available to store large amounts of electricity. Hydropower's ability to provide peaking power, load following, and frequency control helps protect against system failures that could lead to the damage of equipment and even brown or blackouts (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 allows hydropower plants to be used as storage reservoirs. 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. Hydro with its short response time 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.

Reservoir based hydropower store kinetic energy as a potential for electricity production. This is the main storage aspect of hydropower. An example of scale is how Scandinavian hydropower through their reservoirs back up and regulate wind power in Denmark/Germany and also deliver peak production via cables to Europe (ref also chapter 8). Norwegian hydropower alone represent approximate half the total reservoir capacity in Europe. Storing of water is considered storage of energy and can be loosely termed as batteries for the power system. It should be emphasized that while hydropower reservoirs store energy as a source for electricity before it is produced, pumped storage plants store electricity after it is produced.

Electricity already produced cannot be stored directly except by means of small capacitors and hence is 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 (CAES, compressed air energy storage) or flywheels. For large scale energy storage only potential energy through pumped storage schemes are presently viable. Various technologies for storing electricity in the grid are compared in figure 5.21. CAES systems are not shown. CAES can store a substantial amount of energy.

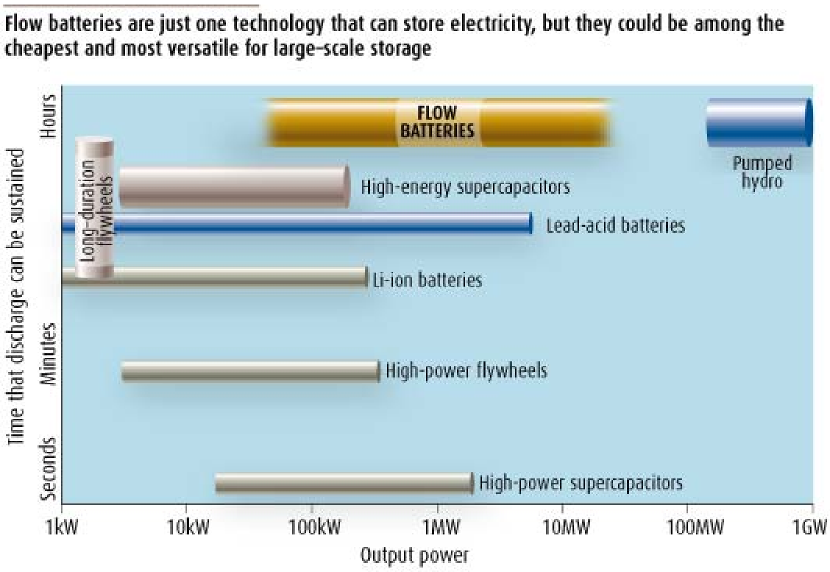


Figure 5.21: Pumped Storage ability to store electricity compared with various technologies (Source: Thwaites, 2007).

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. Pumped storage is the largest-capacity form of grid energy storage now available.

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. 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.

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. Estimates of the ideal mix of electricity storage and conventional power generation suggest that pumped storage should amount to 6 to 8 % of the total power generation capacity.

The most common type of pure pumped storage is the off-stream configuration. The off-stream configuration consists of a lower reservoir on a stream, river or other water source, and a reservoir located off-stream usually at a higher elevation. It is possible to construct an off-stream pumped storage project in which the off-stream reservoir is at a lower elevation such as an abandoned mine or underground cavern.

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.

Grid energy storage lets energy producers transmit excess electricity over the electricity transmission grid to temporary electricity storage sites from where electricity may be transmitted to the places when needed. Grid energy storage is particularly important in matching supply and demand over a 24 hour period of time.

5.5.6 Supply characteristics

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 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 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.

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.

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*. A typical hydroelectric plant's operators can bring it from a stopped condition to full power in just a few minutes.

Example of representative international statistics can be found in table 5.4.

Table 5.4: AVAILABILITY INDEXES NERC 2000 - 2004.

Technology	Number Of Units (Sample)	Service Time (Years)	NCF	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
Notes:							
NCF	Plant Factor						
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.

5.5.6.3 Reliability/quality

Hydroelectric power is usually extremely dispatchable and more reliable than other renewable energy sources. Many dams can provide hundreds of megawatts within seconds of demand, the exact nature of the power availability depending on the type of plant. In run of river plants power availability is highly dependent on the uncontrollable 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

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. Itapúa Hydropower on river Parana in Brazil and Paraguay and Victoria Lake hydropower in Uganda, Tanzania and Kenya are some notable instances of regional cooperation.

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.

5.6 Environmental and social impacts

Like all other energy and water management options, hydropower projects do have up and downsides. 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.

[3] Climate, temperature, inundated biomass, topography, water residence time, oxygen level, etc.

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 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[5] (IEA, 2000a; UNEP, 2007). By far the most effective measure is impact avoidance, weeding out less sustainable alternatives early in the design stage.

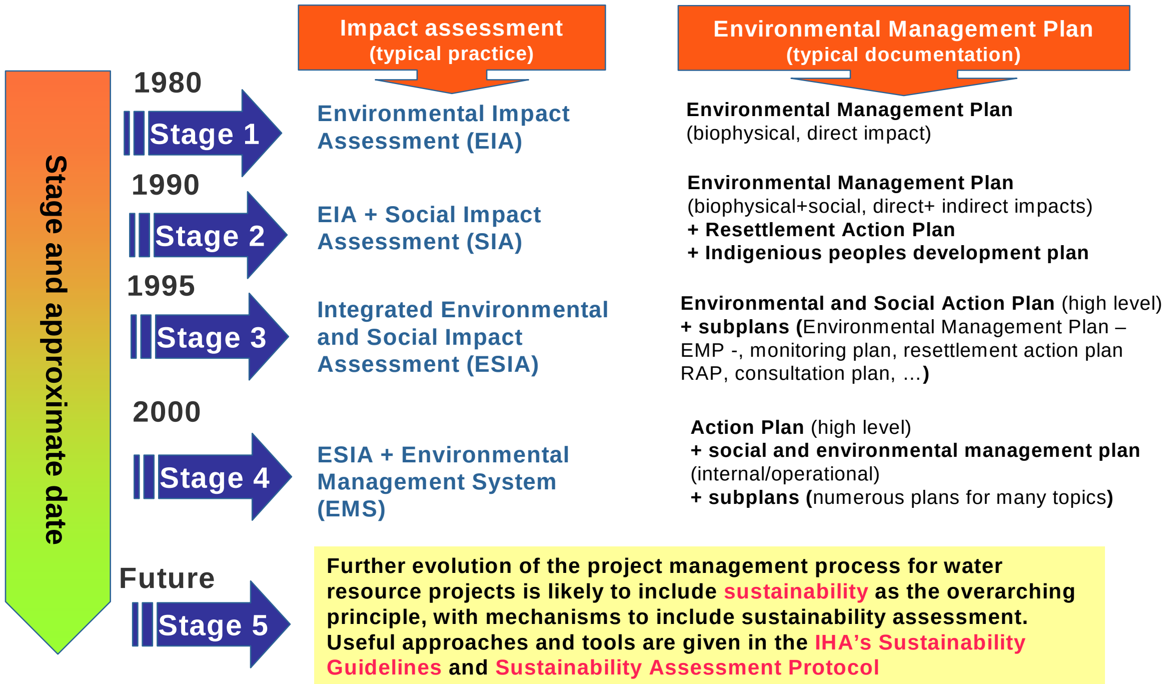


Figure 5.22: Evolution of the E&S process, adopted from UNEP (2007).

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, which can have significant adverse effects according to the project's specific site conditions. Altered flow regimes, erosion and heavily impacted littoral zones

[4] Local/national/regional authorities, affected population, NGOs, etc.
[5] a) IEA/IHASustainable Hydopower Website at www. sustainablehydropower.org

in reservoirs are well known types of negative impacts (Helland-Hansen et.al. 2005). 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 many cases has 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. As documented by Scudder (Scudder, 2005), they 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.

According to hydropower-specific studies realised over a 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:

5.6.1.1 Hydrological Regimes

Depending on the type of hydropower project, the river flow regime is more or less modified. 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 volume 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 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. 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 are good habitat for fish. However, the impacts of reservoirs on fish species will only be perceived positively 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. 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 (Donau, Austria). 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 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. Sedimentation has a direct influence on the maintenance costs and even on the feasibility of a HPP. 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

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. However HPPs which are located in rivers hosting migrating fish species can constitute an important threat to fish during downstream migrations. Most fish injuries or mortalities during downstream movement are due to their passage through turbines and spillways. Improvement in turbine design, spillway design or overflow design has proven to successfully minimize fish injury or mortality rates. 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. 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 large 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. 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 (World Bank 1994 a). 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[6] 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[7], seven strategic priorities[8] 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 (WB, 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 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

[6] E.g. local population, governments, developers, financing institutions, NGOs and others
[7] Equity, efficiency, participatory decision-making, sustainability, and accountability
[8] 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

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 (March 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.

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.
- **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 projects are multi-purpose projects. Yet, a study carried out by IEA (2000b) based on LCA and later published in Energy Policy (EIA, 2002), the amount of CO_2 – equivalent emitted by hydropower is around 15g CO2eq/kWh. 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 numerous experts from all over the world (Tremblay *et al.*, 2005) have lead to the following conclusions:

- All freshwater systems, whether they are natural or man made, emit greenhouse gases (GHG) due to decomposing organic material. This means that lakes, rivers, estuaries, wetlands, seasonal flooded zones and reservoirs emit GHG.

- Within a given region that shares similar ecological conditions, reservoirs and natural water systems produce similar levels of emissions per unit area. In some cases, natural water bodies and freshwater reservoirs even absorb more GHG 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 wetlands, rivers and lakes that were located in the area before impoundment and abstract carbon inflow from the riparian terrestrial ecosystems as well as other human activities.

The main GHG produced in freshwater systems are carbon dioxide (CO_2,) and methane (CH_4). The nitrous oxide (N_2O) could be also an issue in some cases and more particularly in tropical areas or in reservoirs with large drawdown zones. 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. 2008b).

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. 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[9] when methanotrophic bacteria are present. 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). 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.

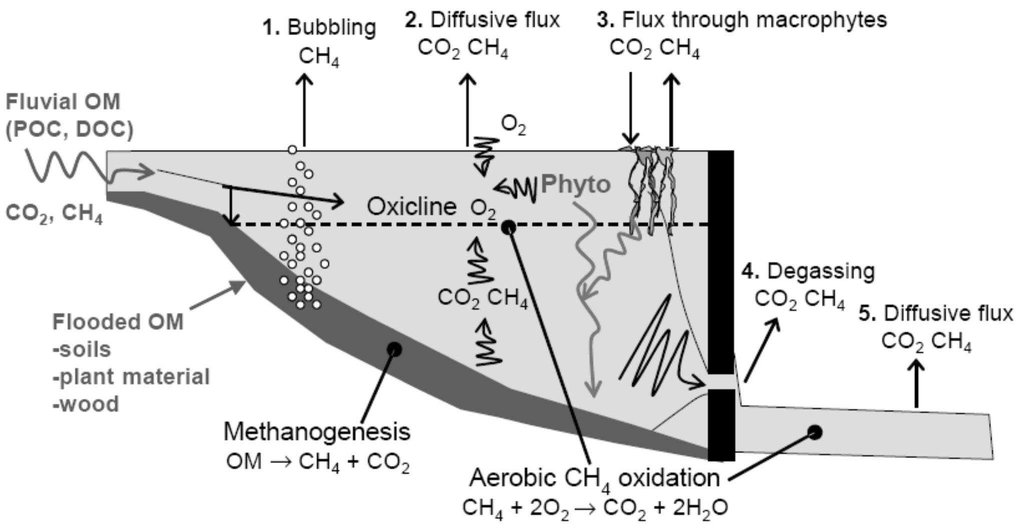


Figure 5.23: Evolution of the E&S process, adopted from UNEP (2007).

[9] Lisstrom et al. 1984; Frenzel et al. 1990; Guerin et al. 2007

Carbon dioxide and methane pathways in freshwater reservoir with an anoxic hypolimnion ((IJHD, 2005); Guerin et al. 2007; Guerin et al 2008b).

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 emissions have been investigated in boreal[10] and temperate[11] regions. Gross emissions measurements in boreal/temperate regions from Canada, Finland, Iceland, Norway, Sweden and USA are summarized in Table 5.5. below.

Table 5.5: 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})

In tropical regions, high temperatures coupled with important demand in oxygen due to the degradation of substantial 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, usually very dense, and soil organic carbon (Abril et al. 2005; Guerin et al. 2008). According to UNESCO/IHA (2008) measurements of gross emissions have been taken in the tropics at four Amazonian locations[12] and additional sites in central and southern Brazil[13] . 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[14]. 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. In boreal and temperate conditions, GHG

10 Rudd 1993; Duchemin et al., 1995; Kelly et al. 1997; Huttunen et al. 2002; Tremblay et al. 2005
11 Therrien et al. 2005; Soumis et al. 2004; Casper et al. 2000) and tropical (Keller and Stallard 1994; Rosa and Scheaffer 1994; Galy-Lacaux et al. 1997; Galy-Lacaux et al. 1999; Fearnside 1995; Fearnside 1997; Fearnside 2001; Fearnside 2002; Delmas et al. 2001; Rosa et al. 2003; Abril et al. 2005; Sikar et al. 2005; Santos et al. 2006; Guerin et al. 2008; Kemenes et al. 2007
12 Balbina, Curuá-Una, Samuel, Tucuruí
13 Barra Bonita, Carvalho, Corumbá, Funil, Furnas, Itaipu, Itumbira, L.C.B., Manso, Mascarenhas de Moraes, Miranda, Ribeirão das Lajes, Serra da Mesa, Segredo, Três Marias, Xing (Duchemin et al. 1995
14 data scheduled to be published during the first semester of 2010

emissions have been observed to return to the levels found in neighbouring natural lakes after the initials 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/IHA 2008)[15].

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.

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, Scatasta and Cestti, 2003). According to the WCD’s Final Report (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 (2005), 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 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 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

[15] More information can be found at http://www.hydropower.org/climate_initiatives.html.

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. 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 hydropower potential (<10 MW) was previously assumed to be 7 TWh. A new study initiated in 2002-2004, revealed a small hydropower potential of nearly 25 TWh at a cost below 0.06 US$/KWh and 32 TWh at a cost below 0.09 US$/KWh (Jensen, 2009).

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 with respect a fixed-speed plant have been found in simulation studies (Terens *et al.*, 1993) (Fraile-Ardanuy, 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 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 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 is most practical application in the near term is likely to be in rivers and streams.

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.*”

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).

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. The examples from the USA show an increase by 20% or more for hydrokinetic projects alone, up to double the existing capacity if all types of new potential for hydropower are utilized.

5.7.5 Abrasive resistant turbines

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).

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$ 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 multi-purpose dams and better planning tools for multi-purpose 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 total hydropower generation potential has been described in section 5.2.1. This potential is not easy to estimate exactly, since it is not only a function of natural resources (water and head) but also limited by the cost of development. The resource potential data for hydropower is in general based upon a large number site-specific studies where only those projects that were considered economically and environmentally feasible have been included.

In a recent study (Gagnon, 2009) the global unexploited hydropower resources have been estimated and grouped according to cost of development. This study is mostly based upon information from known sites provided by countries to the *Hydropower and Dams World Atlas,* 2008. Based on this information, the remaining unexploited potential for hydropower development was estimated for 18 countries/regions in the world. Data for these 18 regions have here been grouped into six larger regions or continents, similar as used previously in 5.2.1 [TSU: Reference to Table 5.6 is missing]. The remaining potential (TWh/year) for each region were divided into three classes, A, B and C, based on energy cost (¢/KWh).

- A: Economically feasible projects – energy cost between 2 and 8 ¢/KWh
- B: Realistic projects – energy cost between 8 and 20 ¢/KWh
- C: Technical potential – energy cost above 20 ¢/KWh

Class A contains projects from known sites with costs lower than or at similar levels as the main competitors today, coal, nuclear, gas etc.

Class B contains projects from known sites that are not considered economically feasible today, in competition with coal, gas and nuclear, but with a cost lower than or similar as other renewables (wind, solar etc).

Class C contains projects from main rivers or known sites that are considered technically feasible, but have a cost higher than other competing technologies. This class has not been included in the resource potential described previously (5.2.1) but it is included here to show the large potential that could be exploited at a higher cost.

The variability in cost for individual projects within each class is not known in detail, but as an approximation we suggest to use a nearly linear distribution curve within each class, ranging from 2 to 8 ¢/KWh with an average cost of 5 ¢/KWh in class A and from 8 to 20 ¢/KWh with an average of 14 ¢/KWh in Class B. For Class C no distribution can be estimated yet, since most projects here are not studied in detail due to the high cost.

Table 5.6: Unexploited Hydropower potentials by Region (TWh/year) (Source: Gagnon, 2009)

Region	**Class A 2- 8 c/kWh**	**Class B 8 – 20 c/kWh**	**Class C > 20 c/kWh**	**Total**
Africa	1023	574	2324	3921
Asia	3894	2457	1612	7963
Europe	905	168	5605	6678
North America	912	598	4607	6117
South America	1600	842	6317	8759
Australia/Oceania	70	28	7955	8053
Sum	8404	4667	28420	41491

As an example, *Hall et al.* (2003) did a study in USA, where 2155 sites with a potential capacity of 43 000 MW were examined and classified according to unit cost in $/KW. The distribution curve show that costs varied from less than 500 $/KW up to over 6000 $/KW (Figure 5.24). Except from a few projects with very high cost, the distribution curve is nearly linear, up to 95% of the projects. Lako *et al.* (2003) presented a similar trend in cost curves for several regions of the world. Gordon (1982) presented cost equation for hydropower project based on a statistical analysis of cost data obtained over 170 hydropower projects worldwide.

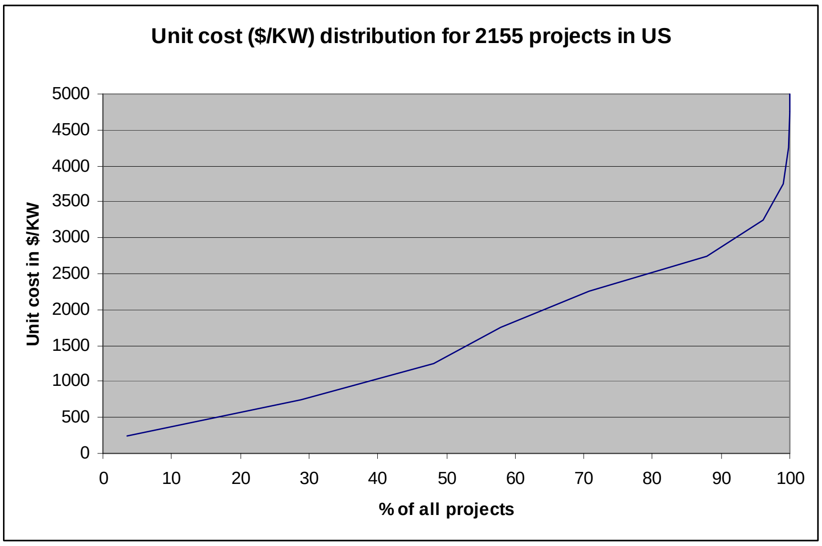


Figure 5.24: Distribution of unit cost ($/KW) for 2155 hydropower project sites studied in USA. (Source: Hall et al., 2003).

Development cost of hydropower also cost on Licensing, Plant construction, Fish and wildlife mitigation, Recreation mitigation, Historical and archeological mitigation and Water quality monitoring cost. Hall *et al*. (2003)in their study also presented typical plant construction cost for new sites in Fig 5.25.

Basically, there are two major cost groups: the civil construction costs, which normally are greater costs, and those that have to do with electromechanical equipment for energy transformation. The civil construction costs follow the price trend of the prices in 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 materials.

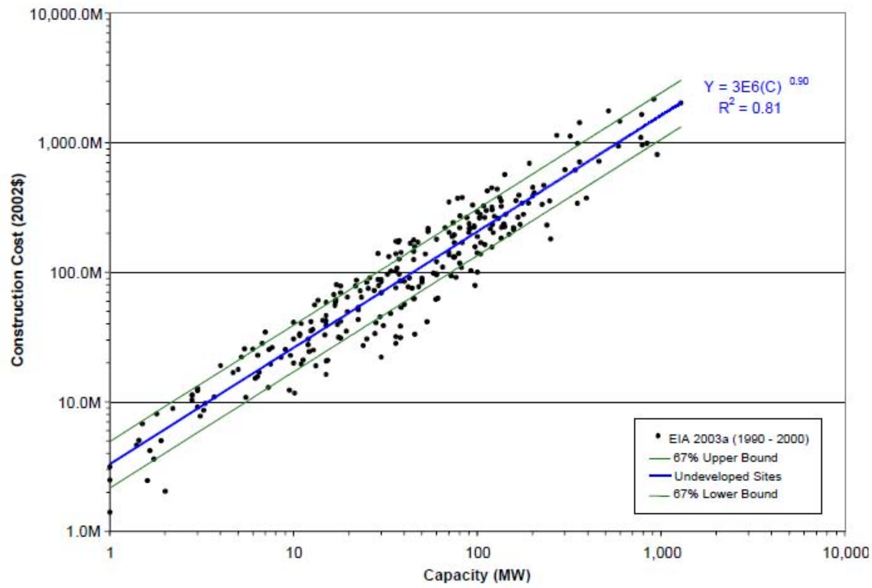


Figure 5.25: Hydropower cost as a function of plant capacity for new sites.

The costs of electromechanical projects follow the tendency of prices at a global level, except in developed countries, where most of the machinery used in the hydropower project is produced, and where prices are more stable. The issue of estimating costs and projections is not an obstacle for the development of hydroelectricity as a renewable resource. 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,) presented the cost of electromechanical equipment from various hydroelectric projects as figure 5.26.

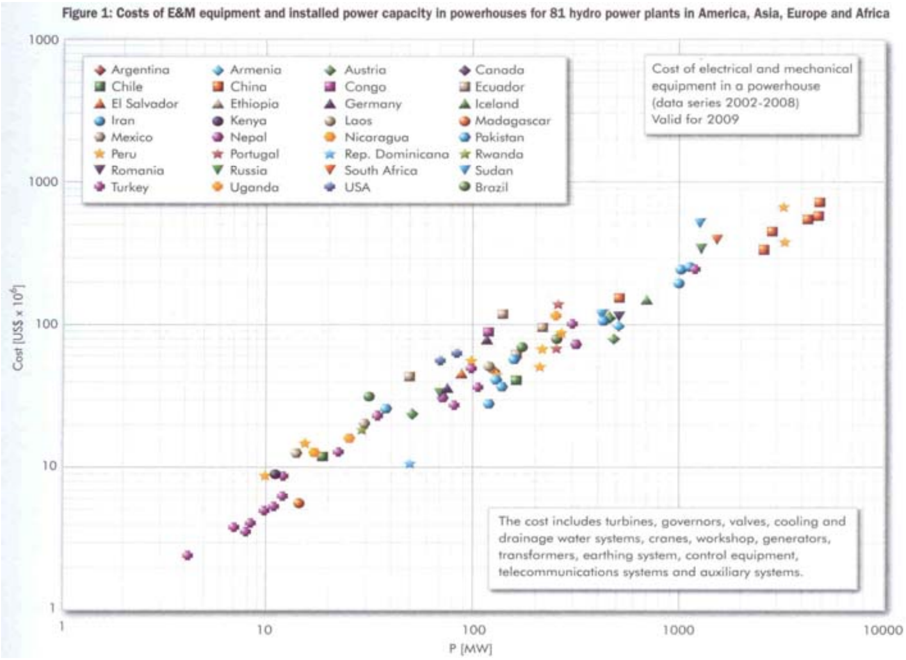


Figure 5.26: Costs of E&M equipment and installed power capacity in powerhouses for 81 hydro power plants in America, Asia, Europe and Africa.

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 have to be 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.

5.8.2 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 carrying out at its separable cost. Separable cost for any purpose is obtained by subtacting 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 recently, reservoirs were mostly funded and owned by the public sector, thus project profitability and their inter purpose was cast sharing 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 Chechoslovakia 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). Government of India later adopted the use-of-facilities method for allocation of joint costs of multi-purpose river valley projects (Jain, 2007).

5.9 Hydropower future deployment

5.9.1 Overall worldwide hydro development

The figure 5.27 presents the development of hydropower :

- historical data: the use of hydropower has expanded gradually worldwide in the past years from about 1000 TWh in 1965 to more than 3000 TWh today
- forecast scenarios: the trends to 2100 is a significant increase.

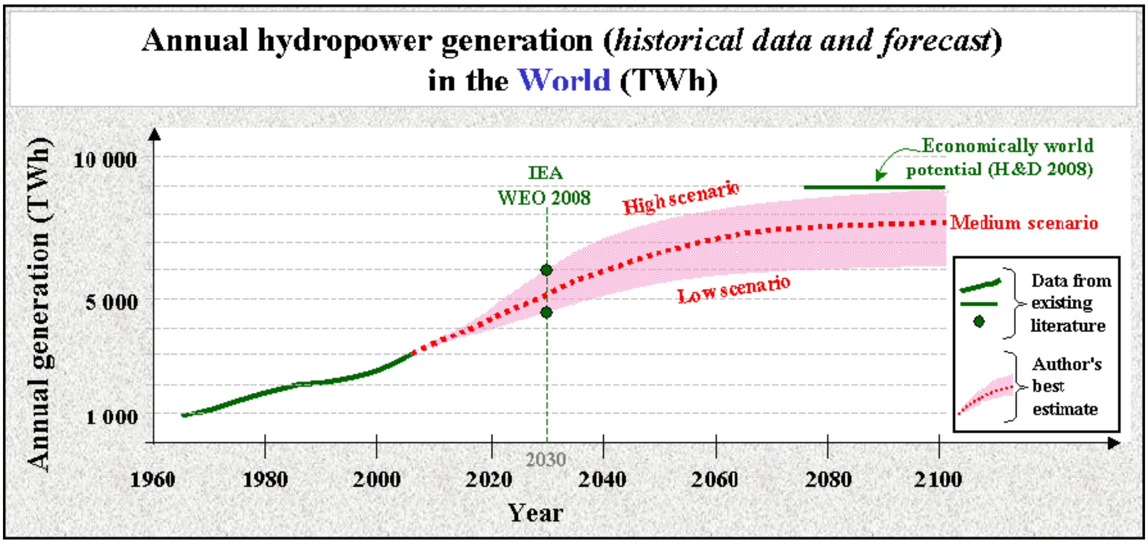


Figure 5.27: Annual Hydropower generation in the world.

At the moment, only one third of the economically feasible hydropower potential has been developed so far across the World (e.g. 3 000 TWh out of ~9 000 TWh).

The different long term prospective scenarios propose a significant increase for the next decades. For instance in 2030, the hydro generation capacity is between 4 500 TWh to more than 6 000 TWh as an annual generation (IEA, 2008).

5.9.1.1 Hydro development by regions

There are subsequent differences among regions, as it was presented below:

- **Europe and Eurasia**: European Union has developed most of its potential but there are however several possibilities to increase its hydropower capacity: rehabilitation and refurbishment of the existing units, development of small hydro, and possible new large plants to fulfil the EU RES targets. In this region the remaining potentials are mostly located in Russia and Turkey. Figure 5.28 presents development in Europe and Eurasia.

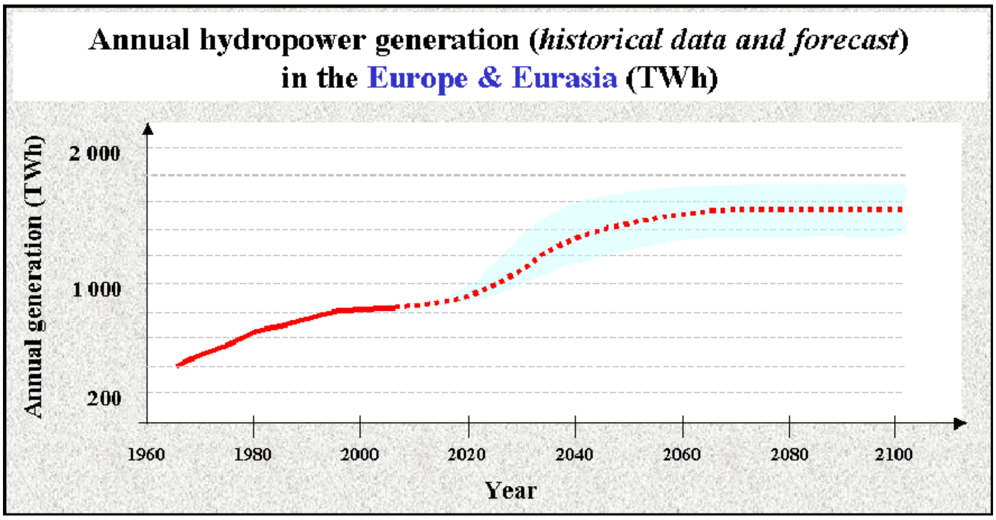


Figure 5.28: Annual Hydropower generation in Europe and Eurasia

- **North America**: even though a large amount of the potential has been so far developed, Canada (and also United States of America) is likely to continue to develop their potential considering national laws on RES, and GHG constraints. Figure 5.29 presents development in Northe America.

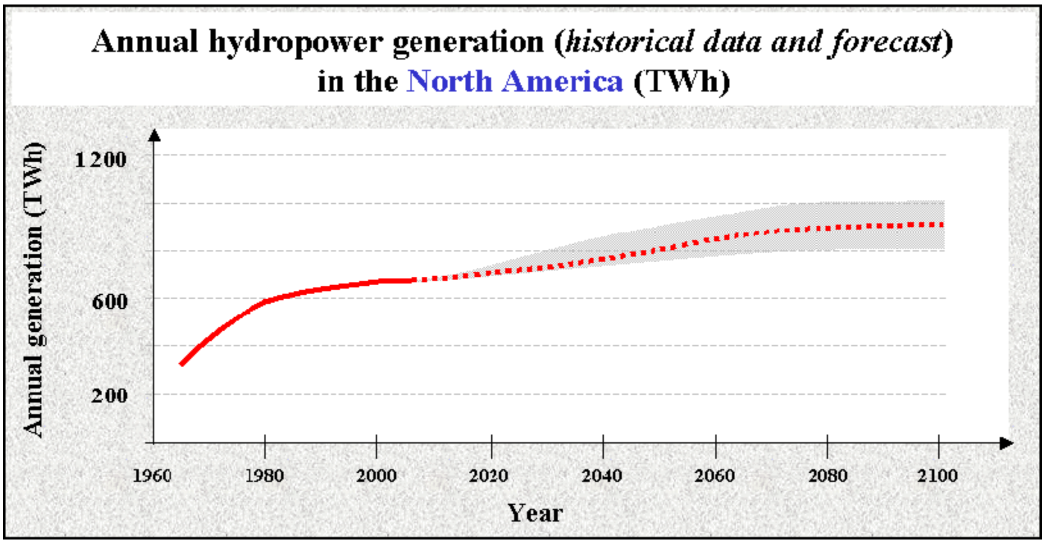


Figure 5.29: Annual Hydropower generation in North America.

– **Africa**: less than 10% of the potential has been developed. The development will rely on the main countries: Democratic Republic of Congo, Ethiopia, Cameroon, Sudan, Uganda, Zambia and Mozambique. Fig 5.30 presents development in Africa.

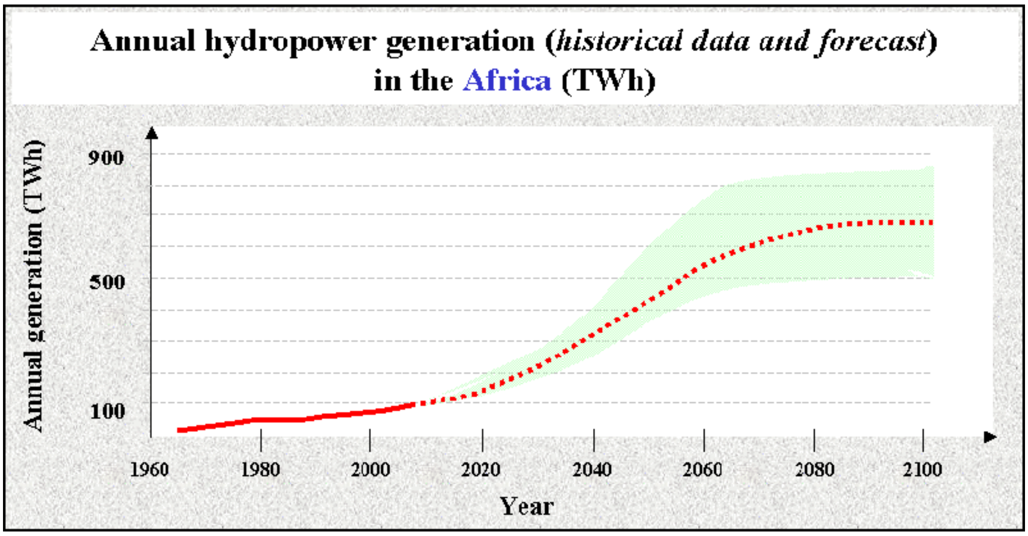


Figure 5.30: Annual Hydropower generation in Africa.

– **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. Fig 5.31 presents hydropower development in South and Central America.

– **Asia Pacific**: the growth will be mainly driven by China and India in the region. There will be also a significant increase in Mekong basin (Laos, Myanmar, etc.) and in Himalaya area (Bhutan and Nepal). Fig 5.32 presents hydropower development in Asia Pacific region.

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.

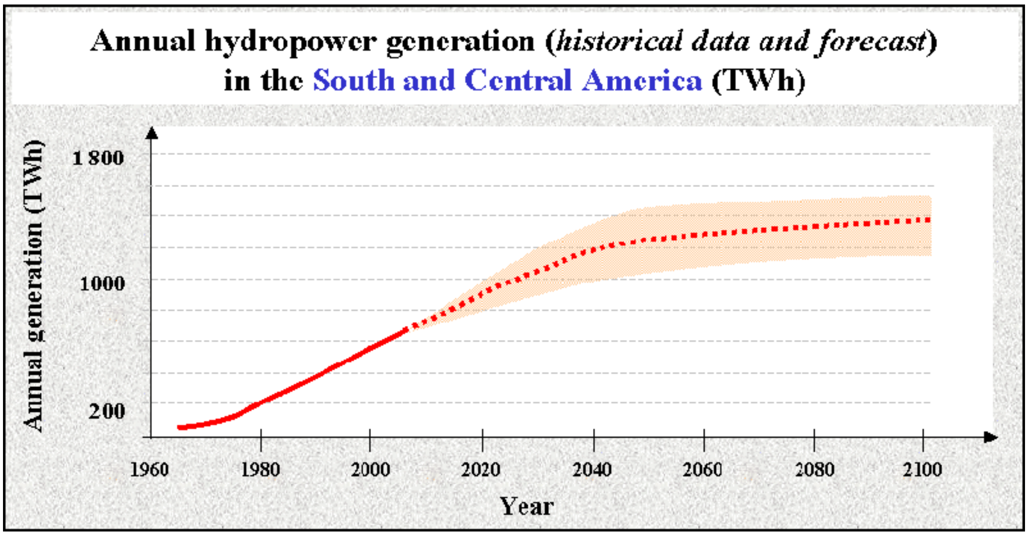


Figure 5.31: Annual Hydropower generation in South and Central America.

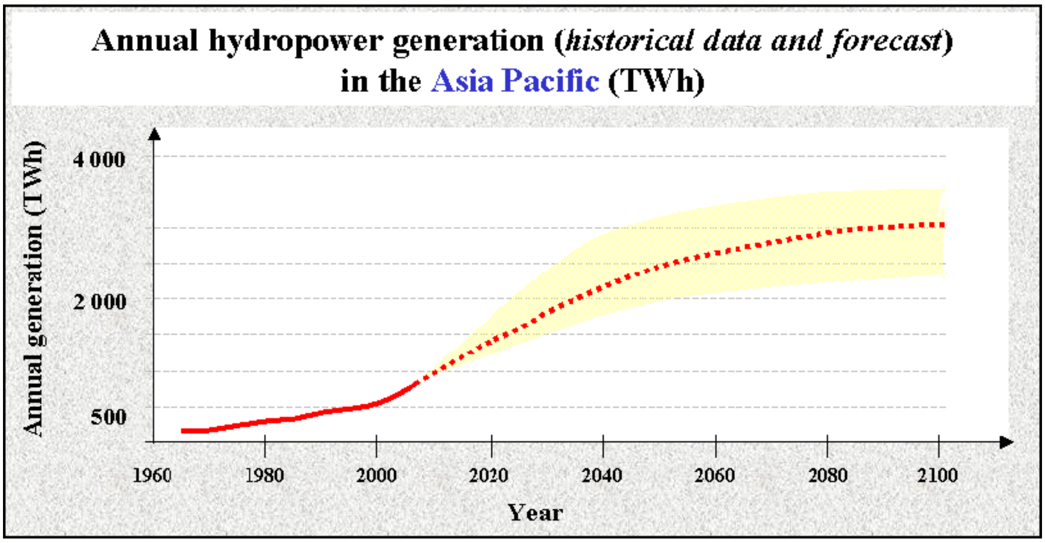


Figure 5.32: Annual Hydropower generation in Asia Pacific.

(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)

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 interbasin 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 WGIII AR4 (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 Multi-purpose 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 multi-purpose 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 multi-purpose 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.

Box 5.2: Multipurpose projects in China

China is now constructing more than 90 000 MW of new hydro, and much of this development is designed for multi-purpose utilization of water resources (Zhu *et al.*, 2008).

For the Three Gorges Project, as an example, the primary purpose of the project is flood control, and more than 50% of the reservoir capacity is used for flood control. Hydropower generation from 22 400 MW of installed capacity is second and navigation is the third main purpose of the project. It is estimated that 15 million people and 1.5 million hectares of farmland will be protected for up to 100 years floods (Zhu *et al.*, 2008).

Box 5.3: Integration between Hydropower, Water Management and Climate Change – The Case of Brazil (Freitas, 2009; Freitas *et al.*, 2009).

Given the uncertainties of the current climatologic models when predicting future rainfall patterns in the Brazilian and our transboundary drainage basins, the recommendations made here are concentrated above all on reducing the vulnerabilities already detected with a view to expanding and sustaining the generation of hydroelectric power in Brazil.

A. Possibilities to integration and conflicts between hydroelectric energy and other users of water resources. The occurrence of extreme events, such as droughts and floods, more often and more severely will increase conflict among water users in the various drainage basins of Brazil. In terms of hydroelectric enterprises specifically, the increase in demand for water resources – in absolute terms and in their various forms – will require a more profound knowledge of the area where those enterprises are, as well as constant supervision of generating conditions, and not only in the power plant or in the reservoir areas. Hydrological balance will have to become more precise, surveys regarding environmental and economic impacts will have to be more detailed, etc.

B. Possibilities to integration and conflicts between hydroelectric energy and other land uses. Demographic growth and expansion of occupation (organized or not) of Brazilian territory tends to increase the number of individuals affected by hydroelectric enterprises, who then gain political power when making their demands. This means the process of making a project viable and putting it into practice becomes an extremely critical stage, since it now depends not only on long-term financing but also on increasingly longer negotiations, with higher transaction costs and fewer guarantees of success.

C. Multiple and integrated management of reservoirs. The increase in frequency and intensity of extreme events, such as the anomalous warming phenomena of the Pacific (El Niño) and Atlantic Oceans, require a more flexible approach to the management of reservoirs, apart from the mere optimization of hydroelectric power generation. Measures must be taken to reduce the negative impacts and increase the benefits to the basin and to the users involved. Such measures are taken both at the moment when the decision is made to build the power plant as well as when deciding how to manage its reservoir, and as a consequence many social costs may finally be imposed on the generating company by the Government, a tendency already observed internationally.

D. New institutional and regulatory arrangements for the generation of hydroelectric power. Reducing vulnerability in hydroelectric enterprises requires above all a major acceptance of those enterprises by society. It has to be accepted that the complexity of the most recent projects is far greater than that observed until the 1980s, essentially due to changes in legislation. Today numerous institutional arrangements and political connections must take place before the decision is made to invest in the building of a dam, a hydroelectric power plant or a large thermal power generation.

E. Technological and economic opportunities in the electricity generating sector. The reduction of vulnerability in the generating sector of the Brazilian power grid depends strongly on integration with other sources of energy and enterprises on several levels. In other words, an additional challenge to be considered concerns the changes that have occurred in the generation industry itself, both in the technological and economic fields. Technical-economic paradigms, such as those of large power plants, have been strongly opposed for instance, and new business opportunities have arisen in the field of establishing and operating small power stations.

Box 5.4: Structural and Non-Structural Actions in the drainage basins and in the management of hydroelectric potential related to climate change and water management (Freitas, 2009; Freitas *et al.*, 2009)

Take into consideration the uncertainties of the stream flow projection models, as well as the vulnerability of drainage basins and the energy sector (and, consequently, of the whole Brazilian power grid) to climate change risks.

Structural actions

1. Building/modification of physical infrastructure
2. Removal of sediments from reservoirs
3. Transfers of energy and water between drainage basins (regional and continental integration).

Non-structural actions

1. Adaptable management of existent water provision systems
2. Changes in operational guidelines
3. Hydrological Cycle Management, in others words, joint use of atmospheric, surface and underground water
4. Integrating operating systems for reservoirs
5. Increasing space-time coordination between supply and demand of water and energy, that is, between drainage basins, energy systems and climatic seasonality, variability and vulnerability. Emphasis should be given to the following factors:
   - Water
     Consumption and non-consumption uses
   - Energy
     Renewable and non-renewable resources
   - Efficient use of energy

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 6

Ocean Energy

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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. [AUTHORS/TSU: ….]

Lenght

Chapter 6 has been allocated a maximum of 34 (with a mean of 27) pages in the SRREN. The actual chapter length (excluding references & cover page) of the original version (prior to TSU commenting and formatting) was 47 pages: a total of 13 pages over the maximum (20 over the mean, respectively).

Expert reviewers are kindly asked to indicate where the Chapter could be shortened in terms of text and/or figures and tables.

References

References of figures/tables are often missing. References from the text that are found missing in the reference list have been highlighted in yellow. In the same manner, references found in the reference list but missing from the text have also been highlighted.

Metrics

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

Figures

Pictures and figures will be replaced by equivalents with higher resolution where necessary.

Headings

The title of subchapter 6.2 was changed back from “Global Technical Resource Potential” to “Resource Potential” as approved by the IPCC Plenary.

Subheadings called “OTEC” have been changed into “Ocean thermal energy conversion”. Please make sure to introduce abbreviations again in each subchapter to allow for selective reading. Changes have been done by TSU accordingly.

Chapter 6: Ocean Energy

CONTENTS

EXECUTIVE SUMMARY

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 technologies for harnessing of ocean energy are probably the least mature of the six principal forms of renewable energy in this Special Report. 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. Whilst some potential ocean energy resources, such as osmotic power from salinity gradients and ocean currents, are globally distributed, other forms of ocean energy are distributed in a complementary way. Ocean thermal energy is principally distributed in the Tropics around the Equator (0° – 35°), whilst wave energy principally occurs between latitudes of 40° - 60°. Further some forms of ocean energy may be able to generate base load electricity, notably ocean thermal energy, ocean currents salinity gradients and, to some extent, wave energy.

Tidal rise and fall energy can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations. Most other ocean energy technologies are at an early stage of development and 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 energy technology 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 energy 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 generator technologies, there is presently no convergence on a single design for ocean energy 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, for instance, over 100 prototype wave and tidal current devices under development (US DoE, 2009). Whilst there are no markets presently buying ocean energy converters, 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 initiatives to support developments. These range from 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 north-western [TSU: "NW" replaced by "north-western".] European coastal countries lead development of ocean energy technologies with the North American, north-western [TSU: "NW" replaced by "north-western".] Pacific and Australasian countries also involved.

Environmental impacts of ocean energy converters can be forecast from maritime and offshore oil and gas industries. Increased numbers of widespread deployments will identify key environmental issues. Ocean energy technologies potentially offer fewer environmental risks and thus community acceptance than other renewable energy developments. [TSU: Sentence incomplete? Fewer environmental risks -> higher (?!) community acceptance]. The 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 energy technologies do not generate greenhouse gases in operation, so they can 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 $/kW) [TSU: US$ (2005)] and unit cost of electricity generated (in $/kWh) [TSU: US$ (2005)] 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 energy will form another energy/water supply option for countries seeking to reduce their GHG emissions to meet internationally agreed targets for such reductions.

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 contribution to the mitigation of climate change.

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,
- **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 (Bhuyan, 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). Waves grow into open ocean swells by constructive interference, the difference being that 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"). There is also an attractive wave climate within ± 30º of the Equator (where trade-winds prevail most of the year). The wave energy resource is lower here than in temperate areas but has lower 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). A map of the global offshore average annual wave power distribution 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).

The regional distribution of the theoretical annual wave power is presented in Table 6.1. These figures were obtained for areas where theoretical wave power (P) ≥ 5 kW/m and latitude ≤ ±66.5 º. The total annual wave power is 29,500 TWh, which represents a decrease of 8% when we compare with the total figure above.

Table 6.1: Regional Theoretical Wave Power (Mørk et al., 2010)

REGION	**WAVE POWER** (TWh)
West and North Europe	2748
Baltic Sea	34
Mediterranean Sea	324
Southern North Atlantic Archipelagos (Azores, Cape Verde, Canaria Islands)	970
North America Eastcoast	900
North America Westcoast	2325
Greenland	741
Central America	1496
South America Eastcoast	1777
South America Westcoast	2840
North Africa	354
West and Central Africa	673
South Africa	1555
East Africa	907
East Asia	1439
Southeast Asia and Melanesia	2481
West and South Asia	791
Asiatic Russia	1467
Australia and New Zealand	5028
Polynesia	555
TOTAL	29407

*) Areas with lat ≥ 66.56083°N and/or Pannual ≤ 5kW/m were not considered

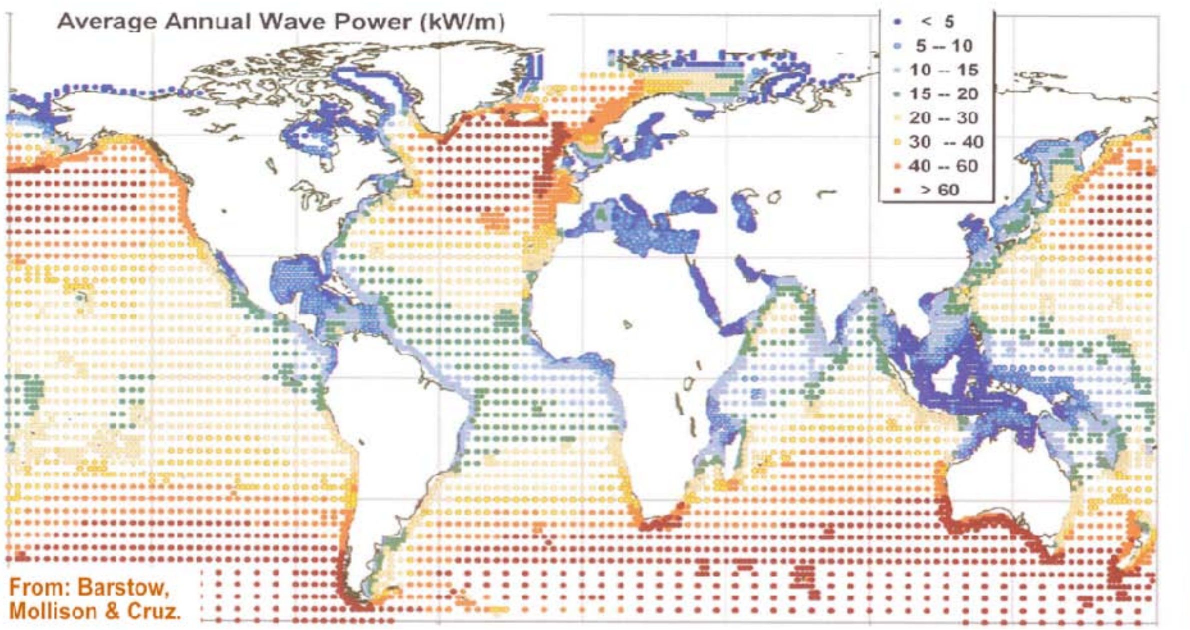


Figure 6.1: Global offshore annual wave power level distribution (Barstow, S., Mollison, D. and Cruz, J., in Cruz, 2008).

Seasonal variations are much larger in the Northern Hemisphere than in the Southern Hemisphere which is an important advantage not recognized yet (Figure 6.2).

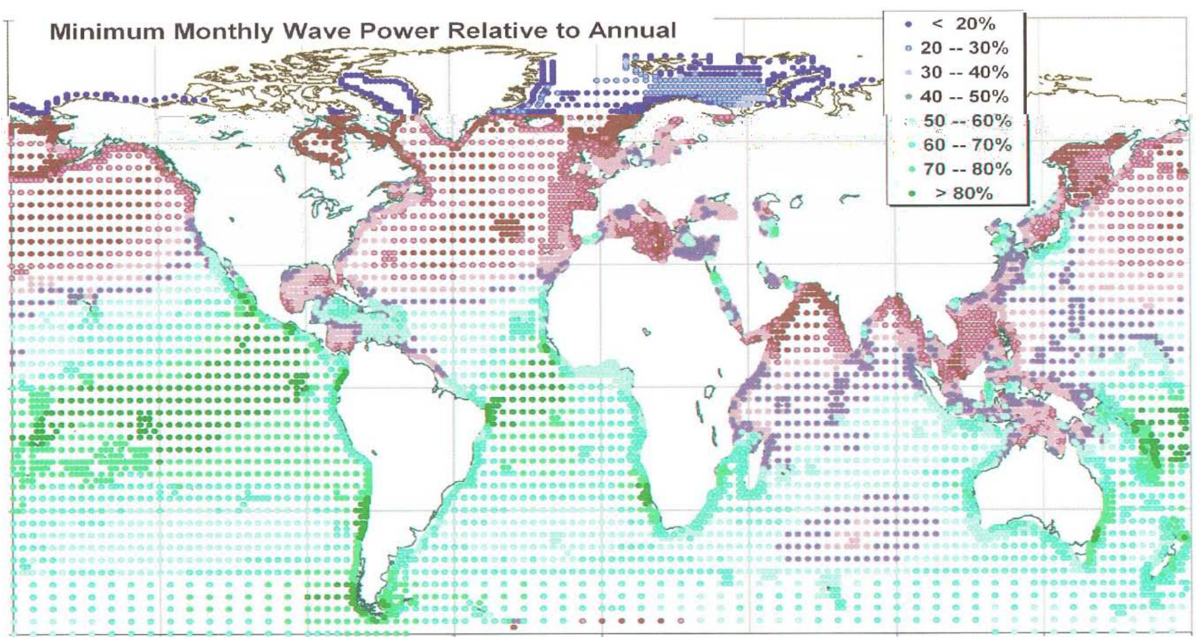


Figure 6.2: Minimum [TSU: monthly] wave power compared to annual [TSU: annual average or annual maximum?] (Barstow, S., Mollison, D. and Cruz, J., in *Cruz*, 2008)

In deep waters, waves travel for very long distances (i.e. tens of thousands of kilometres) with minimal energy dissipation. This has been recognized with swells generated in the Antarctica, Australia and New Zealand that have been observed in California (e.g. Khandekar, 1989). As open sea waves travel towards the shore, when the water depth (*h*) becomes less than half the wavelength, the start to undergo transformations due to frictional interaction with the seafloor

(Lighthill, 1978). The waves start to grow in height and, due to refraction (similar to the optical phenomenon), wave crests tend to become parallel to the bathymetric contours. This, in turn, leads to [TSU: Word "to" was added.] energy concentration in convex zones (e.g. close to capes) and dispersion in concave zones (e.g. in bays). Another cause of resource modification in coastal areas is shelter by neighbouring islands or by the coast itself. As the depth further decreases an early simplified formula states that waves start to break (thus dissipating their energy), when wave height $H < Kh$, with the constant K having values between 0.79 and 0.87 (Sarpkaya and Isaacson, 1981). Another cause of energy dissipation is bottom friction that 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 have lost half of their energy between offshore deep water and water depths of 42 m (Mollison, 1985).

Wave information comes mainly from two sources:

1. Data obtained from in-situ measurements, and

2. Remotely-sensed data, e.g. from satellite altimeters

The results of numerical wind-wave modelling have become increasingly accurate. In situ data are obtained by a number of measuring devices, their selection depending on local conditions (namely water depth) and existing structures. Wave measuring buoys are the systems most used for water depth larger than 20 m (see Allender et al., 1989 for a comprehensive evaluation of directional wave instrumentation). For shallower depths seabed-mounted probes (pressure and acoustic) are used. When offshore structures are available (e.g. oil/ gas platforms) measurements by capacity/resistive probes or down-looking infra-red and laser devices are available.

Note that in situ measurements are made at the point where the sensor is located, whereas remotely sensed measurements, using land- or satellite-based radar systems, integrate information from an area.

Satellite-based altimeters make measurements along track, which can be combined to provide global coverage. They have operated since 1991 and presently three satellite-based altimeters are in operation. These are the ENVISAT (European Space Agency), JASON (National Oceanic and Atmospheric Administration) and Geosat Follow-on (GFO; US Navy). Altimeters provide measurements of significant wave height (H_s) with accuracy similar to wave buoys; analytical models to obtain wave period from altimeter data also provide accurate data (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) provides directional spectra that are becoming increasingly accurate, although they are not useful yet for wave energy resource mapping (Pontes et al., 2008). Numerical wind-wave models that compute directional spectra over the oceans, taking as input wind-fields provided by atmospheric models, are by far the largest source of wave information. The WAM model (The WAMDI Group, 1988 and Komen et al., 1994) running at global and regional scales at ECMWF (European Centre for Medium-Range Weather Forecasts, UK) provides high quality wave results. Other institutions run the WaveWatch III (WWIII; Tolman, 2006) model, e.g. NOAA/NCEP, and the UK Meteorological Office model (The Met Office, 2009).

Different types of wave data 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, shoreline geometry, Coriolis acceleration and atmospheric pressure. Within a tidal system there are points where the tidal range is nearly zero (amphidromic points). 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 of the 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 a useful background reference on tidal theory.

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, 13.5m 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.

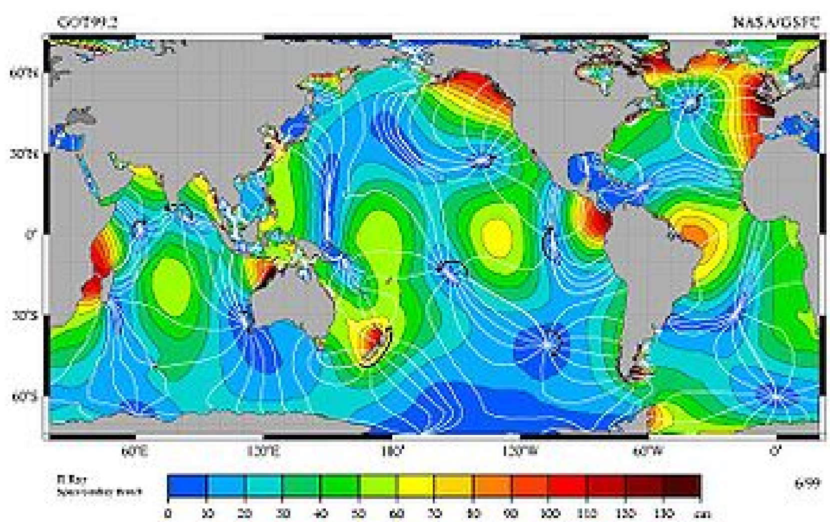


Figure 6.3 - TOPEX/Poseidon: Revealing Hidden Tidal Energy GSFC, NASA. The M2 tidal constituent, the amplitude indicated by color. The white lines are cotidal lines spaced at phase intervals of 30° (a bit over 1 hr).The amphidromic points are the dark blue areas where the lines come together (Ray et al., 2009 [TSU: figure will be replaced with ones with higher resolution. text in figure caption unclear]

Because tidal rise and fall result from astronomical effects, these can be forecasted with a high level of accuracy centuries in advance, although the resultant energy is intermittent. There is therefore little or no hydrological risk associated with devices producing electricity from tidal rise and fall. This is a significant advantage when compared to conventional hydro, to wind or to solar energy.

Conventional tidal rise and fall power stations will generate electricity only at certain times during the tide cycle. The average plant factor observed at power stations in operation varies from 25% to 35% (Charlier, 2003).

It has been estimated that the world 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 the tidal rise and fall is uncertain but, in the worse case, sea level rise should only result in translation of the mean ocean level, with possible impacts linked to the change in shoreline, and not to changes in tidal range.

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. These currents depend on the sinusoidal variation of various tidal components, operating on different cycles, although these flows can be modified by short-term weather fluctuations. Some coasts have single daily tides, whilst others have two tidal cycles per day (i.e. semi-diurnal tides). The potential power of a tidal current is proportional to the cube of the current velocity. For nearshore currents, i.e. in channels between mainland and islands or in estuaries, current velocity varies approximately sinusoidally with time, the period being related to the different tidal components. As a rule of thumb potentially commercially attractive sites require a minimum average sinusoidal current velocity in excess of 1.5 m/s. Below that value (1.0 – 1.5 m/s) evaluation should be on a site-by-site basis. For non-oscillating currents, the maximum current velocity should exceed 1.0 m/s, whereas in the range 0.5 to 1.0m/s its practical exploitation depends on site evaluation.

In the United States a methodology for the assessment of tidal current energy resource has been proposed (Hagerman et al., 2004). 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 the tidal energy resource is of special interest for the UK, Ireland, Greece, France and Italy. A total of 106 promising locations were identified and it was estimated that, using present-day technology, these sites could supply 48 TWh/yr 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 predictability of marine currents and the potential [TSU: potentially] high load factor (20-60%) are important positive factors for their utilization. Sites with pure tidal flow in most cases offer capacity factors in the 40-50% range. For non-tidal flows this range increases to the order of 80%.

6.2.4 Ocean Currents

In addition to oceanic currents associated with tidal flows in coastal regions, there is also significant current flow potential in the open ocean. The large-scale circulation of the oceans is concentrated in various regions – notably the western boundary currents associated with wind-driven circulations – some of which 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 off East Asia, the East Australian Current, and the Gulf Stream off eastern

North America (Figure 6.4). Other current systems may also prove feasible with improvements in turbine efficiencies. The most well-characterized of these systems is the Gulf Stream, and it is discussed here as a promising case study.

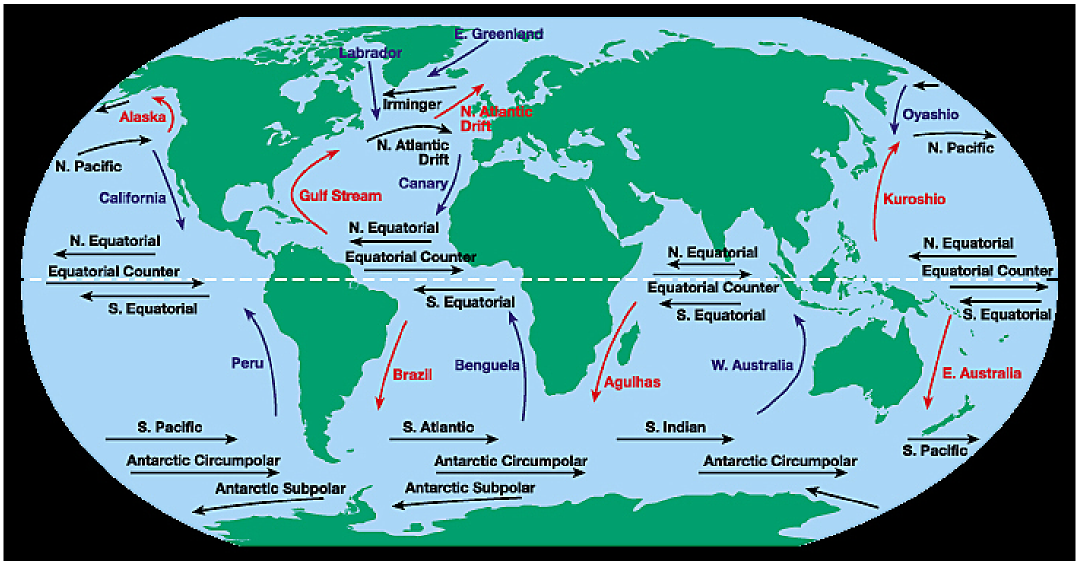


Figure 6.4: Surface ocean currents, showing warm (red) and cold (blue) systems (Windows to the Universe, 2009).

The potential of the Florida Current of the Gulf Stream system for power generation was recognized decades ago at the "MacArthur Workshop" (Stewart, 1974). Although the workshop concluded that the opportunity to generate electrical power from the Florida Current's ~25 GW potential was worth exploring, its recommendations have languished, during which time various oceanographic measurement programs provided additional useful background on the possibilities (e.g. Raye, 2001).

Cross-sections of the current show a core current region 15 - 30 km off the Florida coast and near the surface (Figure 6.5). This core region, although variable, 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 (e.g. Niiler and Richardson, 1973; Johns et al., 1999).

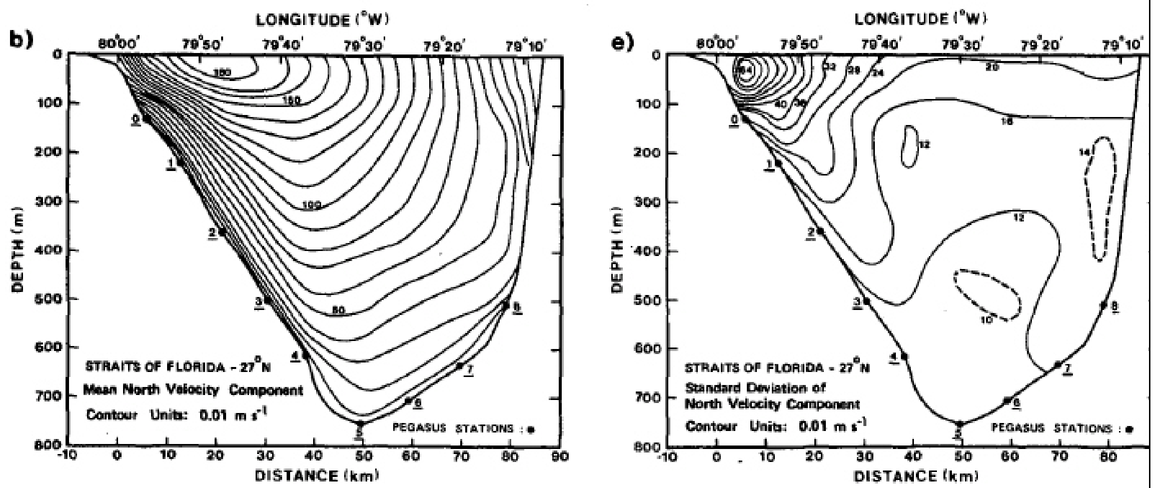


Figure 6.5: Averaged W-E cross-section of northward current in the Florida Straits at 27°N, 1982-1984 (left) and its standard deviation (right). Peak averaged velocity is >1.8 m s^{-1}. Near-shore eddies are the large, near-surface signal in the standard deviation. The flow inside the 180 cm s^{-1} contour represents about 3.5 GW (Leaman et al., 1987).

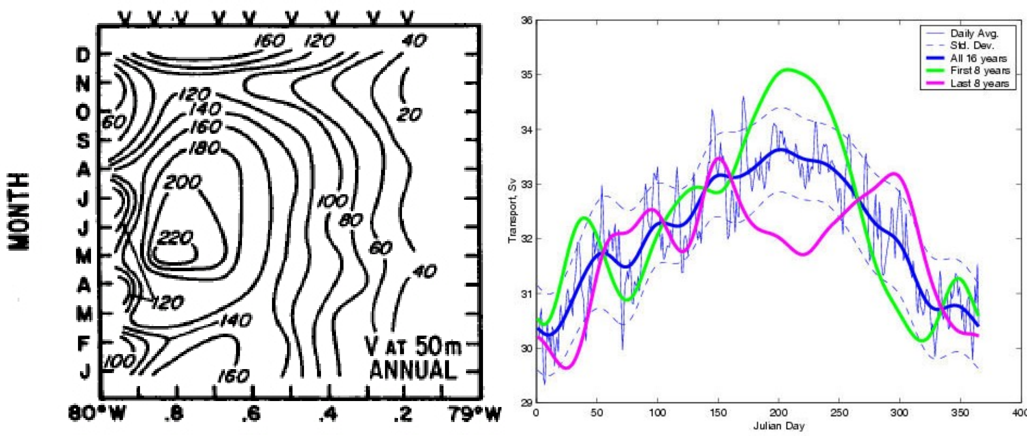


Figure 6.6: Left: Contours of 50-m northward current at 27°N in the Florida Straits, 1982-1984, in cm s^{-1} (Leaman et al., 1987). Right: Channel-integrated transport, 10^6 m^3 s^{-1} (=Sv), showing daily and interannual variability of annual cycle (Baringer and Larsen, 2001). 16 years of data as reproduced at NOAA website.

Figure 6.6 shows (left) the 50-m variability on the annual time scale (for the two years of the Leaman et al. data), and (right) longer-term variations of the system's overall transport. Note that the summertime peak flows are in phase with electrical load demand in South Florida population centers. [TSU: captions of figure 6.6 is doubled]

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 can contribute to base load power supply, substituting this way large quantities of fossil fuel now employed to generate power.

OTEC potential is considered to be much larger than the other ocean energy types (UNDP, UNDESA, WEC, 2000), and also it has ample distribution of the resource throughout the whole world between the two tropics, although experimental and pilot devices are rare and there is no current commercial exploitation.

From the total solar input received by the oceans, only 15% is retained as thermal energy. Since the intensity falls exponentially with depth, the absorption is concentrated at the top layers. Typically in the tropics, surface temperature values are in excess of 25 °C, whilst 1 km below, the temperature is between 5-10°C.

As the warmer (and hence lighter) waters are at the surface, there are no thermal convection currents going up and down, and due to the very low temperature gradients, heat transfer by conduction is negligible. So with neither of the major mechanisms of heat transfer operating, a stable system results: the surface layers remain warm and deeper layers remain cold; thus the system of both layers is like a practically infinite heat source (top layers) and a practically infinite heat sink (deep layers) with a separation of about 1,000 m between them, that occurs naturally and allows the use of heat engines. This temperature difference varies with latitude and season, with the maximum at tropical, subtropical and equatorial waters. Hence in general, the Tropics are the best locations for OTEC systems, as Claude demonstrated with his experiment in Matanzas Bay, Cuba, in 1930.

There is general agreement that the sea water minimum temperature difference of 20° C should be available to operate an OTEC power cycle. Both coasts of Africa, the tropical west and southeastern coasts of the Americas and many Caribbean and Pacific islands are situated where sea water decreases from a surface temperature of 25-30° C to 4-7° C at depths varying from 750 to 1,000 m. An optimistic estimate of the global resource is 30,000 to 90,000 TWh (Charlier and Justus, 1993).

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 difference is generally considered adequate for OTEC (Figure 6.7). Almost everywhere in the Equatorial zone there is [TSU: The verb "has" has been replaced by "there is".] potential for installing OTEC facilities. Countries, which have the OTEC resource within one mile from their shores, could potentially construct the onshore facilities at considerably reduced costs (UN, 1984). A number of Pacific and Caribbean islands could thus potentially take advantage of OTEC (UN, 1984).

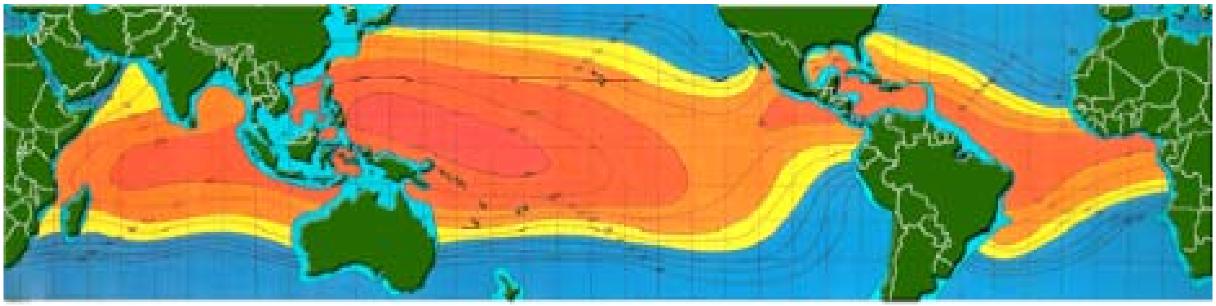


Figure 6.7: OTEC Resource Map (Lockheed-Martin, 2009). [TSU: legend is missing]

Ocean thermal energy conversion is essentially a heat exchange process. However, significant amounts of heat are injected into the ocean from submarine volcanic activity as oceanic spreading ridges. Hydrothermal vents, called 'black smokers', produce plumes of superheated water (c. 350° C) with entrained sulphide minerals, containing gold, silver, copper, lead, zinc and rare earth elements. Most oceanic spreading ridges usually occur at considerable depths (c. 2,000 m) but some, such as in the Gulf of California and the Tonga-Kermadec Arc, north of New Zealand, have submarine geothermal systems at much shallower depths. These shallower resources may be accessible as a form of 'extreme' ocean energy thermal energy conversion (Alcocer and Hiriart, 2008).

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 volumes of both 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.

A number of other factors must also be considered in defining the local potential for an osmotic power plant. These are:

- River water volume regime, especially low flow periods
- Salinity differences between the freshwater and sea water
- Freshwater and sea water quality, due to the risk of fouling of the membranes
- Characteristics of the membrane and the membrane element used, particularly its ability to withstand fouling by polluting substances
- Physical and chemical conditions at the site (usually a river delta or estuary).

These factors will be essential to determine whether the development of a commercial Pressure Retarded Osmosis (PRO) power plant is economically viable (see Section 6.3.6).

Other environmental factors may also be taken into consideration:

- Lateral river migration may be a challenge in some areas, as river channels are not always stable systems
- Erosion and deposition of particulate material may cause the channel to change its form and pathway over time. Typical areas where this occurs are areas subject to significant land use changes, areas with heavy erosion processes, or areas where the downstream parts of rivers run through low-lying land without erosion protection works.

Any installations in estuarine/delta areas should therefore be preceded by environmental assessments, in order to determine the risk for channel migration.

The global generation capacity potential for osmotic power generation has been calculated as 2.6 TW (Wick and Schmitt, 1977). More recently, 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.

Since osmotic power will effectively generate baseload electricity, this form of generation could make a considerable contribution to security of supply, portfolio diversity and grid strengthening.

6.3 Technology and Applications

6.3.1 Introduction

This section describes the state of the technologies used to extract energy from the five [TSU: Ocean and tidal currents are treated separately in section 6.2. but counted as one here] primary ocean energy [TSU: "energy" added.] resources described in section 6.2. Ocean energy may be the least advanced both in terms of technology developments and deployment of all the renewable energy sources covered by this report. The technologies described in this section range mostly from the conceptual stage to the prototype stage, but 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 (which utilize the experience of the hydro-electric industry), there has been relatively [TSU: The adjective is missing?] convergence, due to a fundamental lack of operating experience. In spite of their nascent development, ocean energy technologies show great promise beyond the near-term, in light of the abundant globally distributed resources. 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. Consequently, the success of ocean energy technologies does not depend on any new or major technological breakthrough. Most technology development is focused on the application of basic hydrodynamic principles to engineer new energy extraction and conversion systems. In addition, much of the technological uncertainty can be reduced to more routine questions of cost and reliability.

6.3.2 Wave Energy

There is a wide variety of wave energy technologies representing a range of operating principles that 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 (heaving, surging, pitching, and hydrostatic pressure), as well as water depth and distance from shore (shoreline, near-shore, offshore). Wave energy can be resolved into two forms – potential energy, caused by gravity, and kinetic energy, caused by the water motion. The energy can be resolved into three components:

- Heave – the vertical component caused by gravity
- Surge – the horizontal component
- Pitch – the rotation component of any wave

Devices have been designed to capture one or more of these components, so there are generic designs that seek to extract energy from heave, from surge and from combinations of all three components.

Recent reviews have identified over 50 wave energy devices at various stages of development (Falcão, 2009; Khan and Bhuyan, 2009 and DoE, 2009 (Figure 6.8)).

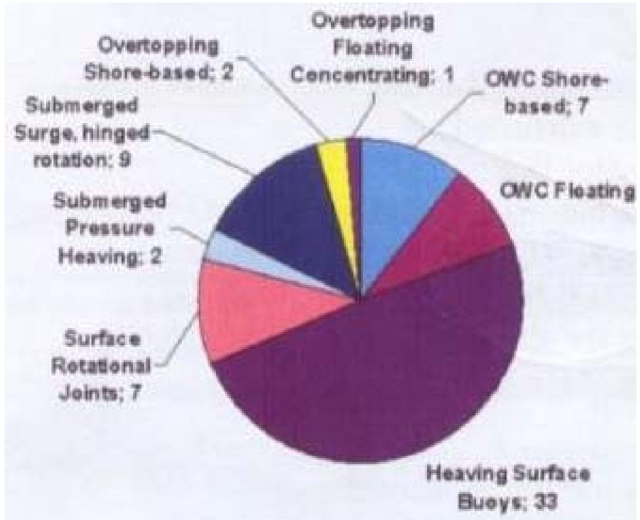


Figure 6.8: Breakdown of wave device types [TSU: Please insert source. Consistency with figure 6.9?]

The dimensional scale constraints of wave devices have not been fully investigated in practice, but the dimension of wave extraction 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. As a result large-scale electricity generation from wave energy will require large arrays of modular devices, rather than increasing scale devices.

Several methods have been proposed to classify wave energy systems (e.g. Falcão, 2009, Khan and Bhuyan, 2009 and DoE, 2009). The classification systems like the Falcão system (Figure 6.9) 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.

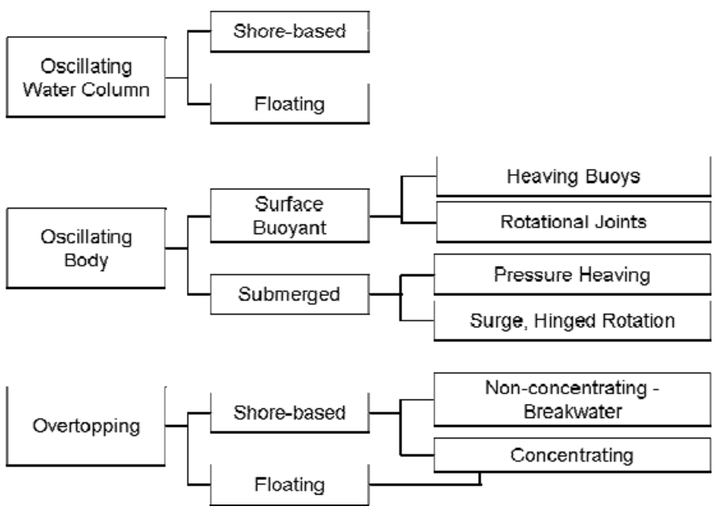


Figure 6.9: Wave energy technologies – Classification based on principles of operation (Falcão, 2009).

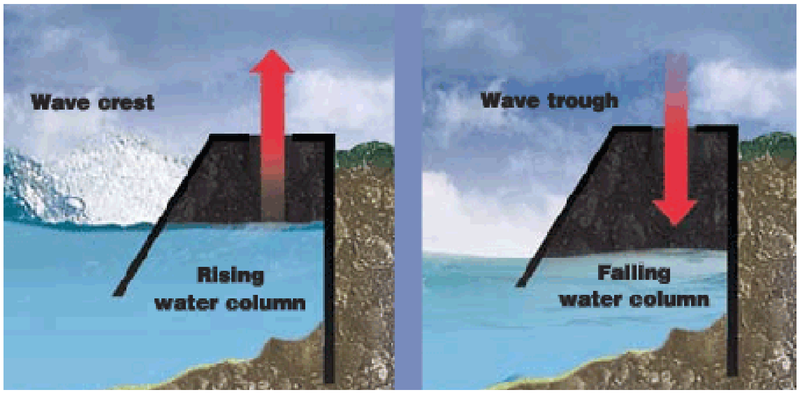
Oscillating water columns [TSU: Please consider using level 4 heading] – Oscillating water column (OWC) are wave energy converters that use wave motion to trap a volume of air and compress it in a closed chamber, where it is exhausted at high velocity through a specialized ducted air turbine coupled to an electrical generator that efficiently converts the kinetic energy of the moving air into electric energy. When the wave recedes, the airflow reverses and fills the chamber, generating another pulse of energy (Figure 6.10a). The turbine is a self-rectifying turbine, generally a Wells turbine (Figure 6.10b). An OWC device can be a fixed structure located at the shore, bottom-mounted in the nearshore or a floating system moored in deeper waters. Shore-based OWC devices can be cliff-mounted or part of a man-made breakwater. Generically, such devices are referred to as 'terminator' devices, as they terminate the wave.

Oscillating-body systems [TSU: Please consider using level 4 heading] – Oscillating-body (OB) wave energy conversion devices use the incident wave motion to induce differential oscillating motion between two bodies of different mass, which motion is 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 (Figure 6.11). 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. Generically, these devices are called 'attenuators', because they attenuate the incident wave energy without terminating it.

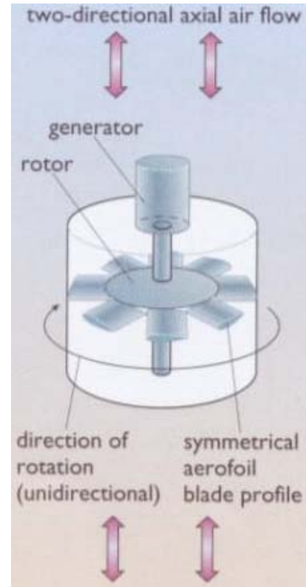
Some OB devices are fully submerged and rely on oscillating hydrostatic pressure to extract the wave energy. An oscillating buoyant part is forced down by increasing hydrostatic pressure under a wave crest and up as the pressure decreases under the wave trough with captured interior air acting as a pressure spring. Pitch and surge forces can also be used to induce motion in another form of oscillating device.

Overtopping devices [TSU: Please consider using level 4 heading] - 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, Figure 6.12. These systems can be offshore floating devices or incorporated in shorelines or man-made breakwaters.

Power Take-off devices [TSU: Please consider using level 4 heading] - In most cases, the converted kinetic energy or potential wave 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 the energy quality to the grid. In practice, some method of short-term energy storage (durations of seconds) may be needed to smooth the energy delivery. Optimal wave energy absorption involves some kind of resonance, which implies that the geometry, mass, or size of the structure may be linked to wave frequency.



(a): Chambers Under Wave Action



(b): Wells Turbine

Figure 6.10: Oscillating Water Column

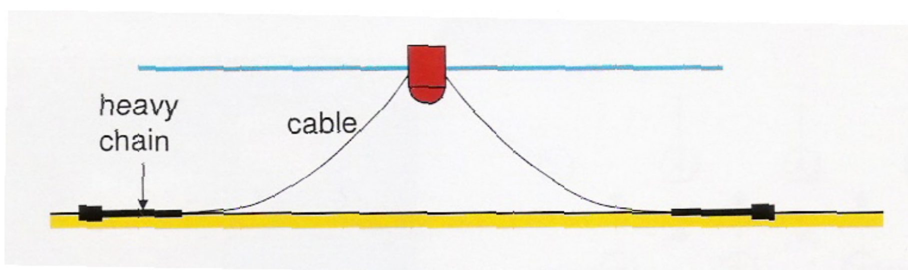


Figure 6.11: Oscillating-Body System

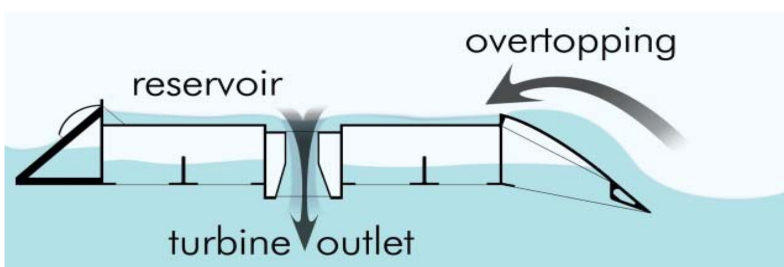


Figure 6.12: Overtopping Wave Terminator

[TSU: Please add sources for figures 6.10, 6.11 and 6.12.]

6.3.3 Tide Rise and Fall

Historically the development of tidal rise and fall hydropower has been based on estuarine developments, where a barrage encloses an estuary, which creates a single reservoir (basin) behind it and incorporates generating units. More recently, barrage configuration has moved to 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 offer advantages over normal schemes in that generation availability can be adjusted with high flexibility, such that it is possible to generate almost continuously. In typical estuarine situations, however, two-basin schemes are very expensive to construct due to the cost of the extra length of barrage. There are some favorable geographies, however, which are well suited to this type of scheme, such as very shallowly shelving coastlines, like the Severn Estuary in southwest [TSU: "SW" has been replaced by "southwest"] England.

The most recent advances focus now on offshore basins (single or multiple), located away from estuaries, which offer greater flexibility, in terms of capacity and output, with little or no impact on delicate estuarine environments. These are called 'tidal lagoons' and rely on the construction of a multi-basin structure. Water is passed between the three basins to allow for continuous electricity generation (Figure 6.13).

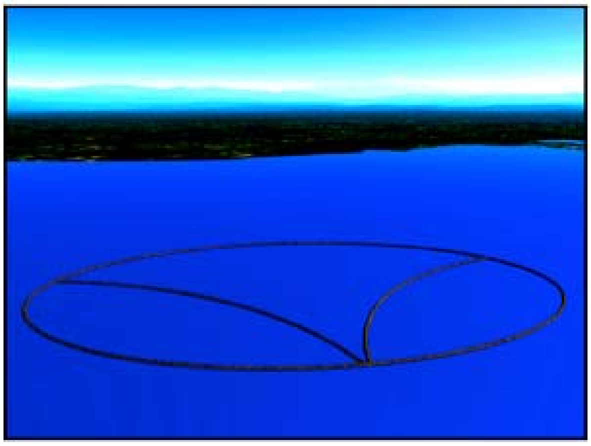


Figure 6.13: TidalElectric's proposed 3-pool Tidal Lagoon (www.tidalelectric.com) [TSU: status of source?]

The conversion mechanism most widely used to produce electricity from tidal rise and fall is the 'bulb-type' unit. A bulb-type unit is a hydroelectric power unit installed in a duct with its centreline coinciding with the flow axis (Figure 6.14). Usually, these units only generate in one direction - either the ebb or flow (simple effect) - and are passive when the tidal flow reverses. In some locations, such as La Rance, the units can generate in both directions (double effect) and may also offer the possibility of pumping, when the tide is high in order to increase the storage in the basin under a low head and with a high efficiency.

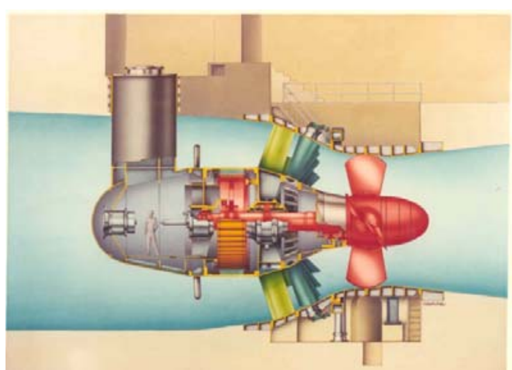


Figure 6.14: Cross section of a bulb unit bay at La Rance, France (courtesy EDF) [TSU: status of source?]

Bulb technology may be improved, for instance with gears allowing different rotation speeds for the turbine and the generator or with variable frequency generation allowing better outputs for the various operating ways and heads. For important schemes and average tidal range between 4 and 8 m, the usual unit capacity will probably be between 20 and 50 MW.

Other types of units have been installed at the 20 MW Annapolis tidal power station in Canada (Figure 6.15)) and in the 1.5 MW Kislaya Guba prototype tidal power station in Russia (orthogonal units). Those new types seem to offer an attractive solution in terms of simplicity, equal efficiency in both directions and cost reduction but have not yet proven their industrial viability.

Figure 6.15: 20 MW tidal power plant at Annapolis Royal, Nova Scotia, Canada. [TSU: Please add source]

Control gates are usually installed in order to facilitate filling or emptying of the basin in order to improve power generation performance and turbines may be used for pumping (as well as generation) to improve storage. The problem of corrosion due to salt water has been solved at the La Rance power station by relying on induced current cathodic protection and by using special materials, surface treatment or electrochemical system. These methods have been applied to units, pipes and gates.

Power plants may be built in situ within cofferdams or pre-fabricated in caissons (steel or reinforced concrete) and floated to site. The caisson solution is particularly adapted to remote sites: caissons with several turbines totalling 200 MW may be used (e.g. at the Sihwa Barrage in the Republic of Korea).

As for embankment dams, the choice of solutions is linked with availability of nearby materials. The underwater parts of barrages may be constructed from sandy materials, often available by dredging in tidal areas. The upper part may use rock fill or pre-fabricated reinforced concrete caissons. Waterproofing may use grouting or diaphragm walls. The necessary waterproofing is not always as perfect as for high onshore dams, because the water head is relatively low and some leakage economically acceptable.

6.3.4 Tidal and Ocean Currents

Technology to extract kinetic energy from tidal, river, and ocean currents are under development, but tidal energy converters are the most common to date. The main difference between tidal and river/ocean current turbines is that river and ocean currents flow in a single direction while tidal turbines reverse flow direction two or four times per day during ebb and flood cycles. Flow reversals provide convenient slack-water periods when installation, service, and inspections can take place.

Several methods have been proposed to classify tidal and ocean current energy systems (Khan et al., 2008; US DOE, 2009 (Figure 6.16)). Usually, they are classified based on the principle-of-operation. Examples of axial flow turbines, (Van Zwieten et al., 2006a; Verdant, 2009), cross flow turbines (Li and Calisal, 2010; Ponte Di Archimede, 2009) and reciprocating devices (Bernitsas et al., 2006) are also shown in Figure 6.17.

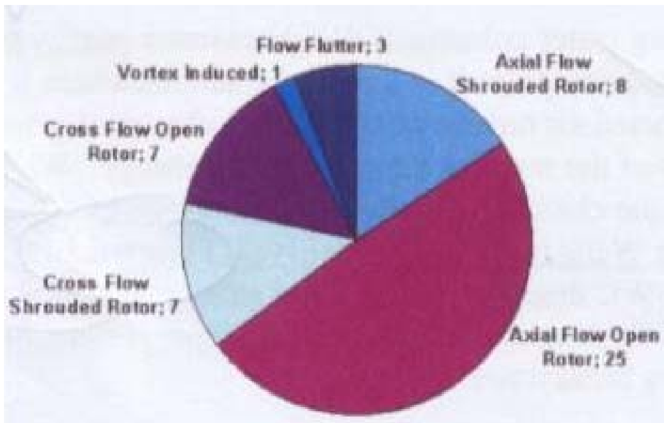
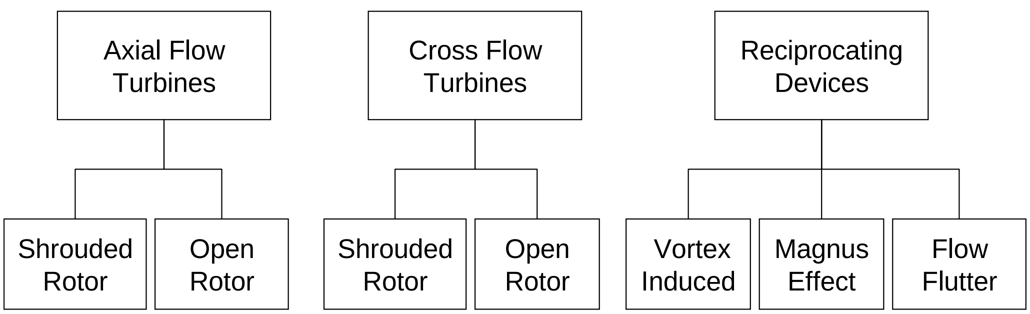


Figure 6.16: Breakdown of tidal and ocean current device types. [TSU: Please insert source. Consistency of naming with figure 6.17?]



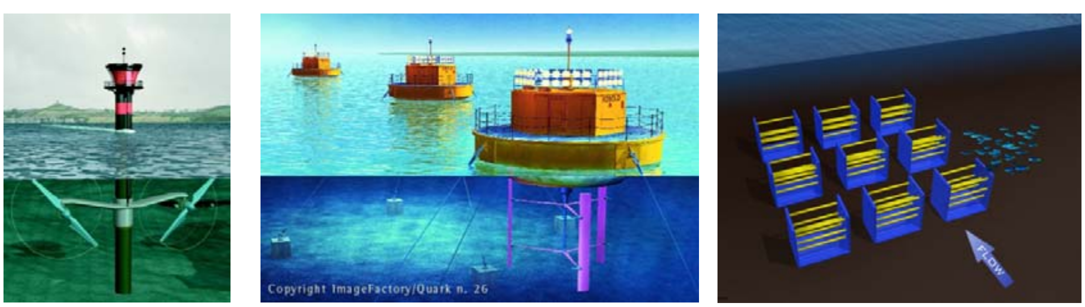


Figure 6.17: Current tidal and ocean energy technologies, classification chart is based on principles of operation with examples of illustrations showing, from left to right, axial flow turbines (courtesy of Mr. Fraenkel) [TSU: status of source?], cross flow turbines (courtesy of Professor Coiro) [TSU: status of source?]and vortex shedding induced vibration reciprocating device (courtesy of Professor Bernitsas) [TSU: status of source?].

Many of the water current energy conversion systems resemble wind turbine technology, but marine turbines must also account for reversing flow, cavitation, and harsh underwater marine conditions (e.g. salt water corrosion, debris, fouling, etc). Axial flow turbines have been widely proven in wind turbines with extraction efficiencies of 45% to 50% based on the total kinetic energy. Although there are offsetting benefits, cross flow rotors are slightly less efficient than axial flow machines with target efficiencies of about 40%. Axial flow turbines in tidal flows must respond to reversing flow directions while cross flow turbines can accept flow direction changes without a mechanical response. Generally, axial flow turbines are designed to change the yaw position of the nacelle 180 degrees in response to tidal flow reversals, or alternatively, the rotors are designed to accept flow from two directions with a fixed yaw position, but with some performance penalty.

Several axial flow and cross flow designs incorporate shrouds (also known as cowlings or ducts) around the outer diameter of the rotor (e.g. Lunar Energy, 2009; Clean Current 2009; Bluenergy 2009). Shrouds can help improve hydrodynamic performance by increasing the velocity of the flow through the rotor and reducing tip losses, but the cost of the shroud may be offset by the additional energy capture. Also, since shrouds encircle the outer path of the blade tip, they could provide some protection against impacts with marine life, although no evidence yet exists to suggest that this is a significant problem or that a shroud would reduce impact frequency. The cost effectiveness and ancillary benefits of shrouded water current turbines have not yet been fully evaluated and further testing and analysis is still needed. 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 essentially the same basic technology as doing so in tidal flows, but some of the infrastructure involved will differ. In particular, for deep-water applications, fixed bottom support structures will be replaced with mooring lines and anchor systems, and neutrally buoyant turbine/generator modules will be required or the systems will be attached to other structures, such as an offshore platform (Van Zwieten et al., 2006a; Ponte Di Archimede, 2009). 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., 2006b; Venezia and Holt, 1995; Raye, 2001). In addition, open ocean currents will not pose a restriction to the rotor size 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) that 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.

6.3.5 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) plants are based in three possible types of cycle for the conversion scheme: open, closed and hybrid (Charlier and Justus 1993).

In the open conversion cycle, sea water is used as the circulating fluid and the warm surface water is flash evaporated in a partial vacuum chamber. The produced steam passes through a turbine, generating electricity, before which it is cooled in a condenser by using cool water pumped from the sea bottom. Using a surface condenser, desalinated water is obtained as an additional output.

Closed conversion cycle is believed to present the best solution in terms of 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. Warm sea water from the ocean surface is pumped through heat exchangers where the secondary working fluid is vaporized, causing a high pressure vapor to drive a turbine. The vapor flows to a surface condenser to return to the liquid phase, cooled by cool sea water. In the closed cycle turbines are reduced in size compared with open cycle turbines, because of the higher operating pressure associated with the secondary working fluid. A schematic OTEC closed conversion cycle is shown in Figure 6.18.

The 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.

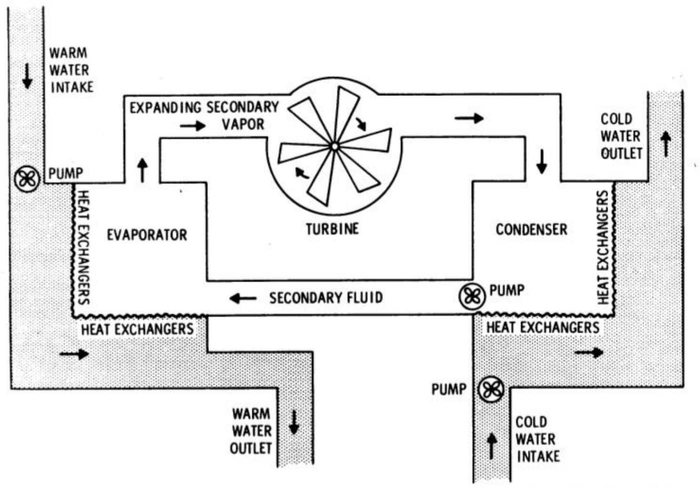


Figure 6.18 : Diagram of a closed cycle OTEC plant , National Science Foundation (Charlier and Justus, 1993).

6.3.6 Salinity Gradient

It has been known for centuries that the mixing of freshwater and seawater releases energy and so a river flowing into a saline ocean releases large amounts of energy (Wick and Schmitt, 1977). 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).

[TSU: Use of level 4 subheadings?]

The Reversed Electro Dialysis (RED) process is a concept where the difference in chemical potential between two solutions is the driving force. To utilise this concept, the concentrated salt solution and freshwater are brought into contact through an alternating series of anion and cation exchange membranes as shown in Figure 6.19.

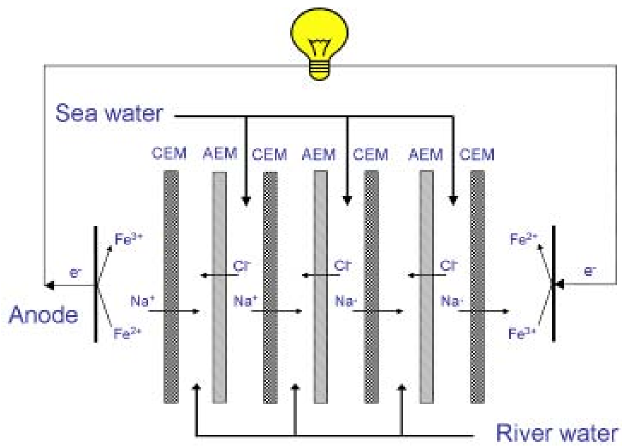


Figure 6.19: Reversed Electro Dialysis (RED) [TSU: Please add source.]

The chemical potential difference generates a voltage over each membrane and the overall potential of the system is the sum of the potential differences over the sum of the membranes. This concept is under development in the Netherlands and there are preparations for the first prototype to be built (Groeman and van den Ende, 2007).

Pressure Retarded Osmosis (PRO), also known as Osmotic Power, is a process where the chemical potential is exploited as pressure as shown in Figure 6.20. This was first considered by Professor Sidney Loeb in the early 1970s (Loeb and Norman, 1975).

The osmotic power process utilises naturally occurring osmosis, caused by the difference in concentration of salt between two liquids (for example, sea water and fresh water). Sea water and fresh water have a strong force towards mixing, 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 the salt concentration of seawater.

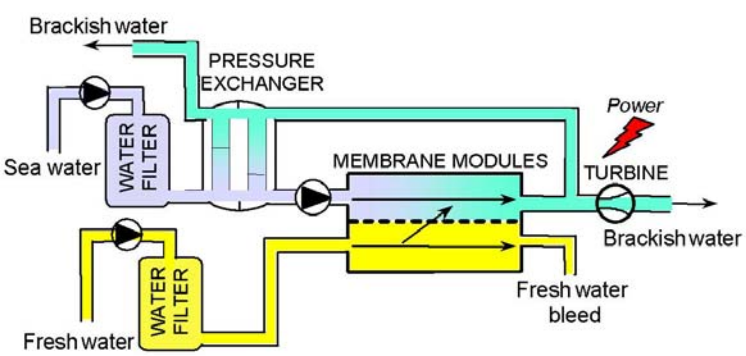


Figure 6.20: Pressure Retarded Osmosis (PRO) process (Scråmestø, Skilhagen and Nielsen, 2009).

In a PRO system filtered fresh water and sea water are fed into the system. Before entering the membrane modules, the seawater is pressurized to approximately half the osmotic pressure, about 12 - 13 bars. In the module freshwater migrates through the membrane and into pressurized seawater. This results in an excess of diluted and pressurised seawater (brackish water), which 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, and the remaining part passes through a pressure exchanger in order to pressurize the incoming seawater. The effluent from a plant will be principally brackish water, which 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

Presently, the only commercial ocean energy technology available is the tidal barrage, of which the best example is the La Rance Barrage in northern France. Tidal barrages effectively use conventional hydroelectric generating equipment but extract power from tidal flows in estuarine environments. Tidal barrages are usually large, very capital-intensive constructions, which require other uses to justify development. These other uses may include communication access, facilitating regional development, such as at the La Rance project in northern France or alleviation of environmental problems, such as at Sihwa in Korea.

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.

Khan and Bhuyan (2009) reviewed the number of ocean energy systems under development so far. What is telling is not only the number of developments but the geographic dispersion of these projects (Figure 6.21).

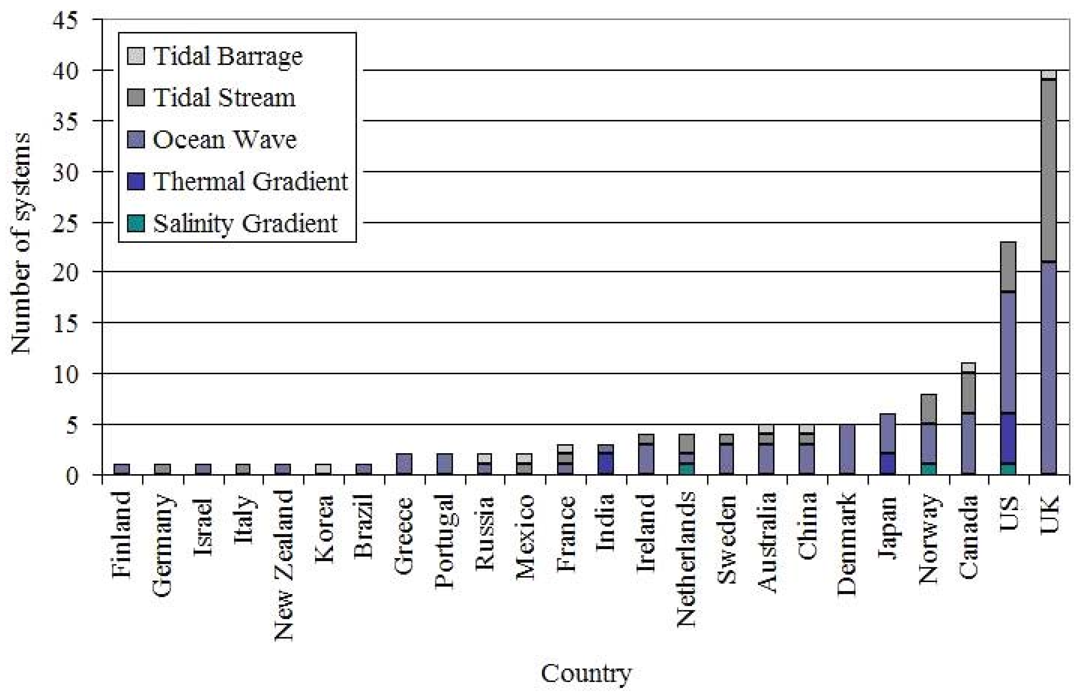


Figure 6.21: Country participation in ocean energy conversion system development (courtesy Khan and Bhuyan, 2009).

6.4.1.1 Markets

Apart from tidal barrages, all ocean energy technologies are conceptual, under research and development or at best have reached pre-commercial prototype stage. Consequently, there is no commercial market for ocean energy technologies at present. Some governments, such as the United Kingdom, Scottish Executive and others promote prototype device deployments through special funds (the Marine Renewables Deployment Fund - MRDF in the UK and the Wave and Tidal Energy Scheme - WATES in Scotland). Others are trying to accelerate market acceptance of ocean energy technologies through the use of renewables obligations or renewable portfolio standards, under which generators must supply electricity from specific technologies, such as ocean energy, or pay a penalty, which is then recycled by the government to promote the development of that technology, e.g. feed-in tariffs for ocean-generated energy introduced in Ireland and Portugal.. The United Kingdom and Scotland have such schemes. The Scottish Executive has introduced a prize, called the Saltire Prize, for the development of the first marine energy technology that meets a continuous generation target.

From a regional perspective it would be reasonable to suggest that the United Kingdom, Ireland and other north-eastern [TSU: "NE" replaced by "north-eastern".] Atlantic coastal countries lead the development of a market for ocean energy technologies and their produced electricity.

Funding mechanisms such as the Clean Development Mechanism (CDM) or Joint Implementation (JI) projects are ways in which governments can secure additional external funding for the development of tidal barrages or other ocean energy projects. The Sihwa barrage project in the Republic of Korea, which is expected to commence operations in 2010, was funded in part by CDM finance.

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, which will advantage renewable technologies, such as wave and tidal stream technologies, which produce no emissions in operation.

6.4.1.2 Industry Development

Industrial development of ocean energy is at a very early stage. There is no true manufacturing industry for ocean energy technologies at present but the growth of interest may lead to the development of new skills and capabilities. Whilst there is little or no capacity in the present marine energy supply chains, redirection of capacity and expertise from existing industries, such as electrical and marine engineering and offshore operations, could lead to rapid growth of supply chains for technology development and manufacturing and deployment projects.

Development of industries will depend on early uptake and support by governments and may thus be regional, rather than global. As noted the north-eastern [TSU: "NE" replaced by "north-eastern".] Atlantic coastal countries from the UK to Portugal are leading developments of technologies and markets. This results from governments in these countries supporting new industry through R&D grants, capital grants for deployments, regional support initiatives for cluster developments and supply obligations for generating companies (see section 6.4.7). These countries have begun to assess the market potential for ocean energy as an industry development or regional development initiative. Industry development road maps and supply chain studies have been developed for Scotland, the United Kingdom and New Zealand (FREDS, 2009; UKERC, 2008; AWATEA, 2008).

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:

1) International Energy Agency's Ocean Energy Systems Implementing Agreement

2) 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)

3) WavePLAM – the WAVe Energy PLanning And Marketing project (a European industry initiative to address non-technical barriers to wave energy).

[TSU: website links as footnotes to the above mentioned initiatives?]

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 and none are truly commercial.

A coast-attached oscillating water column device has been occasionally operational in Portugal since 1999 and a somewhat similar device (Wavegen's LIMPET device) 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) since 2006 and Ireland (OE Buoy) since 2007.

The most advanced oscillating-body device is the 750 kW Pelamis Wavepower attenuator devices, which has been tested in Scotland and deployed in Portugal. The Portuguese devices were sold as part of a commercial project. The company is currently building its next commercial device. The other near-commercial oscillating-body technology is the Ocean Power Technologies' PowerBuoy, a small (40 – 150 kW) vertical axis device, which has been deployed in Hawaii, the US eastern seaboard and off the north Spanish coast. Other oscillating-body devices under development include the Irish device, Wavebob, and the Wave Energy Technology-New Zealand device.

Two Danish overtopping devices have been built at prototype-scale (Wave Dragon and WavePlane).

[TSU: website links as footnotes to the above mentioned devices (marked yellow)?]

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 operation 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, Russia (Figure 6.22).

The conversion mechanism most widely used to produce electricity from tidal rise and fall is the 'bulb-type' unit (Figure 6.13). This technology was first developed in France for an application at the La Rance tidal power station near St. Malo, which was commissioned in 1966 with 24 x 10 MW units. Since 1997 these turbines have operated on both the ebb and flood tide.

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 retro-fitted 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.

By the end of 2010, the world's installed capacity of tidal rise and fall will still be less than 600 MW, Figure 6.22.

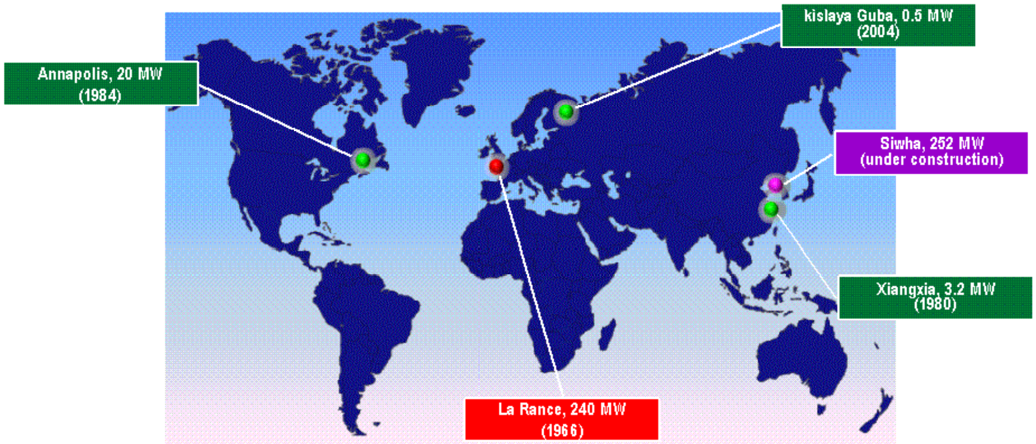


Figure 6.22: Tidal rise and fall power station in operation as of March 2009 (courtesy EDF) [TSU: status of source?]

However, numerous projects have been identified, some of them with very large capacities. Some are of the estuary type, some rely on the new offshore or coastal basin concept, Figure 6.23.

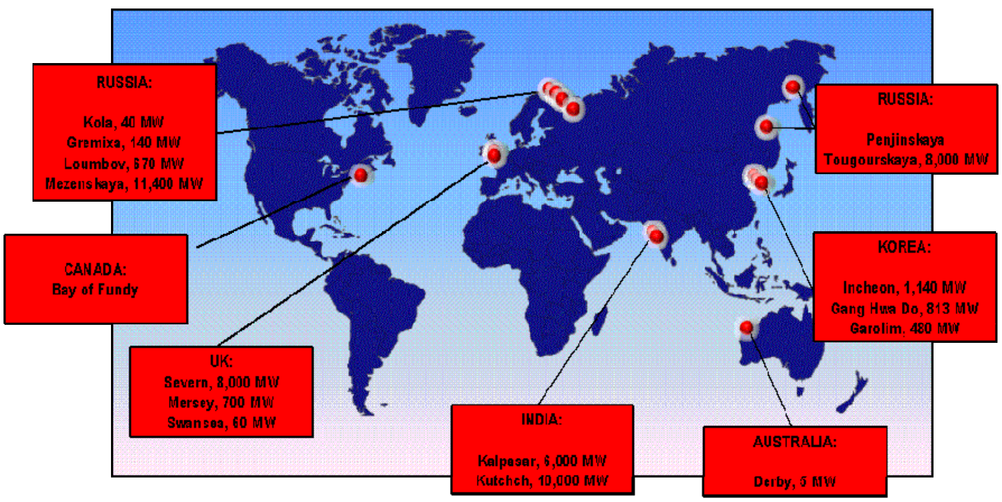


Figure 6.23: Tidal rise and fall power station planned as of March 2009 (courtesy of EDF) [TSU: status of source?]

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 is now an accredited 'power station' but there are competitors so far advanced, it is not yet known what the true market potential is. Most of these projections 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 [TSU: "NE" replaced by "northeast".] Asia, and Scandinavia (EDF, 2009).

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. They have a very low visual impact, so in this regard they can also be located close to populations. Tidal flows are also very predictable, which is extremely valuable in utility generation planning and forecasting.

Generally, the resource for tidal energy is not widespread and tends to be located in specific sites where the current velocities are high enough for economic viability. The threshold for this velocity is thought to be at least 1 m/s but not enough is known about costs and this value may vary as technology improvements are introduced. Generally, the global resource and hence, markets, must be large enough to support enough deployment and experience for the technology to reach commercial maturity. International collaborations and collaborations among tidal, river, and ocean current technology sub-sectors will be essential to achieve necessary market acceleration and cost reductions.

Open ocean currents, such as the Gulf Stream, are being explored for their potential. Unlike tidal stream flows, ocean currents tend to be slower, unidirectional but involve much larger bodies of water. Harnessing open ocean currents may require different technologies from those presently being developed for the faster, more restricted tidal stream currents (MMS, 2006).

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 at one point successfully produced fresh water at a rate of 100,000 liters per day. The design for this barge was created in co-operation with Saga University of Japan, and used a closed cycle system, with ammonia as a working fluid. The design, which was originally from 1984, was rated at 1 MW and apparently began construction in 2000; however, some equipment was lost due to various problems during implementation. It is unclear whether the 2005 barge was capable of power production and whether it was still based on a closed-cycle design. Another barge, which is intended for long-term production, is moored in water 1 km deep near Chennai and has its cold-water intake pipe at a depth of 500m. The barge can produce one million liters of fresh water per day, however, rather than generate power it currently uses diesel generators to power the pumps.

In 2005, a land-based plant, capable of producing 100,000 liters per day of freshwater was built on the island of Kavaratti, using a cold-water intake pipe mounted 350 m deep in the ocean (National Institute of Ocean Technology, 2007). The location offered access to water at 400 m depth only 400 m from shore, making it an ideal site for OTEC. The current plant does not incorporate electrical generation.

A small OTEC demonstration plant, called Mini-OTEC, 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; however, efficiency problems with the pumps allowed it to generate only 18 kW. One year later, another floating OTEC plant, called OTEC-1, was built. It used the same closed-cycle system and was rated at 1 MW; however, 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 with the technology were encountered, including problems with out-gassing of the seawater in the vacuum chamber, the vacuum pump itself, 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. Several smaller closed-cycle plants were also constructed in the following years, but were not kept operational long-term. The Institute of Ocean Energy (IOES) at Saga University / Japan created a small-scale 30 kW Hybrid OTEC plant during 2006. The prototype was based on a mixed water/ammonia working fluid, and was able to successfully generate 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. Along with the closed-cycle electrical generation system, an open-cycle system will be run in parallel to provide fresh water and additional generation. Although concept designs of the plants have been created, it is unclear if any development is still occurring.

6.4.6 Salinity Gradient

[TSU: sources missing.]

Osmotic power is still a concept under development. 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 in related technologies, such as desalination, will benefit the osmotic power industry.

In addition several governments and organisations have already engaged in both supporting the development itself and consideration of necessary instruments to bring this source of renewable energy to the market.

6.4.7 Ocean Energy-Specific Policies

Because ocean energy technologies are relatively new but offer the opportunity for yet another GHG-free electricity- and water-generation technology, 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 and other regulatory initiatives to reward developers of marine energy technologies and deployment projects.

There are now too many initiatives to list fully, so the following table gives well-established examples of such policy settings (Table 6.2). Policies fall into four categories:

- Targets for installed capacity or contribution to future supply
- Capital grants and financial incentives, including prizes
- Research and testing facilities and infrastructure
- Permitting/space/resource allocation regimes, standards and protocols

It is notable that most of the countries that have ocean energy-specific polices are those that are 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 OE-specific [TSU: chapter-specific abbreviations, OE: ocean-energy.] targets relate to proposed ocean energy installed capacity targets. These specific targets complement other targets – for percentage increases of renewable energy generation or renewably generated electricity.

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.

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.

Table 6.2: Examples of Ocean Energy-Specific Policies [TSU: Please add source.]

Policy Instrument	Country	Example Description
Aspirational Targets and Forecasts	United Kingdom Basque Country, Spain	3% of UK electricity from ocean energy by 2020 5 MW off Basque coast by 2020
Legislated Targets (total energy or electricity)	Ireland Portugal	Specific targets for marine energy installations 500 MW by 2020 550 MW by 2020
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	Most W. European and N. American countries	E.g. European Marine Energy Centre; there are c. 14 centres under development worldwide
Offshore Hubs	United Kingdom	E.g. wave hub, connection infrastructure for devices
Standards/protocols	United Kingdom	National standards for ocean energy (as well as participation in development of international standards)
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

6.5 Environmental and Social Impacts

[TSU: references missing.]

6.5.1 Introduction

All renewable energy projects will produce positive and negative environmental and social impacts. Since all ocean energy devices produce no CO_2 during operations, they must be accounted 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, loss of access to space for competing users, such as fishing and navigation. The effects of each ocean energy projects will be different both on the environment in which they are located and on the communities that live near them or benefit from their products. Projects under construction will have different effects than projects in operation. Although most ocean energy projects are likely to be long-lived (25 – 100 years), the lasting effects of their development will be important. There is a growing environmental concept: reversibility, which considers that any project development should be reversible without any long-term or permanent effects.

Wave devices are unlikely to produce too many environmental effects. Offshore wave devices themselves must, at least partially, float in the water column in a very energetic environment. The key potential environmental effects will be loss of space around the deployment site for other uses, including fishing and navigation. Moorings on the seabed may affect both benthic and pelagic species and concern is frequently expressed about the potential collision risk for marine mammals and cetaceans. However, this risk is currently unrealized and may be very small. The absence of any significant noise or visual impacts is a benefit to wave devices.

Tidal barrages are usually located in estuaries, which are complex, dynamic and potentially fragile environments. Further a barrage is a massive construction and not easily removed. This problem, also faced by coast-attached wave energy devices, may face the challenge of reversibility. Tidal stream devices may benefit from having little irreversible effects. Like wave energy devices, tidal stream devices will be located mainly in the water column and in a very energetic environment. Apart from the effects of moorings on the seabed and benthic fauna and competition for space, there may be little long-term effects of a tidal energy project.

The principal environmental impacts of both ocean energy thermal conversion (OTEC) and salinity gradient projects will be the outflow of significant quantities of exotic cold water (OTEC) and brackish water (salinity) from these plants.

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.

Increasingly governments are undertaking Strategic Environmental Assessments (SEAs) to assess and plan for potential environmental effects of ocean energy projects.

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. 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, developments of regional clusters, whilst individuals may benefit from new employment opportunities, training for new skills and development of new capabilities.

6.5.2 Wave Energy

The public perception of the importance of 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. The potential impacts on the marine environment can be expected to be similar in many aspects 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 in this case, and visual impacts of marine energy converters should be negligible, except large arrays of devices located nearshore.

The following impacts on the biosphere in the vicinity of the converters are of concern: infauna (aquatic animals that live within the bottom substratum rather than on its surface) and hard bottom substrate; fish habitat, communication and orientation, marine mammal behavior and orientation.

The potential impact of electromagnetic fields around devices and electrical export cables that connect wave farms to the mainland electrical grid is an important issue that has been investigated for offshore wind farms. These effects are expected to be relevant to sharks and rays that use electromagnetic impulses to navigate and find prey. Another important impact is chemical footprint due to accidents (e.g. oil leaks from hydraulic power-take-off systems (PTO)) and abrasion (paints and anti-fouling chemicals).

Noise is one of the potentially most important impacts that needs investigation. It can be emitted during deployment and decommissioning and during operation, at frequencies that depend on the PTO.

Energy capture and thus downstream effects on wave height are a potential concern of surfing communities. They fear that wave energy farms will reduce swell conditions at adjacent beaches. This can be assessed through numerical and tank testing studies.

Regarding the socio-economic impacts it is expected that the 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. However there can be a number of conflicts of interest namely with fishing industry leading to some potentially negative socio-economical impacts (loss of income for local fishing industry) or just a change in methods (trawling will be impossible in the wave energy farms area). However, installation of a wave device array may cause general better use of fish resources whose stocks has decreased to dangerous levels due to overfishing in the last decades.

6.5.3 Tide Rise and Fall

Development of tidal rise and fall power projects are often considered as local or regional development projects. They always produce impacts, positive and negative, on the natural environment and on the local economy, whether they are barrages across natural estuaries or stand-alone offshore impoundments (i.e. tidal lagoons).

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 project, although the estuary was closed for the construction period, biodiversity comparable to that of neighboring 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 project have been very limited since the barrage already existed.

A barrage will affect the amplitude of the tides inside the basin and therefore modify both fish and bird life and habitat, water salinity and sediment movements in the estuary. The need to ensure a minimum head between the basin and the sea will also lengthen the flat 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, it is noticeable that sediments are accumulating towards the upstream end of the basin, requiring regular and costly dredging operations.

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 and temporary.

In terms of social impact, projects 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 an impact on fishing activities but this impact should be limited, when the projects are located 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 construction of the civil works, which often represent a significant amount of investment and economic benefit to local communities.

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

Tidal current technologies are likely to be large submarine, 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) and the passive nature of the rotating device. Substantial research is under way to establish likely environmental effects and mitigation strategies.

Another potentially serious effect will be on fishing, particularly trawling, which will clearly be banned near submarine rotating equipment. Accommodations with present commercial, recreational and customary fishing activities will be required. 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. None of these has been fully explored in the literature.

Ocean current systems, which have sufficient velocities to be cost-effective, are all associated with wind-driven circulation systems, and 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 alterations in the patterns of meandering and in upper-ocean mixing processes, because the characteristics of the boundary current do depend on dissipation. The impacts of these effects need to be fully evaluated prior to full site development. In the case of the Atlantic Ocean’s Florida Current, modelling studies using the HYCOM high-resolution regional simulation capability are underway to assess these potential impacts (e.g. Chassignet et al., 2009).

Because open-ocean deployments will require mooring systems, benthic communities will be affected – potentially both adversely and positively – by anchor emplacement. While many sites are sufficiently deep that, generally, these potential impacts are not likely to be an issue, the deep-water coral communities off the coast of Florida may be vulnerable and will be carefully monitored for impacts during early deployments.

Open-ocean generating systems will operate at depths below the draft of even the largest surface vessels so hazards to commercial navigation will be minimal. Undersea naval operations could be impacted, although the stationary nature of the systems will make avoidance relatively simple. Of more potential impact is the fish habitat that may be created in association with the underwater structures and its attraction to sports fishing. Because underwater structures are known by marine scientists and recreational fishers to become fish aggregating devices (FAD) (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 (e.g. Battin, 2004).

6.5.5 Ocean thermal energy conversion

The four main sources of environmental concerns associated with deployment and operations of ocean thermal energy conversion (OTEC) plants are (Charlier and Justus, 1993):

(a) Redistribution of oceanic properties: ocean water mixing, impingement/entrainment, climate/thermal;

(b) Chemical pollutions: biocides,working fluid leaks, corrosion;

(c) Structural effects: artificial reef, nesting/migration;

(d) Socio-legal economic: worker safety, enviro-maritime law, secondary economic impact.

Potential changes in the oceanographic properties of sea water due to OTEC pumping operations are a major environmental concern. Considering that large amounts of cold deep water and warm shallow water will be pumped to the heat exchangers, parameters such as temperature, salinity, density, dissolved oxygen, nutrients, carbonates etc will be modified by mixing with ambient ocean water in the vicinity of the eventual discharge.

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.

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 eventually mixed naturally. The other outputs of the process produce no significant effluents that could interfere with the global climate. Like other renewable energy sources, 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 a deltaic/estuarine river mouth have not identified any serious obstacles. Major cities and industrial area are often sited at the mouths of major rivers, so osmotic power plants need not be constructed in unspoilt areas. The plants can be constructed partly or completely underground to reduce their environmental footprint on the local environment. Onshore environmental impacts are likely to be limited to such aspects as construction of electricity connections, access roads, etc.

Although there are few known environmental impacts, this will be carefully monitored as the industry develops. Water take will need to be monitored to ensure that water is not extracted in low flow conditions. Brackish water is the main waste product of osmotic power and the discharge of brackish water into the marine environment may alter the environment and result in changes for animals and plants living in the local location. The impact of produced brackish water on the local marine environment will need to be monitored. Deltaic/estuarine environments are notably sensitive to changes in water level and pollution so baseline studies and operational monitoring will be required.

Developed areas, such as cities, may have already affected the river mouth adversely. Careful and controlled building of the plant inlet, osmotic power plant and outlet could improve the present condition of biotopes of the river, the estuary and the sea.

6.6 Prospects for Technology Improvement, Innovation and Integration

[TSU: references missing.]

6.6.1 Wave Energy

Wave energy technologies are still largely at a very nascent stage of development and all are pre-commercial. 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. Nevertheless, a priority for the wave device developers is to gain enough operating experience on early devices so that engineering practices and technology development can advance. Wave energy devices are likely to follow a long-term development path which allows scaling to the largest practical machine size to minimize the number of operation and maintenance (O&M) service visits, lower installation and decommissioning costs, and reduce mooring requirements, similar to the wind energy industries progression to larger rotors. Maximizing energy production will play a large part in the overall cost reduction of wave energy systems. This will depend on building efficient capture devices as well as dependable and 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.

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 construction improvements can still be achieved. Firstly, in the design of the facilities, very large offshore facilities will allow the development of cost effective projects. Secondly, the use of multiple 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. Thirdly, in terms of electromechanical equipment, general turbine efficiency and, more specifically, the ability to improve generation efficiency in both flow directions are future challenges that will be determinant on the future of tidal rise and fall hydropower. The turbines should have the ability to operate both ways and the units should preferably operate as well as pumps. Such equipment has been used successfully for 40 years at La Rance in France. 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 for the various operating ways and heads.

As regards civil works, power plants may be built in situ within cofferdams or pre-fabricated in caissons (steel or reinforced concrete) and floated to site. The caisson solution is particularly adapted to remote sites: caissons with several turbine bays totalling 200 MW may be used.

6.6.3 Tidal and Ocean Currents

Like wave energy, tidal current technologies are in an early stage of development. All technologies are pre-commercial, so cost and reliability projections are speculative with a high level of uncertainty, because assumptions must be made about optimized systems that have not yet been proven at the prototype level. Extensive operational experience with horizontal axis wind turbines, may provide axial flow water current turbines with a developmental advantage, since the operating principles are fairly well known. As with wave energy technologies a high priority for tidal turbines is to gain operating experience to advance engineering practices and technology development. A premium should be placed on building reliable prototypes that can be studied and improved on the basis of technology, environmental impacts, cost, and reliability. Water current designs are likely to increase swept area (i.e. rotor diameter) to the largest practical machine size to minimize the number of O&M service visits, lower installation and decommissioning costs, and reduce substructure requirements (as happened with wind turbine technologies.

Tidal device performance may be limited by the geometry of the specific channel transect dimensions, constrained by navigational requirements that limit their distance below the surface. To date, assessments of the tidal current energy resources have been predominantly made on a site-specific basis but the total resource could be much larger, if lower current velocities can be considered for device deployments. If significant lower velocity sites exist, tidal device optimization may follow a path toward larger 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 in order to gain access to 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 little servicing, which can continue to produce energy reliably without costly maintenance. To accelerate this maturity and promote reliable systems, new materials to resist degradation caused by corrosion, cavitation, water absorption, and debris impact will be needed. New operating control strategies will be developed to resist extreme loads and mitigate fatigue damage. As environmental impacts become better understood (no significant impacted have been documented to date), tidal turbines will incorporate mitigation systems for the avoidance of these impacts.

6.6.4 Ocean thermal energy conversion

The heat exchanger system is one of the most important components of the 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. The performance of the thermal conversion cycle is highly dependent on the heat exchangers, their performance causes substantial losses in terms of energy production and therefore the economic viability of the entire OTEC system. Considering that evaporator and condenser units are responsible for 20 - 40% of the plant total cost, most of the research efforts are directed toward some special subjects related to the heat exchanger. In addition to materials selection and design under the operating flow rates, temperatures and pressures, aspects related to biofouling, corrosion and maintenance should be carefully considered (Charlier and Justus (1993).

Marine organisms, mainly plankton and dissolved organic material, will be attracted by the provision of marine nutrients by the OTEC plant. This will stimulate the formation of bacterial slimes and consequent degradation of the heat exchangers performance, unless preventive procedures are implemented.

Special care should be taken in relation to the material to be used for the hest exchanger system. One of the best options is titanium, which resists corrosion. However, due to its high cost, aluminium is an alternative to titanium, if regularly scheduled planned replacement is incorporated in lifetime maintenance activities. Copper-nickel alloys and stainless steel alloys are also candidate materials to be considered in the design stage.

A number of options are available for the working fluid, which has to boil at a low temperature (warm water from surface) and condense at a slightly lower temperature (cold water from deep layers). Three major candidates are ammonia, propane and a commercial refrigerant R-12/31. The main advantages are that it has the highest heat of evaporation and high thermal conductivity, especially in the liquid phase. Non-compatibility with copper alloys should be taken into account during design.

Another important component of an OTEC plant is the large diameter pipe employed to transfer the cold water from deep water to the surface. Experience obtained in the last decade with risers for oil &gas production can be easily transfer to the OTEC plant design.

6.6.5 Salinity Gradient

The World’s 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 simplified the approval process and at the same time 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.

The plant will be used for further testing of technology developed from parallel research activities to substantially increase the efficiency. These activities will mainly be focussed on membrane modules, pressure exchanger equipment and power generation (i.e. the turbine and generator). There will be a focus on further development of control systems, water pre-treatment equipment, as well as infrastructure around the water inlets and outlets (Scråmestø, Skilhagen and Nielsen, 2009).

6.7 Cost Trends

[TSU: All monetary values provided in this document will be adjusted for inflation/deflation and then converted to US$ for the base year 2005. US$ will be used as standard abbreviation for 2005 United States Dollar throughout the text]

6.7.1 Introduction

It is difficult to accurately assess the economic viability of most ocean energy technologies, because very little experience is available for validation. There are no commercial markets yet to drive marine energy technology development and national policy incentives and government-supported technology R&D are driving most innovation and deployment (US DoE, 2009).

Several studies have been based on extrapolations from prototype cost data (BBV, 2001; Li and Florig, 2006; EPRI, Previsic, 2004 [TSU: Previsic et al., 2004 ?]; Callaghan, 2006; IEA, 2008). These studies make assumptions about key variables, which include:

- total installed capital cost (Capex),
- Reliability (i.e. operations and maintenance (O&M)),
- Performance (energy production)
- Learning curve (total industry wide deployment),
- Economies of scale (project size, production capacity),
- Impact of R&D and value engineering (innovation and implementation)

These studies generally indicate that initial capital costs for marine energy generation can decline to costs achieved by other renewable energy technologies such as wind energy. However, this cost reduction 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 do not reflect commercial capex costs.

The Carbon Trust reported in 2006 that the prototype and pre-commercial wave energy converters had capex ranging from £4,300/kW (US$7,679/kW) to £9,000/kW (US$16,071/kW) with a midpoint of US$11,875/kW (Callaghan 2006). Similarly they found that prototype tidal stream energy generator costs ranged from £4,800/kW (US$8,571/kW) to £8,000/kW (US$14,286/kW) with a midpoint of £6,400/kW (US$11,428/kW). They emphasized that some device concepts may have even greater capex costs but that this may be offset by future cost reductions, which would be large enough to make them economically viable. In the same study, they estimated that energy from initial wave energy farms installed in the UK would have levelized costs of energy (LCOE) between 12p/kWh (21.4 US¢/kWh) and 44p/kWh (78.8 US¢/kWh) while initial tidal stream farms were estimated to have LCOEs between 9p/kWh (16.1 US¢/kWh) and 18p/kWh (32.1 US¢/kWh). They did not take into account value engineering, economies of scale, R&D improvements, or learning curve effects.

6.7.2 Wave Energy

Previsic (2004) [TSU: Previsic et al., 2004 ?] conducted a detailed study to examine a commercial scale project costs using arrays of Pelamis Wave Energy generators. The overall plant size was assumed to be 106.5 MW (213 x 500 kW devices), at which size economies of scale were also included. Other assumptions were a full 20-year life, 95% availability and energy capture potential that took advantage of near-term R&D improvement opportunities not yet realized but which were thought to be achievable at current capex costs. Some of these assumptions may be optimistically high. The study concluded that an LCOE of 13.4 US¢/kWh is possible with a total capex of $279 million, a discount rate of 7.5%, capacity factor of 38%, and O&M costs of US$ 13.1 million annually (i.e. US$ 0.44/kWh).

This hypothetical study provides a credible benchmark to demonstrate that wave energy projects could have lower LCOEs than wind energy did in the 1980s. However, the study's optimistic assumptions about high reliability and availability of wave energy machines ignored numerous deployment problems and premature mortality experienced by early wind turbines, which were retroactively accounted for in the LCOE for wind energy technologies.

The greatest uncertainty in estimating the LCOE of ocean energy is in establishing realistic performance (energy capture) estimates and operation and maintenance (O&M) costs. Reliability and energy production levels must be estimated with some expectation that ocean energy systems will become reasonably efficient, and with reasonable repair costs, because analysts do not have the advantage of operational experience on which to base their O&M or energy production estimates. Moreover, there is a high degree of uncertainty in estimating capex costs for mature and reliable systems. Cost models assume that the machines will run for a reasonable life with a nominal service schedule (Previsic, 2004 [TSU: Previsic et al., 2004 ?]; Buckley, 2005).

An important downward cost driver for LCOE is the learning curve effect. As deployments increase and installation capacity rises, costs will move down the learning curve due to natural production efficiency gains and assimilated experience. Theoretically, every doubling of installed capacity will result in a percentage decline in costs. Early decline rates will be high but decrease over time. This learning curve effect has been documented for wind energy technologies, which experienced learning curve rates ranging from 10% to 27% per doubling of installed capacity (based on a review of nine global studies). A summary of this learning curve literature is given in Chapter 7, Table 7.8.2 [TSU: numbering changed].

Limiting this analysis to studies that span the full development of the wind industry (i.e. the 3 decades from 1980s to the present day) indicates that the learning curve effect converges to about 11% per doubling, without including an R&D factor (Wiser and Bolinger 2009). For the purposes of this analysis, it is assumed that future ocean energy industries (wave, tidal current, ocean current and ocean thermal energy conversion (OTEC)) will follow the same 11% learning curve as the wind industry. Figure 6.24 shows a wave and tidal current learning curve plot for capex only, beginning with the midpoints for the capex costs given by the Carbon Trust (2006). Given 11% learning and assuming worldwide deployments of 2-5 GW by 2020 for each technology, the learning curve would bring capex cost reductions ranging from US$ 2,600/kW to US$ 5,400/kW for both technologies, US$ 4,000/kW on average.

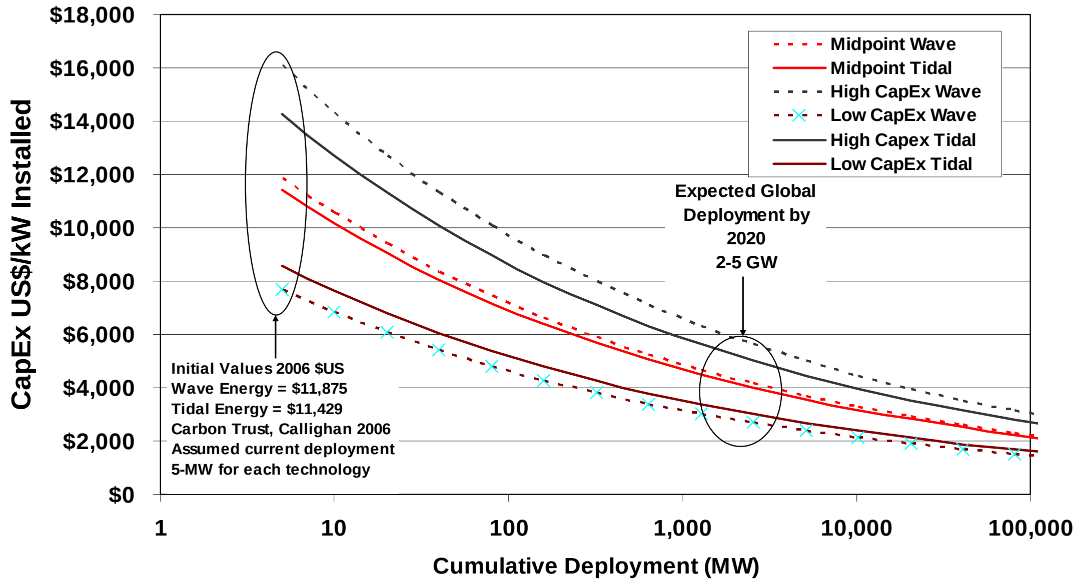


Figure 6.24: Capex learning curve reductions [TSU: Learning curves/capex reductions] for wave and tidal energy devices based on current cost and 11% cost reduction per doubling of capacity (Carbon Trust 2006).

One way to assess reliability, performance and costs together is to examine the LCOE as a function of the capacity factor. Figure 6.25 shows projections of LCOE for wave and tidal energy technologies using a calculation worksheet provided by Ryan Wiser (Wiser 2009).

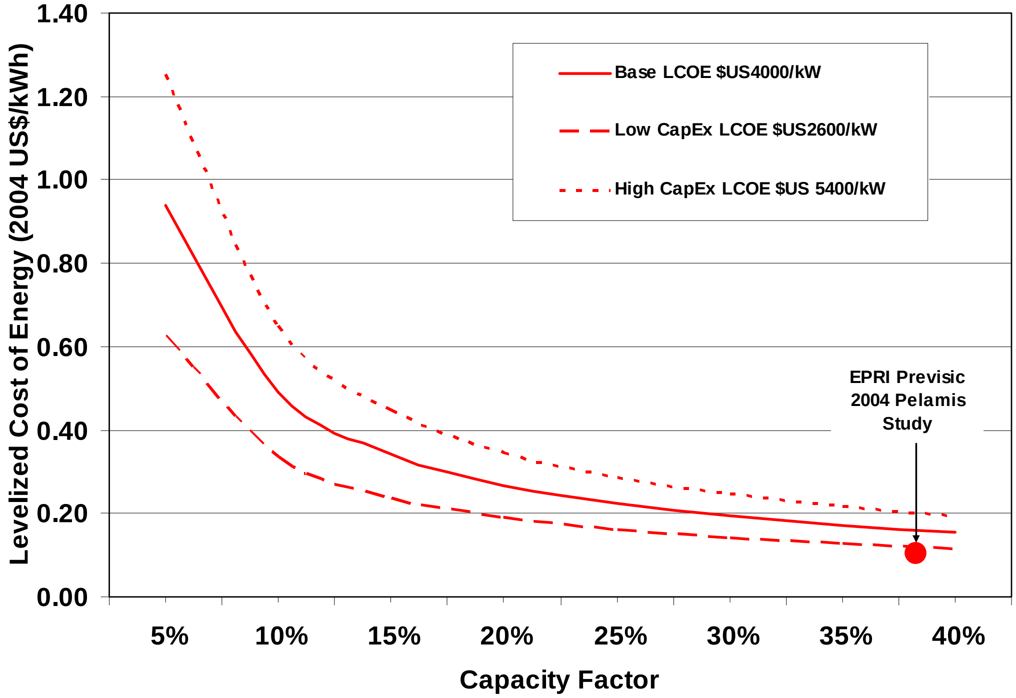


Figure 6.25: LCOE estimates for 2020 ocean energy projects and showing EPRI design point using Pelamis 500-kW Wave Power machines (EPRI, Previsic, 2004 [TSU: Previsic et al., 2004?]).

The three curves shown in Figure 6.25 correspond to the calculated high, base, and low learning curves, i.e. US$ 5,600/kW, US$ 4,000/kW, and US$ 2,600/kW, respectively. The variation of LCOE with capacity factor indicates that devices operating with high capacity factors (i.e. 30% to 40%) can potentially generate electricity at rates competitive with other technologies. However, to achieve these capacity factors devices must be optimally sited in a high quality wave or tidal current resource and be very reliable (to minimize O&M costs and energy losses due to downtime over the design life).

In addition to the learning curve effects, cost reductions through manufacturing at scale, technology innovations can also contribute to rapid LCOE reductions, as designers implement new technologies, transfer innovations from other industries and take advantage of design opportunities realized through operation and experience.

6.7.3 Tide Rise and Fall

[TSU: sources and concrete estimates missing.]

The cost of tidal rise and fall projects may appear to be a barrier to such developments. These projects usually require a very high capital investment at the outset, with relatively long construction periods. Consequently, costs associated with tidal rise and fall technologies may appear high when compared to other sources of energy. The costs of civil construction in the marine environment are very high and construction sites need to be prepared and protected against the harsh sea conditions.

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: the scale of projects reduces unit costs of generation.

The annual output of a given tidal barrage or impoundment plant is linked to the surface area (volume) of the reservoir. In a circular tidal lagoon, the surface area increases with the square of the radius, while the cost of the enclosing dyke walls is proportional to the radius. A small increase in the radius will therefore cause a nominal increase in construction costs but yield a noticeable increase in generation output.

As predictable, fully renewable projects, tidal rise and fall 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 Tidal and Ocean Currents

It is difficult to determine the final likely costs of tidal and ocean current devices, since devices are at such an immature stage of development. A number of studies have been undertaken in recent years but these quickly become out-of-date as economic conditions change and device developments advance (e.g. BBV, 2001). Recent studies show that the unit cost [TSU: LCOE] of tidal turbines is likely to become competitive with costs of other forms of renewable energy, such as wind power (Fraenkel, 2006, Bedard et al., 2006, UKERC, 2008).

The 2006 Carbon Trust report notes that detailed design optimisation of generic device concepts could not be considered in full but that optimisation for UK resource conditions were possible (Callaghan, 2006). These optimisations are not described in detail but were estimated to contribute 5-10% learning rate cost reductions. This was attractive in order to understand whether tidal stream energy could become cost-competitive in the UK, given the country's estimated share of the worldwide resource (10-15%). Such optimisations are likely to be possible for device developments and deployments in other countries.

The Carbon Trust publication is perhaps the most authoritative recent study on the cost of wave and tidal energy-generated electricity. The study showed that the uptake of tidal stream energy and unit cost of electricity generation were intimately linked through the market price of electricity for other generation sources and learning rate (or experience curve). The study showed that initial unit costs of tidal stream-generated electricity could be high, £ 0.08/kWh (14.3 US¢/kWh) but the final costs could decline to £ 0.025/kWh (44.6 US¢/kWh [TSU: 0446 US$/kWh]) by the time installed capacity had reached 2,800 MW. Government support through either feed-in tariffs or renewables obligation certificates (ROCs) will accelerate installations and cause concomitant reduction of unit costs.

More recently a 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).

The cost and economics for open-ocean current technologies should track closely the evolution of tidal stream energy technologies. Inherent differences between these technologies may introduce some cost variance but cost trends will be similar. No definitive cost studies are available in the public domain for ocean current technologies.

6.7.5 Ocean thermal energy conversion

Because there is no real experience yet with commercial ocean thermal energy conversion (OTEC) operations, it is hard to foresee cost trends. Literature does provide a variety of cost projections made at various times, however. These include $5,000-$11,000/kW (Francis, 1985); $12,200/kW for the 1984 plans for a 40 MW plant for Kahe Point, Oahu, or $7,200/kW for an on-shore open-cycle plant (SERI 1989), $4,200/kW, $6000/kW, or $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); $9,400/kW or $0.18/kWh or 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 $0.16-$0.20/kWh, dropping to $0.08-$0.16/kWh once enough plants have been built (Cohen, 2009). These estimates are in different-year dollars and cover a range of different technologies and locations. Many are also highly speculative.

The Lockheed-Martin pilot plant estimates ($32,500/kW for 10 MW pilot plant to $10,000/kW for a commercial 100-MW plant) are probably the best current cost information available for multi-megawatt [AUTHORS: Reference missing here] (Cooper, 2009; Cohen 2009). 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, should 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. And, as with any new technology, costs can be expected to decrease dramatically as more plants are built.

6.7.6 Salinity Gradient

Osmotic power is one of the most promising renewable ocean energy sources. To utilise this form of green energy, the membrane which is the heart of the process, has to be optimized. Osmotic power has excellent environmental performance and yields CO_2-free power production. It will qualify for green certificates and other supportive policy measures for renewable energy.

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. This is a similar range to other renewable technologies such as wind power, wave and tidal power, and power generated from biomass.

These calculations are based on current hydro power knowledge, general desalination (reversed osmosis) engineering information, and on a specific membrane target as a prerequisite. The capital cost of installed capacity is expected to be high compared to other renewable energy sources. To ensure competitiveness, given the requirement of large volumes of membranes, membrane cost and operational life will be important. However, each MW installed is very productive, with continuous operating time. This should generate approximately twice the energy supplied (GWh) per installed MW per year, compared to wind turbines, which are designed to operate an average 3,500 hours per year at various capacities.

6.8 Potential Deployment

[TSU: references missing, website links as footnotes to demonstration projects/prototypes mentioned in this section (highlighted in yellow)?]

6.8.1 Wave Energy

During the last 15 years, development of technology has being carried out mostly by enterprises (SMEs and also large industrial companies). Offshore oil and gas expertise and experience is valuable for bringing floating wave energy converter development to a commercial stage. Investors are already active in this new energy business. Unit costs of produced electrical energy claimed by technology development teams are frequently unreliable. At the present stage of technological development and for the systems that are close to commercialization, it is widely acknowledged that costs are still three times larger than those of energy generated by onshore wind (the gap is smaller when compared with offshore wind). Therefore technology developers tend to deploy their full-size prototypes in the coastal waters of the countries that provide significant incentives, e.g. in the form of high feed-in tariffs and/or access to electrical connecting cables to the onshore grid.

The Oscillating-Water-Column (OWC) type wave energy device is the most mature technology. For fixed plants, whether located in the shoreline, bottom-mounted in the nearshore or incorporated in breakwaters, OWCs can be considered as a pre-commercial technology, since various grid-connected prototypes have been in operation for many years. The cost of electricity produced by these systems is not competitive yet with electrical energy produced by other renewable energy technologies, like wind, geothermal or conventional hydro. For floating OWCs development of equipment is still underway.

Of the many floating device designs that have been developed and deployed, only Pelamis has become a pre-commercial technology. The first 3-unit Pelamis wave farm was deployed off Portugal in July – November 2008.

Full-size floating prototypes are planned to be deployed in specific test sites that are being created in various countries, including Norway, UK, Ireland, France, Spain and Portugal. Financial support by the European Commission has been instrumental to technology development and presently enables the construction and testing in the sea of a number of full-scale prototypes. This is the reason why Europe is leading the development of ocean energy technologies. In the USA the first federal support grants were awarded in 2008, whilst in Canada federal and regional government programmes (in British Columbia, Nova Scotia and New Brunswick) have been developed. In Brazil principal developments are being encouraged by a mix of private and government financial support.

6.8.2 Tide Rise and Fall

The world's largest tidal power plant (254 MW) is currently under construction at Sihwa in Republic of Korea. The plant has been installed in an existing dam and will incorporate 10 bulb turbines, each rated at 26 MW, with a runner diameter of 7.5 m. Korea has also announced other larger tidal plants, for example, a 520 MW barrage planned for Garolim Bay (Shanahan, 2009).

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. Ten proposals to generate electricity were submitted from a public call for proposals in May 2008. Proposals were made at a variety of scales (ranging from 624 MW to 14.8 GW) and included barrages, offshore lagoons, continuous line of underwater tidal current turbines and a tidal reef. The British Government is currently considering these proposals.

6.8.3 Tidal and Ocean Currents

A series of devices to produce electricity from tidal currents are presently in different stages of development, some of them already deployed (OES-IA, 2007). In addition, new tidal stream devices also entered the field in 2008. A number of large tidal stream developments are planned over the next five years, based on 1 to 1.5 MW turbines from different manufacturers (Bahaj, 2009).

There are many different designs of tidal and ocean current turbine devices and there is presently no single convergent designs. The European Marine Energy Centre website lists 53 different designs of tidal and ocean current devices (see website in references [TSU: websites as footnotes]). Design options include horizontal versus vertical axis rotation, turbine types (2- and 3-bladed rotors, ring turbines), mounting (seabed, mid-water and surface-piercing). However, it is true that submarine devices, similar to wind turbine generators, are beginning to dominate. These devices have a horizontal axis turbine with an up-current 2- or 3-bladed rotor fixed to a vertical tower, which is either gravity-based or drilled into the seabed.

The most developed device is the Marine Current Turbines' "Seagen", which is similar to this concept, except that it has two generators on a horizontal hydrofoil. This device has been generating electricity in Northern Ireland since July 2008. The developers describe it as a 'pre-commercial demonstrator'. There is thus no commercial tidal or ocean current device presently available.

Tidal currents are created by the tidal range and, in most cases, constrictions caused by submarine topography, such as narrow passes between islands and the mainland. The deployment of tidal current devices is thus 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). Wider deployments of tidal current devices will depend on careful examination of individual sites. Current conditions will determine not only the selection of turbine types but also the micro-siting of individual turbines in an array.

Ocean currents are much more widespread than tidal currents but generally operate at slower speeds, which may be too slow for most devices. Harnessing slower ocean currents may require some specific device designs. These designs are likely to be based on similar principles to tidal current devices. Perhaps the best example is the Gulf Stream off Florida, which has been shown to have the potential for up to 10 GW of installed ocean current capacity.

6.8.4 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) offers a large potential for long-term reduction of carbon emission through many of its aspects. Power production directly translates to substantial avoided CO_2 emissions. Cooling using deep ocean water can also displace the use of fossil-based electricity. Production of drinking water using renewable energy, which is likely to be a highly sought-after commodity in coming decades, will be central to meeting future world demands responsibly. Mariculture and aquaculture using nutrient-rich cold ocean water can enhance local economies without fossil fuel use.

For the near-to-mid-term, the potential to use OTEC power is likely more limited by appropriate markets than by any constraints on the resource. Small onshore or nearshore multi-use plants could contribute a modest amount of total energy but could prove to be highly significant to local economies for many small island nations. Ocean energy could be the catalyst for many of these nations to become independent of imported resources for power.

Larger floating-platform OTEC plants sending electricity to shore by submarine cable are likely to be limited to large populations in locations such as Oahu, Hawaii; Puerto Rico; U.S. Gulf Coast cities (Tampa, Key West, New Orleans and Brownsville and perhaps the southeast Florida coast). Cuba; Taiwan; the Philippines; and India all have large sea water temperature differentials close to shore with 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. Adaptation of motor vehicles to use ammonia as fuel for internal-combustion engines or ammonia-derived hydrogen for fuel cells could be a key research and development area in this respect.

6.8.5 Salinity Gradient

The Statkraft prototype plant, which became operational in October 2009, is an important milestone following several years of osmotic power research & development (R&D). In addition to further development, it is intended to be a meeting place for parties from governments and industries with ambitions or commitment to this new and promising technology.

With increased focus on the environmental challenges and the need for more clean energy, the prototype plant is a significant contribution to the generation of renewable energy and increases the momentum in development of new clean technologies.

In the longer term, technology development at 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 (Scråmestø, Skilhagen and Nielsen, 2009).

Like most new technologies, this technology will need governmental assistance with support schemes in the early development phase to make it economically attractive. Given continued technology development and declining prices for components, osmotic power is a realistic technology with huge potential for renewable energy generation.

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 7

Wind Power

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Yellow highlighted – original chapter text to which comments are referenced

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Length

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 72 pages: a total of 4 pages over the maximum (21 over the mean, respectively).

Expert reviewers are kindly asked to indicate where the Chapter could be shortened by 4-21 pages in terms of text and/or figures and tables to reach the mean length.

References

References highlighted in yellow are either missing or unclear.

Chapter 7: Wind energy

CONTENTS

EXECUTIVE SUMMARY

Wind energy offers significant potential for near- and long-term carbon emissions reduction. The wind energy capacity installed at the end of 2008 delivered roughly 1.5% of worldwide electricity supply, and that contribution could grow to in excess of 20% by 2050. Though wind speeds vary regionally, all continents have areas with substantial resource potential. On-shore wind is a mature technology that is already being deployed at a rapid pace in many countries. In good wind resource regimes, the cost of on-shore wind can be competitive with other forms of electricity generation, and no fundamental technical barriers exist that preclude increased levels of wind penetration into electricity supply systems. Continued technology advancements in on- and off-shore wind are expected, further improving wind energy's carbon emissions mitigation potential.

The wind energy market has expanded rapidly. Modern utility-scale wind turbines have evolved from small, simple machines to large-scale, highly sophisticated devices, driven in part by more than three decades of basic and applied research and development. The resulting cost reductions, along with government policies to expand renewable energy supply, have led to rapid market development. Cumulative installed wind capacity increased from just 10 GW in 1998 to more than 120 GW at the end of 2008, and wind energy was a significant contributor to the electricity capacity additions of Europe and the United States during the latter years of this period. Most additions have been on-shore, but several European countries are embarking on ambitious programmes of off-shore wind deployment. Total investment in wind installations in 2008 equaled roughly US$45 billion, while direct employment totaled 400,000. Despite these developments, global wind energy capacity at the end of 2008 supplied a modest fraction of worldwide electricity demand, and growth has been concentrated in Europe, the U.S., and segments of Asia; the top five countries by cumulative installed capacity at the end of 2008 were the U.S., Germany, Spain, China, and India. Policy frameworks continue to play a significant role in the expansion of wind energy utilization, and further growth – especially off-shore and in under-represented regions – is likely to require additional policy measures.

The scale of the global wind resource is sizable. On a worldwide basis, studies have consistently found that the technically-exploitable wind energy resource (on- and off-shore) exceeds global electricity demand. Though the wind energy resource is not fixed (but instead reflects the status of the technology, among other factors) and further advancements in wind resource assessment methods are needed, the resource itself is unlikely to constrain further global wind development. Sufficient wind resource potential also exists in most regions of the world to enable significant additional wind development. That said, the resource is not evenly distributed across the globe, and wind energy will not contribute equally in meeting the needs of every region. Additionally, the wind energy resource is not uniformly located near population centres – some of the resource is therefore economically inaccessible given the costs of new transmission infrastructure. Research into the effects of global climate change on the geography and variability of the wind resource is nascent; however, research to date suggest that it is unlikely that these changes will 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 electricity system planners and operators, such as variable electrical output, reduced predictability, and locational dependence. Nonetheless, wind electricity has been successfully integrated into existing electricity networks without compromising system security and reliability; in some countries, wind energy supplies in excess of 10% of aggregate annual electricity demand, while instantaneous wind energy deliveries have exceeded 45% of demand. Because the characteristics of the existing electricity system determine the ease of integrating wind energy, acceptable penetration limits and the operational costs of integration are system-specific. Nevertheless, theoretical analyses and practical experience suggest that at low to medium penetration levels the operational integration of wind energy poses no fundamental economic or technical challenges. As wind energy increases, network integration issues must be addressed both at the local and network levels through system stability and balancing requirements. Active management through a broad range of strategies is anticipated, including the use of flexible generation resources (natural gas, hydropower), wind energy forecasting and output curtailment, and increased coordination and interconnection between power systems; increased demand management and electrical storage technologies may also be used. Finally, significant new transmission infrastructure, both on-shore and off-shore, would be required to access the most robust wind resource areas.

Environmental and social issues will affect wind energy deployment opportunities. Wind energy has significant potential to reduce GHG emissions, together with the emissions of other air pollutants, by displacing fossil fuel-based electricity generation. The energy used, and emissions produced, in the manufacture and installation of wind turbines is small compared to the energy generated and emissions avoided over the lifetime of the turbines. In addition, the variability of wind energy production does not significantly affect the carbon emissions benefits of increased reliance on wind energy. Alongside these benefits, however, the development of wind energy can have detrimental effects to the environment and people [TSU: humans]. Modern wind technology involves large structures up to 100 metres high, so wind turbines are unavoidably visible in the landscape, and planning wind energy facilities often arouses local public concern. Appropriate siting of wind turbines is important in minimizing the impact of noise, flicker, and electromagnetic interference, and engaging local residents in consultation during the planning stage is an integral aspect of project development. Moreover, the environmental impacts of wind energy extend beyond direct human interests, as the construction and operation of both on- and off-shore wind projects can directly impact wildlife (e.g., bird and bat collisions) and indirectly impact ecosystems. Attempts to measure the relative impacts of power generation suggest that wind energy has a low environmental footprint compared to other electricity generation options, but local impacts do exist, and techniques for assessing, minimizing, and mitigating those concerns could be improved. Moreover, while public acceptance and scientific concerns should be addressed, streamlined planning and siting procedures for both on-shore and off-shore wind may be required to enable more-rapid growth.

Technology innovation and underpinning research can further reduce the cost of wind [TSU: energy]. Current wind turbine technology has been developed for on-shore applications, and has converged to three-bladed upwind rotors, with variable speed operation. Though on-shore wind technology is reasonably mature, continued incremental advancements are expected to yield improved design procedures, increased reliability and energy capture, reduced operation and maintenance [TSU: (O&M)] costs, and longer turbine 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, two-bladed downwind rotors). Advancements can also be gained through more-fundamental research to better understand the operating environment in which wind turbines must operate. It is estimated that continued research and development, testing, and operational experience could yield reductions in the levelized cost of on-shore wind energy of 7.5-25% by 2020, and 15-35% by 2050. The available literature suggests that off-shore wind energy applications have 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 maturity and cost of on-shore wind 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 technology, 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 1.5% at the end of 2008 to 20% or greater by 2050 if ambitious efforts are made to reduce carbon emissions. Achieving this level of global wind energy utilization would likely require not only economic incentive policies of adequate size and stability, but also an expansion of wind energy utilization regionally, increased reliance on off-shore wind energy, 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.

7.1 Introduction

This chapter addresses the potential role of wind energy in reducing global and regional 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 wind speeds vary considerably by location, all continents have substantial regions with a technically viable and economically exploitable resource.

Wind energy relies, indirectly, on the energy of the sun. Roughly two percent 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. Global equilibrium is maintained, in part, through wind currents, with the earth's rotation, geographic features, and temperature gradients greatly affecting the location and nature of those 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 generation are highly sensitive to local wind conditions.

Wind energy has been used for millennia (for historical overviews of the use of wind energy, 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 produce electricity are often credited to Charles Brush (1887) and Paul La Cour (1891). Use of wind electricity in rural areas and, experimentally, in utility-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 produce electricity from larger, utility-scale wind turbine generators, deployed either in a great number of smaller wind energy projects or a smaller number of much larger projects. Such turbines typically stand on tubular towers of 60-100 [TSU: all towers?] meters in height, with three-bladed rotors that are often 70-100 meters in diameter; larger machines are under development. Such projects are commonly sited on land: as of 2009, wind projects sited in shallow and deeper water off-shore are a relatively small proportion of global wind energy installations. As wind energy deployment expands and as the technology becomes more mature, off-shore wind 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 these larger on- and off-shore wind electricity applications. 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, to meet local needs. 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 high-altitude wind energy machines are also under consideration, and in addition to electricity generation wind will continue to meet mechanical energy 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 wind resource (Section 7.2). The chapter then reviews the status of and trends in modern utility-scale wind technology, both on-shore and off-shore (Section 7.3). The chapter then turns to a discussion of 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 variable wind into electricity networks are addressed (Section 7.5), as is available evidence on the environmental and social impacts of wind energy development (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 7.8).

Text box 7.1. Other wind energy applications and technologies.

Beyond the use of large, modern wind turbines for electricity generation, 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 technology from the perspective of carbon emissions reduction, at least in the near- to medium-term.

Small wind turbines for electricity generation. Smaller-scale wind turbines can be and 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 utility-scale wind energy, they can sometimes 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 (EWEA, 2009). As an example, China had 57 MW of cumulative small (<100 kW) wind capacity installed at the end of 2008 (Li and Ma, 2009). Small wind turbines can also be employed in grid-connected applications in both rural and urban settings, and for both residential and commercial electricity customers (the use of medium-sized turbines of perhaps 500 kW to 1 MW is also promising for utility-scale applications in certain developing countries where road infrastructure and manufacturing capacity may limit the production and transport of larger turbines). Though the use of wind energy in these 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 global installations of <100 kW wind turbines from leading manufacturers at under 40 MW in 2008. In addition, for urban settings where the wind resource can be quite poor, the carbon emissions associated with the manufacture and installation of small wind turbines may not be repaid in the form of zero-carbon electricity generation (Carbon Trust, 2008b).

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 on mid-sized vessels and studies have found that these systems may yield fuel savings of 10-50%, depending on the technology and wind conditions (O'Rourke, 2006; Naaijen and Koster, 2007; Aschenbeck *et al*., 2009).

High-altitude wind electricity. High-altitude wind energy systems have recently received some attention as an alternative approach to generating electricity from the wind (Argotov and Silvennonein, 2007; Canale *et al*., 2007; Roberts *et al.*, 2007; Archer and Caldeira, 2009; Argotov *et al*., 2009). The principal motivation for the development of this technology is the sizable resource of high-speed winds present in jet streams. There are two main approaches to high-altitude wind energy that have been proposed: (1) tethered wind turbines that are maintained at altitudes up to 10,000 meters and transmit electricity to earth via cables, and (2) base stations that convert the kinetic energy from the wind collected via kites at altitudes of about 1,000 meters to electricity at ground level. 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 and institutional challenges must be overcome before a realistic estimate of the carbon emissions reduction potential of high-altitude wind can be developed.

7.2 Resource potential

The global exploitable wind resource is not fixed, but is instead related to the status of the technology, the economics of wind energy, and other constraints to wind energy development. Nonetheless, a growing number of global wind resource assessments have demonstrated that the world's technically exploitable wind energy resource exceeds global electricity demand, and that ample potential exists in most regions of the world to enable significant wind 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 region. This section summarizes available evidence on the size of the global wind energy resource (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 resource potential; for a discussed [TSU: discussion] of seasonal and diurnal patterns, as well as shorter-term wind output variability, see Section 7.5.

7.2.1 Global technical resource potential

A number of studies have been conducted to estimate the technically-exploitable global wind energy resource. In general, two methods can be used to make these estimates: first, an observation-based method can construct a surface wind distribution by interpolating available wind speed measurements; and second, numerical weather prediction models can be applied to an area of interest. The studies that have investigated the global wind resource use varying combinations of these two approaches, have sometimes focused on only on-shore wind energy applications, and have typically used relatively simple analytical techniques with coarse spatial and temporal resolution.[1] Additionally, it is important to recognize that any estimate of the potential wind resource is not a single, fixed quantity – it will change as wind technology develops and as more is learned about technical, environmental, and social concerns that may influence development.

Despite these caveats, the growing numbers of global wind resource assessments have demonstrated that the world's technically exploitable wind energy resource exceeds total global electricity supply. Synthesizing the available literature, the IPCC's Fourth Assessment Report identified 600 EJ/yr of available on-shore wind energy resource potential (IPCC, 2007), just 0.95 EJ (0.2%) of which was being used for wind energy applications in 2005. The IPCC (2007) estimate appears to derive, originally, from a study authored by Grubb and Meyer (1993). Using the standard IEA method of deriving primary energy equivalence (where electricity supply, in TWh, is translated directly to primary energy, in EJ), the IPCC (2007) estimate of on-shore wind energy potential is 180 EJ/yr (50,000 TWh/yr), almost three times greater than global electricity demand in 2007 (19,800 TWh).[2]

Since the Grubb and Meyer (1993) study, a number of additional analyses have been conducted to estimate the global technical potential for wind energy (Table 7.1).

[1] Wind project 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 energy projects of significant scale.

[2] The IPCC (2007) cites Johansson *et al.* (2004), which obtains its data from UNDP (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 renewable electricity supply is assumed to substitute the primary energy of fossil fuel inputs into conventional power plants, accounting for plant conversion efficiencies). The IEA's primary energy accounting method does not take this last step, and instead counts the electricity itself as primary energy (that is, it translates TWh of electricity supply directly into EJ), so this chapter reports the IPCC (2007) figure at 180 EJ/yr, or roughly 50,000 TWh/yr. This figure is close to that estimated by Grubb and Meyer (1993).

Table 7.1. Global assessments of technical wind resource potential.

Study	Scope	Methods and Assumptions*	Results**
Lu *et al.* (2009)	On-shore & Off-shore	>20% capacity factor (Class 1); 100m hub height; 9 MW/km^2; 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	Theoretical/Technical: 840,000 TWh 3,050 EJ
Hoogwijk and Graus (2008)	On-shore & Off-shore	Updated Hoogwijk *et al.* (2004) by incorporating off-shore wind, assuming 100m hub height for on-shore, and altering cost assumptions; for off-shore wind, study updates and adds to earlier analysis by Fellows (2000); other assumptions as listed below under Hoogwijk *et al.* (2004); technical potential defined here in economic terms: <$0.18/kWh (2005$) for on-shore wind and <$0.09/kWh (2005$) for off-shore wind in 2050	Technical/Economic: 110,000 TWh 400 EJ
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; technical potential = 20% of theoretical potential	Theoretical: 627,000 TWh 2,260 EJ Technical: 125,000 TWh 450 EJ
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 1,000 EJ Sustainable 39,000 TWh 140 EJ
Hoogwijk *et al.* (2004)	On-shore	>4 m/s at 10m (some less than Class 2); 69m hub height; 4 MW/km^2; assumptions for availability and 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-use categories; economic potential defined here as <$0.10/kWh (2005$)	Technical: 96,000 TWh 350 EJ Economic: 53,000 TWh 190 EJ
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: <$0.23/kWh (2005$) in 2020; focus on four regions, with extrapolations to others; some countries omitted altogether	Technical/Economic: 46,000 TWh 170 EJ
WEC (1994)	On-shore	>Class 3; 8 MW/km^2 spacing; 23% average capacity factor; based on an early global wind resource map;	Theoretical: 484,000 TWh

		technical potential = 4% of theoretical potential	1,740 EJ Technical: 19,400 TWh 70 EJ
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 technical potential = ~10% of theoretical potential, globally)	Theoretical: 498,000 TWh 1,800 EJ Technical: 53,000 TWh 190 EJ

* Where used, wind resource classes refer to the following wind densities at a 50 meter hub height: Class 1 (< 200 W/m^2), Class 2 (200-300 W/m^2), Class 3 (300-400 W/m^2), Class 4 (400-500 W/m^2), Class 5 (500-600 W/m^2), Class 6 (600-800 W/m^2), and Class 7 (>800 W/m^2).

** Converting between EJ and TWh is based on the primary energy method of accounting used by IEA. 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 these studies, the global technical potential for wind ranges from a low of 70 EJ/yr to a high of 1,000 EJ/yr, or from 19,400 to 278,000 TWh/yr (excluded here is Lu *et al*., 2009, as that study estimates potential wind generation that is arguably somewhere in between technical and theoretical potential); this range equates to one to 15 times 2007 global electricity demand. Results vary based on whether off-shore wind is included, the wind speed data that are used, the areas assumed available for wind development, the rated output of wind turbines installed per unit of land area, and the assumed performance of wind projects, which itself is related to hub height and turbine technology.

There are three main reasons to believe that many of the studies reported in Table 7.1 may understate the technically exploitable global wind resource. First, several of the studies are dated, and advances in wind technology and resource assessment methods have occurred since that time. The five most-recent studies listed in Table 7.1, for example, calculate larger technical resource potentials than the earlier studies (i.e., Hoogwijk *et al.*, 2004; WBGU, 2004; Archer and Jacobson, 2005; Hoogwijk and Graus, 2008; Lu *et al.*, 2009).

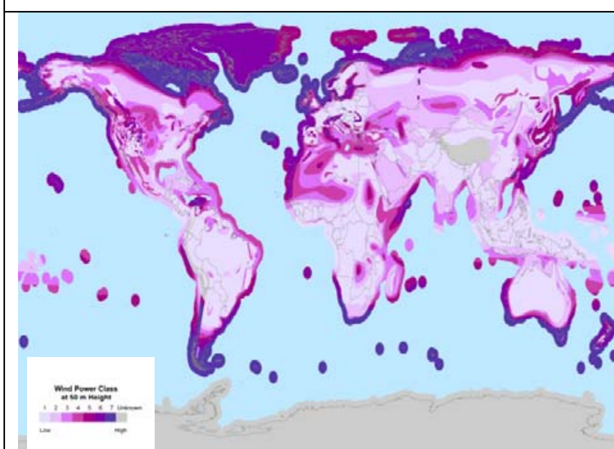
Second, a number of the studies included in Table 7.1 exclude off-shore wind energy. The scale of the off-shore wind energy resource is, at least theoretically, enormous, and constraints are less-technical [TSU: less technical] than they are economic. In particular, water depth, accessibility, and grid interconnection may constrain 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 (EWEA, 2009). Relatively few studies have investigated the global off-shore technical wind 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 potential of 37,000 TWh/yr at depths less than 50m. Building from Fellows (2000), Hoogwijk and Graus (2008) estimate a global off-shore wind potential of 6,100 TWh/yr by 2050 at costs under $0.09/kWh in real 2005$ (Fellows, 2000, provides an estimate of almost 5,000 TWh/yr). In another study, Siegfriedsen *et al*. (2003) calculate the technical potential of off-shore wind outside of Europe as 4,600 TWh/yr. Lu *et al*. (2009) estimate an off-shore wind resource potential of 150,000 TWh/yr, 42,000 TWh/yr of which is available at depths of less than 20m, though this number represents theoretical – not technical – potential. Regionally, studies have estimated the scale of the off-shore wind resource in the E.U.

(Matthies *et al*., 1995; Delft University *et al*., 2001), the U.S. (Kempton *et al*., 2007; Jiang *et al*., 2008; Heimiller *et al*., 2010), and China[3]. In general, these studies have found that the scale of the off-shore wind resource is significant, and highly dependent on assumed technology developments.

Finally, even some of the more-recent studies reported in Table 7.1 likely understate the global wind energy resource due to methodological limitations. The global assessments described here 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. Enabled in part by an increase in computing power, more sophisticated and finer-resolution atmospheric modelling approaches are beginning to be applied (and, increasingly, validated) on a country or regional basis, as described in more depth in Section 7.2.2. Experience shows that these increasingly sophisticated techniques have often identified greater actual wind resource potential than the earlier global assessments had previously estimated, especially in areas that previously were found to have limited resource potential (see Section 7.2.2). These approaches have only begun to be applied on a global basis, and the results of these analyses are likely to lead to revisions to global estimates of technical wind resource potential, and to an improved understanding of the location of that potential. As visual demonstration of some of these advancements, Figure 7.1(a,b) presents two global wind resource maps, one created in 1981 (Elliott *et al*., 1981) and another in 2009 (3TIER, 2009).

(a) 1981 Global wind resource map

(Elliott *et al*., 1981)



(b) 2009 Global wind resource map

(3TIER, 2009)

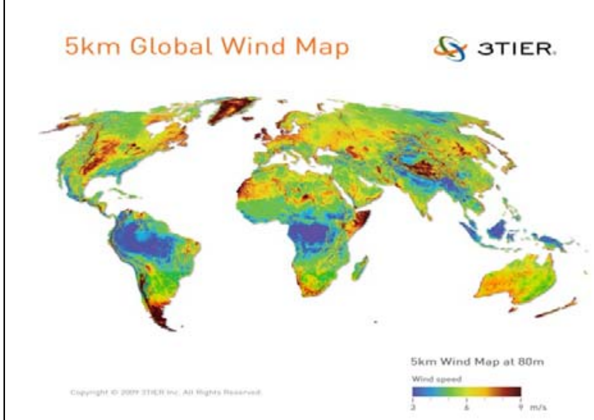


Figure 7.1(a,b). Example global wind resource maps from 1981 and 2009.

Despite these limitations, the current body of literature does support one main conclusion: the global wind resource is unlikely to be a limiting factor on global wind 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 the absolute technical limits to harvesting the wind resource are met.

7.2.2 Regional technical resource potential

7.2.2.1 Global assessment results, by region

The global wind resource assessments summarized is Section 7.2.1 generally find that not only is the wind resource unlikely to pose a significant *global* barrier to wind energy expansion, but also

[3] http://swera.unep.net/

that ample technical potential exists in most regions of the world to enable significant wind development. That said, 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.

The global assessments presented earlier have come to varying conclusions about the relative on-shore wind resource potential of different regions, and Table 7.2 summarizes results from a sub-set of the assessments. These differences 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 development, and assumed wind project performance (Hoogwijk *et al.*, 2004); differing regional categories also complicate comparisons. Nonetheless, the wind resource in North America and the former Soviet Union are found to be particularly sizable, while some areas of Asia appear to have relatively limited on-shore resource 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 potential (e.g., Fellows, 2000), and more detailed country and regional wind resource assessments have come to differing conclusions on, for example, the wind resource in East Asia and other regions (Hoogwijk and Graus, 2008)**.**

Table 7.2. Regional allocation of global technical on-shore wind resource potential*.

Grubb and Meyer (1993)		**WEC (1994)**		**Hoogwijk and Graus (2008)****		**Lu et al. (2009)**	
Region	%	Region	%	Region	%	Region	%
Western Europe	9%	Western Europe	7%	OECD Europe	4%	OECD Europe	4%
North America	26%	North America	26%	North America	41%	North America	22%
Latin America	10%	L. America & Carib.	11%	Latin America	11%	Latin America	9%
E. Europe & FSU	20%	E. Europe & FSU	23%	Non-OECD Europe & FSU	18%	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	9%	Oceania	15%	Oceania	13%
Rest of Asia	9%	Pacific	14%	Rest of Asia	3%	Rest of Asia	9%
		Rest of Asia	4%				

* Some regions have been combined to improve comparability among the four studies.

** Hoogwijk et al. (2004) show similar results.

Hoogwijk *et al.* (2004) also compare on-shore [TSU: emphasis helpful] technical potential against regional electricity consumption in 1996. In most of the 17 regions evaluated, on-shore wind potential exceeded electricity consumption in 1996. The multiple is over five in 10 regions: East Africa, Oceania, Canada, North Africa, South America, Former Soviet Union, Central America, West Africa, United States, and the Middle East. Areas in which on-shore wind 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.

The estimates reported in Table 7.2 ignore off-shore [TSU: emphasis helpful] wind potential. Hoogwijk and Graus (2008) estimate that of the 6,100 TWh of technically/economically exploitable off-shore wind resource by 2050, the largest opportunities exist in OECD Europe (approximately

22% of global potential), Latin America (approximately 22%), non-OECD Europe and FSU (approximately 17%), with somewhat less but still significant potential in Asia and Oceania (approximately 13%, each), North America (approximately 9%), and Africa and the Middle East (approximately 4%).

With some exceptions, virtually every region or continent appears to have adequate technically exploitable wind resource potential to enable significant wind energy development. As a result, economic, institutional, social, and land-use constraints are most likely to restrict the growth of wind energy, at least in the medium term.

7.2.2.2 ´Regional assessment results

The global wind energy assessments described previously have, historically, relied primarily on relatively coarse and imprecise estimates of the wind resource, sometimes relying heavily on measurement stations in urban areas with relatively poor exposure to the wind resources (Elliott, 2002; Elliot *et al*., 2004). The regional results from these global assessments, as presented in Section 7.2.2.1, should therefore be considered uncertain, especially in areas in which wind measurement data is of limited quantity and quality. More-detailed country and regional assessments, on the other hand, have benefited from wind energy specific wind speed data collection, increasingly sophisticated numerical wind resource prediction techniques, enhanced validation of model results, and a dramatic growth in computing power. These advancements have allowed more-recent country and regional resource assessments to capture smaller-scale terrain features and temporal variations in predicted wind speeds, at a variety of possible turbine heights.

Initially, these techniques were applied primarily in the E.U.[4] and the U.S.[5], but there are now publicly available high-resolution wind resource assessments covering a wide range of regions and countries. The United Nations Environment Program's Solar and Wind Energy Resource Assessment (SWERA), for example, provides information about wind energy resources in a large number of its partner countries around the world,[6] while the European Bank for Reconstruction and Development has developed RE assessments in its countries of operation (Black and Veatch, 2003). A number of other publicly available country-level assessments have been produced by the U.S. National Renewable Energy Laboratory,[7] Denmark's Risø DTU[8], and others.[9] Additional details on the status of wind resource assessment in China and Russia are offered in Text Box 7.2.

These more-detailed regional wind resource assessments have generally found the scale of the known wind energy resource to be greater than estimated in previous global or regional assessments. This is due primarily to improved data and analytic techniques, and greater resolution of smaller-scale terrain features, but it 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). Additional methodological improvements to provide even greater spatial and temporal resolution, and enhanced validation of model results with observational data, are needed, as is an expanded coverage of these assessments to a growing number of countries and regions (see, e.g., IEA, 2008; Schreck *et al*., 2008). These developments will further improve our understanding of

[4] For the latest publicly available European wind resource map, see http://www.windatlas.dk/Europe/Index.htm. Publicly available assessments for individual E.U. countries are summarized in EWEA (2009).

[5] 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).

[6] See http://swera.unep.net/index.php?id=7

[7] See http://www.nrel.gov/wind/international_wind_resources.html

[8] See http://www.windatlas.dk/World/About.html

[9] A number of companies offer wind resource mapping assessments for a fee; those assessments are not included in the table.

wind energy resource potential, and will likely highlight regions with high-quality potential that have not previously been identified.

Text box 7.2. Advancements in wind resource assessment in China and Russia

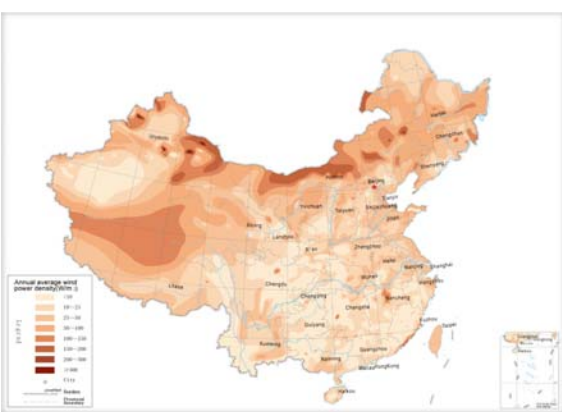
As demonstration of the growing use of sophisticated wind resource assessment tools outside of the E.U. and U.S., historical and ongoing efforts in China and FSU to better characterize those areas' wind resources are described here. In both cases, the wind resource has been found to be sizable compared to present electricity consumption, and recent analyses offer enhanced understanding of the 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 of technically exploitable on-shore wind resources (Xue *et al*. 2001). More recently, increased access to meteorological observation data and improved data quality are facilitating a more-detailed assessment. This third assessment is based primarily on data from 2,384 meteorological stations, supplemented with data from other sources (CMA, 2006). Though it is still mainly based on measured wind speeds at 10m, most data cover a period of over 50 years. Figure 7.2.2 shows the results of this investigation, focused on the on-shore wind resource. Based on this work, the CMA now estimates 297 GW of on-shore wind potential; other recent research has estimated a far-greater potential resource (see, e.g., McElroy *et al.*, 2009; Li and Ma, 2009). To further improve its estimations, the CMA is also executing several projects that rely on mesoscale atmospheric models for wind resource mapping, and is performing higher-resolution resource assessments in several key wind resource areas in China.

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 (see Figure 7.2.2). Based on this work, and after making assumptions for 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/yr, 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, 2006)



(b) Russia, CIS, Baltic wind resource map

(Nikolaev *et al*., 2008)

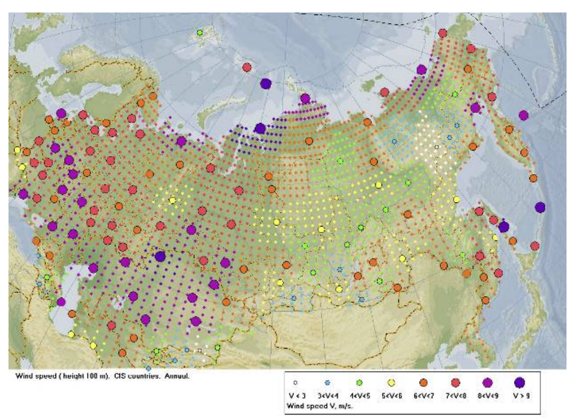


Figure 7.2(a,b). Wind resource maps for China and Russia/CIS/Baltic.

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 external conditions for wind developments. However, research in this field is nascent, 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). Additionally, empirical and dynamical downscaling studies show large model-to-model variability (Pryor *et al.*, 2005; Pryor *et al.*, 2006). Nevertheless, based on the state-of-the-art, it appears unlikely that mean wind speeds and energy density will change by more than the inter-annual variability (i.e. ±15%) over most of Europe and North America during the present century (Breslow and Sailor, 2002; Pryor *et al.*, 2005; Pryor *et al.*, 2006; Walter *et al.*, 2006; Bloom *et al.*, 2008; Sailor *et al.*, 2008). Brazil has a large wind resource that was estimated to substantially decline by up to 60% by 2100 in one study (Schaeffer *et al.*, 2008), possibly due to the simplifying assumptions employed. Conversely, simulations for the west coast of South America showed increases in mean wind speeds of up to +15% over the same period (Garreaud and Falvey, 2009). Inter-annual variability across much of Europe (the standard deviation of annual wind indices) is ±10-15%, while inter-decadal variability is ±30% (Petersen *et al.*, 1998). Whether this variability has or will change as the global climate evolves is uncertain (Pryor *et al.*, 2009) [TSU: link to previous sentence unclear (South America/Europe)].

The prevalence of extreme winds and the probability of icing have implications for wind turbine design, as well as operation and maintenance [TSU: please use abbr. O&M] (Claussen *et al.*, 2007; Dalili *et al.*, 2009). Preliminary studies from northern and central Europe show some evidence for increased magnitude of 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 projects, and changes in sea ice and/or permafrost conditions may also influence access for wind farm maintenance (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).

7.3 Technology and applications

7.3.1 Introduction

Modern utility-scale wind turbines have evolved from small, simple machines to large-scale, highly sophisticated and complicated devices. Scientific and engineering expertise, as well as computational tools and design standards, have developed to support modern wind technology. As a result, wind turbine size has increased by a factor of 100 since the late 1970s and early 1980s, while the cost of energy production from wind has been reduced by a factor of five (EWEA, 2009).

On-shore wind technology can be considered reasonably mature; additional advances in R&D are anticipated, and are expected to further reduce the cost of wind electricity, but current technology is already being manufactured and deployed on a commercial scale. Off-shore wind technology, on the other hand, is still developing, with greater opportunities for additional advancement. This section summarizes the historical development and technology status of utility-scale on-shore and off-shore wind turbines (7.3.2), discusses international wind technology standards (7.3.3), and reviews grid connection issues (7.3.4); a later section (7.7) describes opportunities for further advancements.

7.3.2 Technology development and status

The generation of electricity from wind requires that the kinetic energy of moving air be converted to mechanical and then electrical energy, and the engineering challenge for the wind industry is to design efficient wind turbines to perform this conversion. The amount of energy in the wind available for extraction increases with the cube of wind speed. However, a turbine can capture only a portion of that increase because, 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). Modern utility-scale wind turbines employ rotors that start extracting energy from the wind at speeds of roughly 3-5 m/s. The turbine maximizes power production until it reaches its rated power level, corresponding to a wind speed of approximately 12-15 m/s. At higher wind speeds, control systems limit power output to prevent overloading the wind turbine, either through stall control or through pitching the blades. Turbines will stop producing energy at wind speeds of approximately 25-30 m/s to limit loads on the rotor and prevent damage to the turbine's structural components.

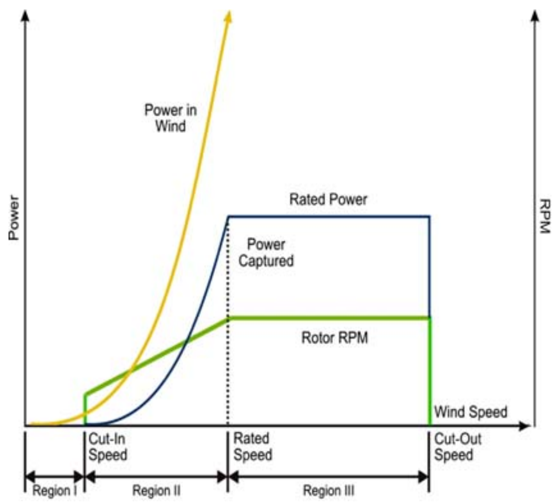


Figure 7.3. Conceptual power curve for modern wind turbine (U.S. DOE, 2008).

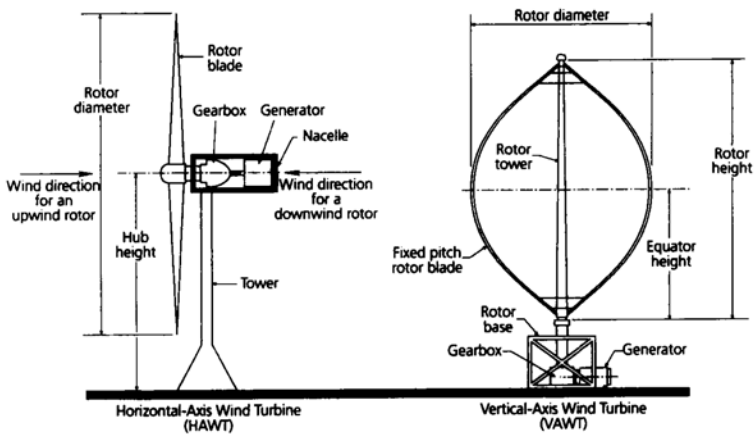
In general, the speed of the wind increases with height above the ground, encouraging wind engineers to design taller and larger wind turbines while minimizing the cost of materials. Wind speeds also vary geographically and temporally, influencing the location of wind projects, the economics of those projects, and the implications of increased wind generation on electric power system operations.

7.3.2.1 On-shore wind technology

In the 1970s and 1980s, a variety of wind turbine configurations were investigated (see Figure 7.4), including both horizontal and vertical axis designs (see Figure 7.5). 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 turbine (Figure 7.5). 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.

Source: Risø DTU

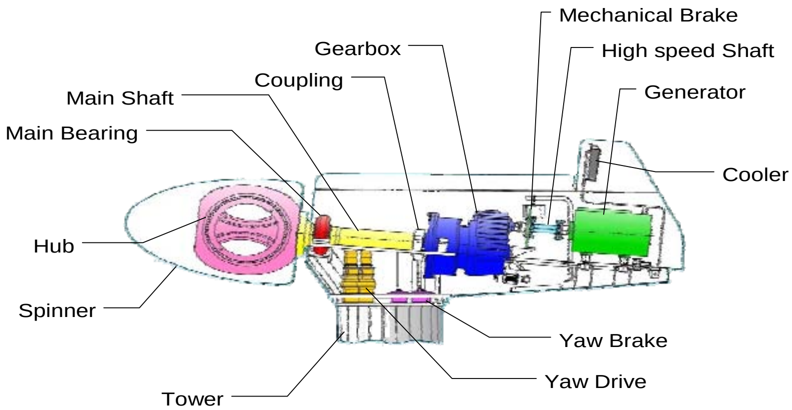
Figure 7.4. Early wind turbine designs.



Source: Risø DTU

Figure 7.5. Horizontal- and vertical-axis wind turbine designs.

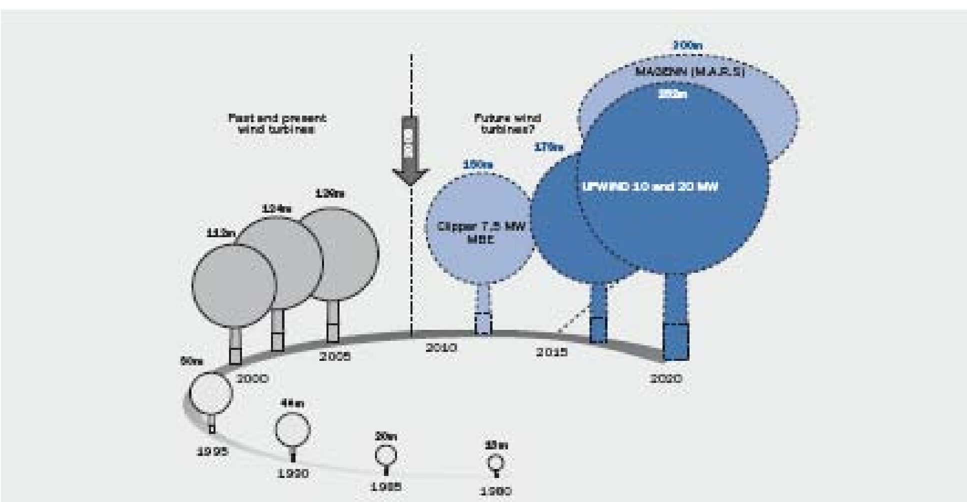
In the 1980s, larger machines were rated at around 100 kW and relied on aerodynamic blade stall to regulate power production from the fixed blades. These turbines generally operated at one or two rotational speeds. As turbine size increased over time, development went from stall control to full-span 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 utility system operators require the continued operation of large wind projects 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 grid integration issues). Today, wind turbines typically operate at variable speeds using full-span blade pitch control. Blades are commonly constructed from glass polyester or glass epoxy, and the towers are usually tubular steel structures that taper from the base to the nacelle at the top. Figure 7.6 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.



Source: Vestas

Figure 7.6. The basic components of a modern wind turbine with a gearbox.

Over the past 30 years, average wind turbine capacity ratings have grown significantly (Figure 7.7), with the largest fraction of land-based utility-scale wind turbines installed globally in 2008 having a rated capacity of 1 MW to 3 MW; the average size of turbines installed in 2008 was 1.6 MW (BTM, 2009). Such turbines typically stand on 60-100 meter towers, with rotors 70-100 meters in diameter. The main reason for this continual increase in size has been to try to optimize wind installations by increasing electricity production (taller towers provide access to a higher-quality wind resource, and larger rotors allow a greater exploitation of those winds), 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 maintenance 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; the cost of and difficulty in obtaining large cranes to lift the components in place; and the impact of larger turbines on the visual quality of the landscape especially in areas of high population density. As a result, some turbine designers do not expect land-based turbines to grow to a size much larger than about 3-5 MW (U.S. DOE, 2008).



Source: Garrad Hassan

Figure 7.7. Growth in size of commercial wind turbines.

Modern on-shore wind turbines are typically grouped together into wind farms, sometimes called wind projects, which can range from a few megawatts to up to or even exceeding 500 MW. 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 over a decade operates a total of 6,666 hours.

As a result of the above developments, on-shore wind technology has reached a state of relative maturity such that the industry is considered a viable electricity producing option for power systems. As demonstration of the maturity of the technology [TSU: sentence incomplete?], 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. 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 Betz limit. Moreover, operation and maintenance [TSU: please use abbr. O&M] teams work to maintain high plant availability despite component failure rates that have, in some instances, been higher than expected. 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 2009b). Though these results are encouraging, and the technology has reached sufficient commercial maturity to allow large-scale manufacturing and deployment, additional advancements to improve reliability, increase electricity production, and lower costs are anticipated, and are discussed in Section 7.7.

In summary, on-shore wind turbine technology is relatively mature, and is ready for wide-scale deployment. Most of the historical technology developments, however, have occurred in developed countries. Increasingly, developing countries are investigating the potential installation of wind technology. Opportunities for technology transfer in wind turbine design, component manufacturing, and wind project siting exist. In addition, 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 technology

The first off-shore wind project was built in 1991 at Vindeby, Denmark, and consisted of eleven 450 kW wind turbines. Since then, most off-shore wind installations have taken place in the UK, Denmark, the Netherlands, and Sweden. The off-shore wind sector remains relatively immature and, at the end of 2008, about 1,500 MW of off-shore wind capacity was installed globally, just 1.1% of overall installed wind capacity (BTM, 2009). Interest in off-shore wind is the result of several factors: the higher-quality wind resources located at sea (e.g., higher wind speeds, lower turbulence, and lower shear); the ability to use even-larger wind turbines due to reduced transportation constraints and the potential to thereby gain further economies of scale; the ability for more-flexible turbine designs given the uniqueness of the off-shore environment (e.g., lower turbulence, less wind shear, no constraints on noise); a potential reduction in the need for new, long-distance, land-based transmission infrastructure[10]; the ability to build larger projects than on-shore, gaining project-level economies of scale; and the potential reduction of visual impacts and mitigation of siting controversies if projects are located far-enough from shore (Carbon Trust, 2008a; Snyder and Kaiser, 2009). These factors, combined with a significant off-shore wind resource potential, has created considerable interest in off-shore wind technology in the E.U.; that interest has begun to expand (albeit more slowly) to the U.S., China, and elsewhere.

[10] Of course, transmission infrastructure would be needed to connect off-shore wind projects with electricity demand centers as well. Whether that infrastructure is more or less extensive than that needed to access on-shore wind varies by location.

Average turbine size for off-shore wind projects is 2-4 MW (as of 2005-2009), with a maximum size of 5 MW, and even larger turbines are under development. Off-shore wind projects installed through 2008 range in size up to roughly 200 MW, with a clear trend towards larger turbines and projects over time. Water depths for off-shore wind turbines installed to date have generally been modest, starting at 5-10 meters and reaching a typical 15-20 meters by 2009, and sea conditions have often been somewhat sheltered. However, as experience is gained, it is expected that water depths will increase and that 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, 2008a). The mono-pile foundation is the most common, though concrete gravity-based foundations have also been used; a variety of alternative foundation designs are being considered, especially as water depth increases, 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, in part because concerns about noise are reduced for off-shore projects and higher tip speeds can sometimes lead to greater aerodynamic efficiencies, and 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 technology is still under development, and lower project availabilities and higher operations and maintenance (O&M) [TSU: please use abbr. O&M] costs have been common for the early installations (Carbon Trust, 2008a). Wind 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 (E.U., 2008). More subtle differences in technology are also emerging, due to the different environment in which off-shore turbines operate and the increased need for turbine reliability. For example, the availability of off-shore wind turbines is lower than for on-shore projects due to reduced accessibility resulting from harsh operating conditions; both high winds and seas can make access impossible at times, and jobs that require off-shore cranes can involve considerable delays while waiting for suitably calm conditions. There is therefore a push to design off-shore turbines to reach higher levels of reliability than on-shore turbines (EWEA, 2009).

7.3.3 International wind 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 projects. 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, testing. Figure 7.8 (a) illustrates the design and testing procedures required to obtain a wind turbine type certification.

Project certification, shown in Figure 7.8 (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 project commissioning.

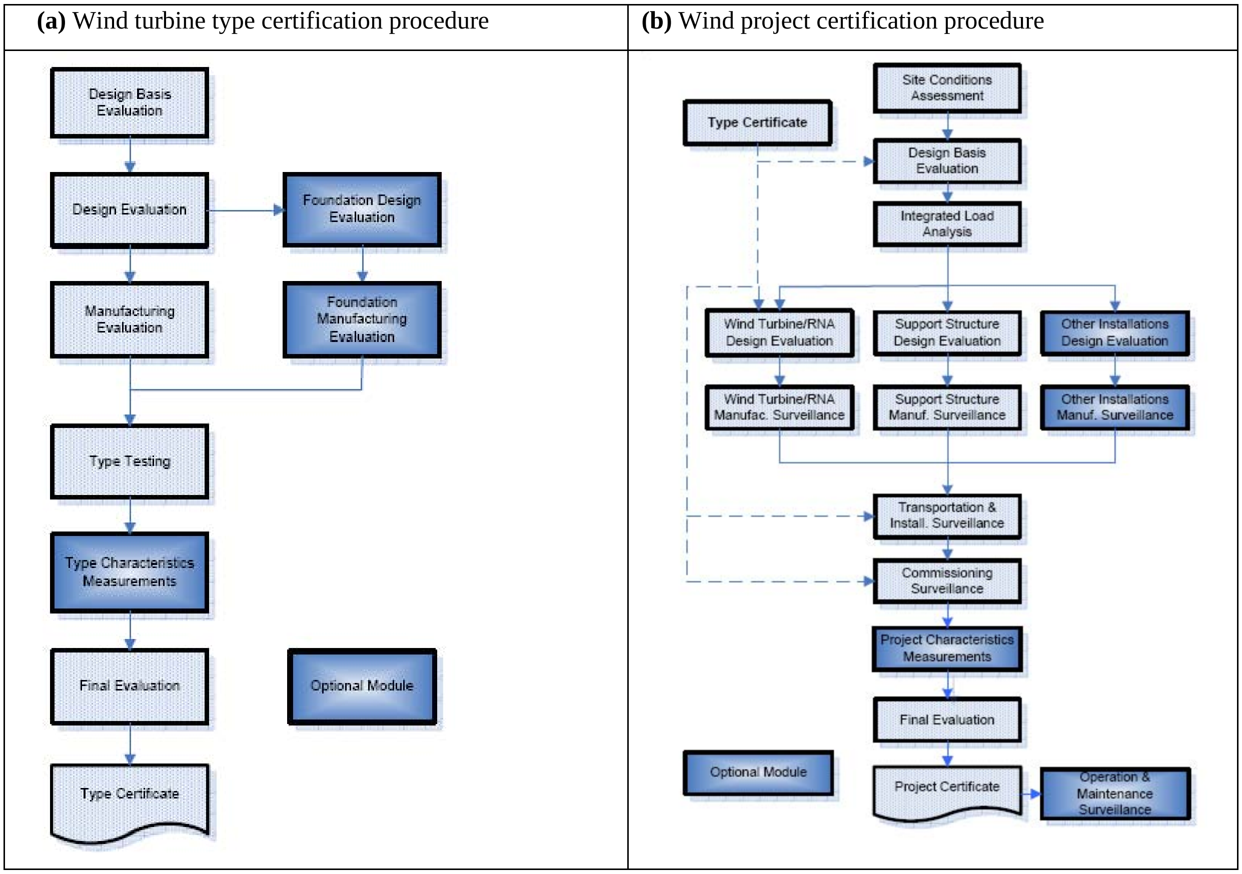


Figure 7.8(a,b). Modules for (a) type certification and (b) project certification (IEC, 2008a).

Insurance companies, financing institutions, and project owners normally require some form of certification for projects 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 Grid connection issues

Wind turbines can affect the reliability of the electrical network. As wind turbine installations have increased, so too has the need for wind projects to become more active participants in maintaining (rather than passively depending on) the operability and power quality of the grid. 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 grid operators have developed minimum requirements (sometimes called “grid codes”) that wind energy facilities (and other power plants) must meet when connecting to the power system (further discussion of these requirements and the institutional elements of wind energy integration are addressed in Section 7.5, and a more general discussion of RE integration is covered in Chapter 8). These requirements can be met through turbine manufacturer modifications to wind turbine designs, or through the addition of auxiliary equipment such as power conditioning equipment.

From a power system reliability perspective, an important part of the wind turbine is the electrical conversion system, which for large grid-connected turbines comes 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 power system. These designs have now been largely replaced with variable speed wind turbines. 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 fault ride-through capability, which are increasingly being required for power system reliability. Variable speed machines therefore offer a number of power quality advantages over the earlier turbine designs (Ackermann, 2005). These variable speed designs essentially decouple the rotating masses of the turbine from the electrical power system, a design that offers a number of power quality advantages over the earlier turbine designs (EWEA, 2009). However, this design results in no intrinsic inertial response capability; additional turbine controls must be implemented that create the effect of inertia (Mullane and O'Malley, 2005). Wind turbine manufacturers have recognized this lack of intrinsic inertial response as a long term impediment to wind penetration and are actively pursuing a variety of solutions.

7.4 Global and regional status of market and industry development

The wind energy market has expanded substantially in the 2000s, demonstrating the maturity of the technology and industry, the relative economic competitiveness of wind electricity, and the importance placed on wind energy development by a number of countries through policy support measures. This section summarizes the global (7.4.1) and regional (7.4.2) status of wind energy development, discusses trends in the wind industry (7.4.3), and highlights the importance of policy actions in the wind energy market (7.4.4). Overall, the section demonstrates that the on-shore wind energy technology and industry is already sufficiently mature and cost effective to allow for significant deployment. At the same time, off-shore wind energy is developing slowly, and even on-shore wind expansion has been concentrated in a limited number of regions and contributes just 1.5% of global electricity supply. Further expansion of wind energy, especially off-shore and in under-represented regions, is likely to require additional policy measures.

7.4.1 Global status and trends

Global wind energy capacity has been growing at a rapid pace and, as a result, wind energy has quickly established itself as part of the mainstream electricity industry (see Figure 7.9). From 1998 through 2008, the average annual increase in cumulative installed capacity was 29%. From a cumulative capacity of 10 GW in 1998 the global installed capacity increased twelve-fold in ten years to reach more than 120 GW at the end of 2008, an average annual increase in cumulative capacity of 29%. In another [TSU: wording unclear] record year for new installations, global annual wind capacity additions equalled more than 27 GW in 2008, up from 20 GW in 2007 and 15 GW in 2006 (BTM, 2009; GWEC, 2009). A slower rate of growth in cumulative capacity is expected in 2009, however, in part due to the global economic crisis (BTM, 2009).

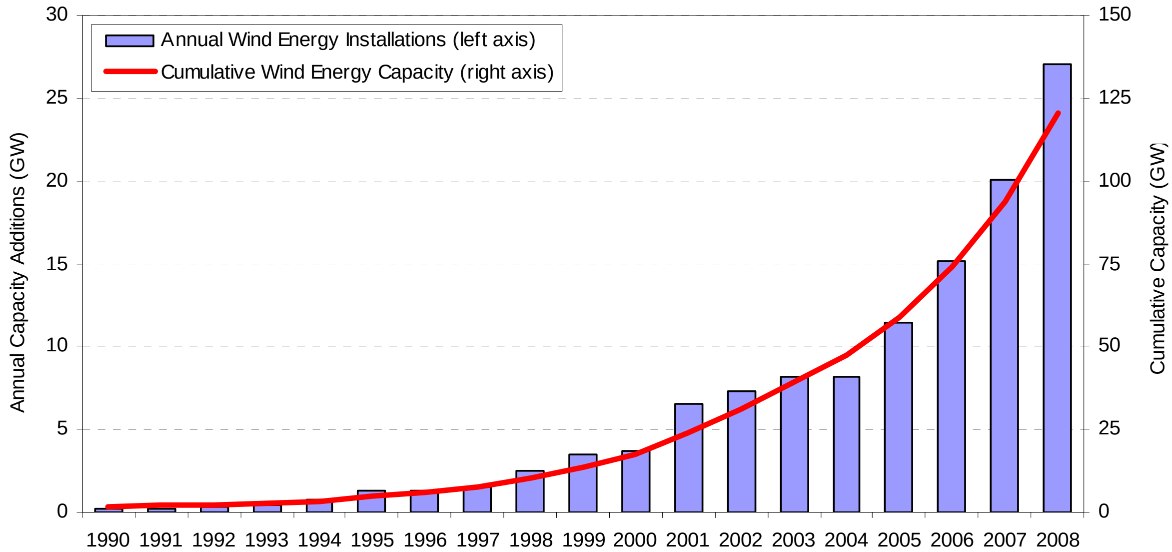


Figure 7.9. Global cumulative and annual installed wind capacity (EWEA, 2009; GWEC, 2009; Wiser and Bolinger, 2009).

The bulk of the capacity has been installed on-shore, with off-shore installations constituting a small proportion of the total wind turbine market. About 1,500 MW of off-shore wind turbines have been installed, primarily in European waters, with plans for a further 4 GW of off-shore wind installation by 2010 (GWEC, 2009). Off-shore wind is expected to develop in a more-significant way in the years ahead as the technology becomes more mature, and as on-shore wind sites become constrained by resource availability and/or siting challenges in some regions (BTM, 2009).

In terms of economic value, the total cost of new wind generating equipment installed in 2008 was US$45 billion (2005$; REN21, 2009). Direct employment in the wind energy sector in 2008 has been estimated to equal roughly 105,000 in the E.U. (Blanco and Rodrigues, 2009) and 85,000 in the United States (AWEA, 2009a). Worldwide, direct employment in the wind industry is estimated at approximately 400,000 (GWEC, 2009).

Despite these trends, wind generated electricity remains a relatively small fraction of worldwide electricity supply. The total wind energy capacity installed by the end of 2008 would, in an average year, deliver roughly 1.5% of worldwide electricity supply, up from 1.2% at the end of 2007 and 0.9% at the end of 2006 (Wiser and Bolinger, 2009).

7.4.2 Regional and national status and trends

The countries with the highest total installed wind energy capacity at the end of 2008 were the United States (25 GW), Germany (24 GW), Spain (17 GW), China (12 GW), and India (10 GW). After its initial start in the United States in the 1980s, wind energy growth centred on countries of the E.U. during the 1990s and the early 2000s. In the late 2000s, however, the United States and China became the locations for the greatest growth in annual capacity additions (see Figure 7.10).

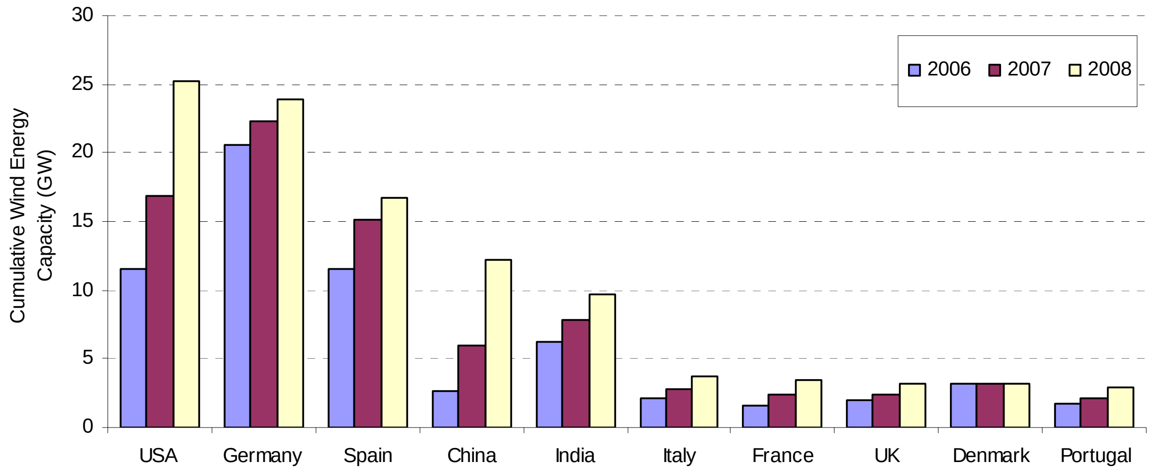


Figure 7.10. Top-10 countries in cumulative wind capacity by the end of 2008 (GWEC, 2009).

Regionally, Europe continues to lead the market with nearly 66 GW of cumulative installed wind energy capacity at the end of 2008, representing 55% of the global total. Despite the continuing growth in Europe, the general trend has been for the wind energy industry to become less reliant on a few key markets over time, and other regions are starting to catch up with Europe (see Figure 7.11). The growth in the European wind energy market in 2008, for example, accounted for just one third of the total new wind energy additions in that year, down from nearly three quarters in 2004. For the first time in decades, more than 60% of the annual wind additions occurred outside of Europe, with particularly significant growth in North America and Asia (GWEC, 2009). 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.

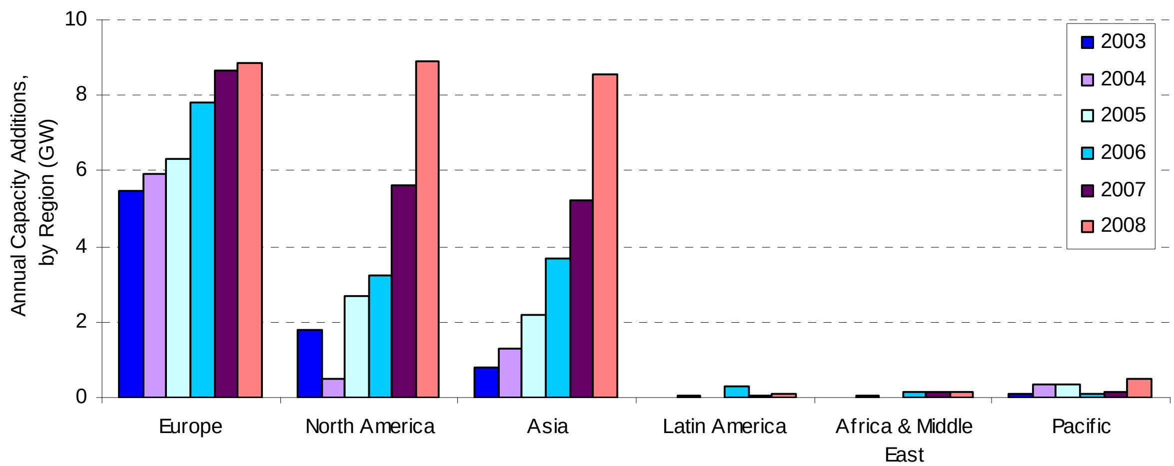


Figure 7.11. Annual wind capacity additions by region (GWEC, 2009).

Despite the increased globalization of wind energy capacity additions, the market remains concentrated regionally. Latin America, Africa, the Middle East, and the Pacific regions have to date installed relatively little wind energy generation capacity. And, even in the regions of significant growth, most of that growth is occurring in a limited number of countries. In 2008, for example, 88% of wind capacity additions occurred in the 10 largest markets, and 54% was concentrated in just two countries: the United States and China.

In both Europe and the United States, wind represents a major new source of electric capacity additions. From 2000 to 2008, wind was the second-largest new resource added in the U.S. (8% of all capacity additions) and E.U. (32% of all capacity additions) in terms of nameplate capacity, behind natural gas, but ahead of coal (Figure 7.12). In 2008, 42% of all capacity additions in the U.S. and 36% of all additions in the E.U. came from wind energy (Figure 7.12). On a global basis, from 2000 through 2008, wind represented roughly 10% of total net capacity additions; in 2008 alone, that figure was roughly 18%.[11]

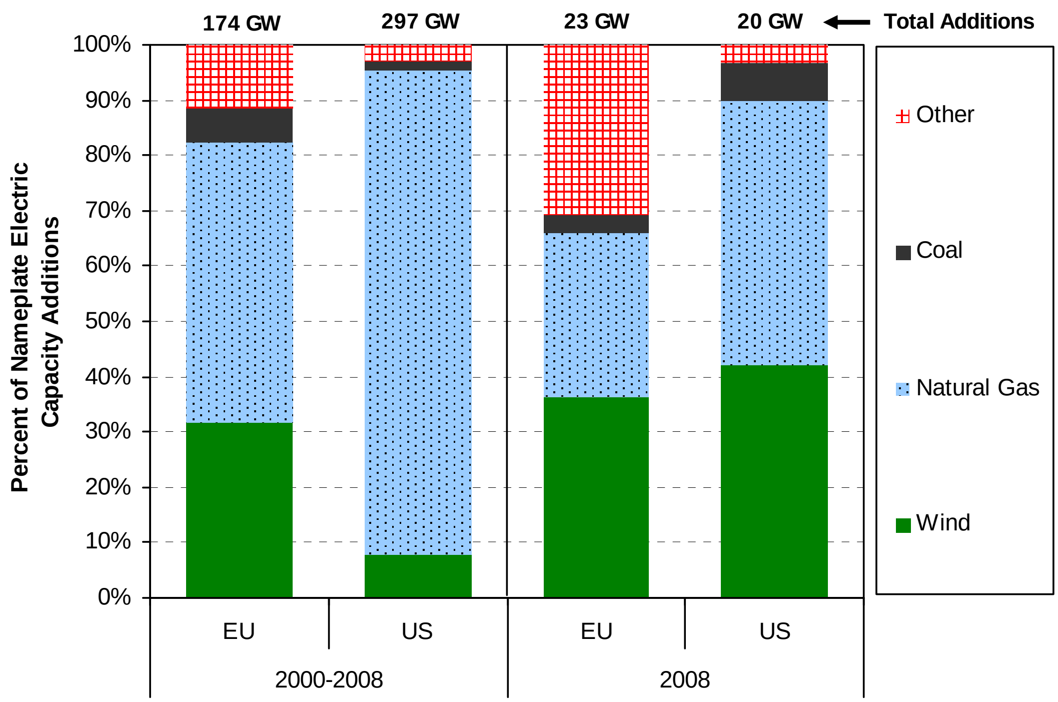


Figure 7.12. Relative contribution of generation types to capacity additions in the E.U. and U.S. (Wiser and Bolinger, 2009).

Though wind energy remains a modest contributor to global electricity supply, a number of countries are beginning to achieve relatively high levels of wind energy penetration in their respective electricity grids as a result of this expansion. Figure 7.13 presents data on end-of-2008 (and end-of-2006/07) installed wind 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 installed wind capacity, end-of-2008 wind capacity is projected to supply roughly 20% of Denmark's electricity demand, 13% of Spain's, 12% of Portugal's, 9% of Ireland's, and 8% of Germany's (Wiser and Bolinger, 2009). In the E.U. as a whole, wind capacity installed at the end of 2008 was able to meet 4.2% of electricity consumption (GWEC, 2009).

[11] Worldwide capacity additions from 2000 through 2006 come from historical data from the U.S. Energy Information Administration. Capacity additions for 2007 and 2008 are estimated based on U.S. Energy Information Administration forecasts (U.S. EIA, 2009).

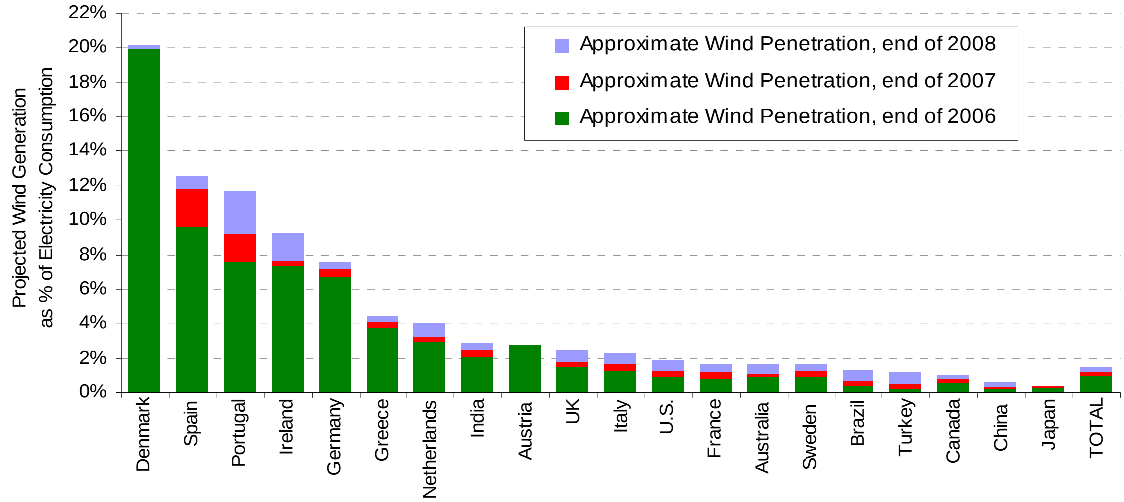


Figure 7.13. Approximate wind energy penetration in the twenty countries with the greatest installed wind capacity (Wiser and Bolinger, 2009).

7.4.3 Industry development

The growing maturity of the wind sector is illustrated not only by wind energy additions, but also by trends in the wind energy industry. In particular, companies from outside the traditional wind industry have become increasingly involved in the sector. There has been a shift in the type of companies developing and owning wind projects, from relatively small independent project developers towards large power generation companies (including electric utilities) and large independent project developers, often financed by investment banks. On the manufacturing side, the increase in the size of the market and the requirement for a substantial investment in expanded production facilities has brought in new players. The involvement of these new and larger players has, in turn, encouraged a greater globalisation of the industry. Manufacturer product strategies are shifting to address larger scale project implementations, higher capacity turbines, and lower wind speeds. More generally, wind's significant contribution to new electric generation capacity investment in several regions 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, 2009; GWEC, 2009).

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 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 (BTM, 2009). Wind turbine sales and supply chain strategies are expected to continue to take on a more international dimension as volumes increase. Already, turbine and component suppliers have an increasing focus on new production facilities in the U.S., China, and India.

Amidst the growth in wind capacity also come challenges. From 2005 through 2008, supply chain difficulties caused by growing demand strained the industry, and prices for 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 (Blanco, 2009; Bolinger and Wiser, 2009). 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. Large-scale investment decisions are more easily made based on a sound long-term outlook for the industry; but in most markets, 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. The impact of the financial crisis in 2008 and 2009 also illustrates the challenges of forecasting future growth, with wind energy additions falling in 2009, thereby at least temporarily easing supply chain bottlenecks.

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, wind energy remains more expensive than fossil-fuel generation options, at least if environmental impacts are not monetized. 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 needed to enable access to the most-attractive wind resource areas; (3) cumbersome and slow planning, siting, and permitting procedures that impede wind 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 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. 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, fed in large measure by Danish wind technology [TSU: sentence unclear] (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. In the mid to late 2000s, growth in the United States (Bird *et al.* 2005; Wiser and Bolinger, 2009) and China (Li *et al.*, 2007) was based on varied policy frameworks, including renewable portfolio standards, tax incentives, feed-in tariff mechanisms, 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 incentive policies differ, and a healthy debate exists over the relative merits of different approaches, a key finding is that policy continuity and market stability are important (see Chapter 11). Moreover, though it is not uncommon to focus on economic incentive 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 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, 2009b). 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. As a result, 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 projects to ease project implementation; access to the existing electricity grid and strategic grid planning and new investment for wind energy; and proactive efforts to manage wind energy's inherent variability. In addition, research and development by government and industry has been found to be essential to enabling incremental improvements in on-shore wind energy technology and to driving the improvements needed in off-shore wind 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) transfer can help facilitate early wind energy installations.

7.5 Near-term grid integration issues

7.5.1 Introduction

The integration of wind energy into electricity systems has become an important topic as wind energy penetration levels have increased (WWEA, 2008; Holttinen *et al.*, 2009). The nature and size of the integration challenge will be system specific and will vary with the degree of wind energy penetration. Nonetheless, the existing literature generally suggests that, in the near term, the integration of increased levels 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 additional research should facilitate the integration of even greater quantities of wind energy without degrading electrical reliability.

The near-term integration issues (approximately the next ten years) covered in this section include how to address wind energy variability and uncertainty, how to provide adequate transmission capacity to connect wind generation to electricity demand centres, and the development of connection standards and grid codes. Longer-term integration may depend on the availability of additional flexibility options to manage high wind energy penetrations, 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 power systems. These longer-term options relate to broader developments within the energy sector that are not specific to wind energy (Doherty and O'Malley, 2006; SmartGrids, 2008), and are addressed in Chapter 8.

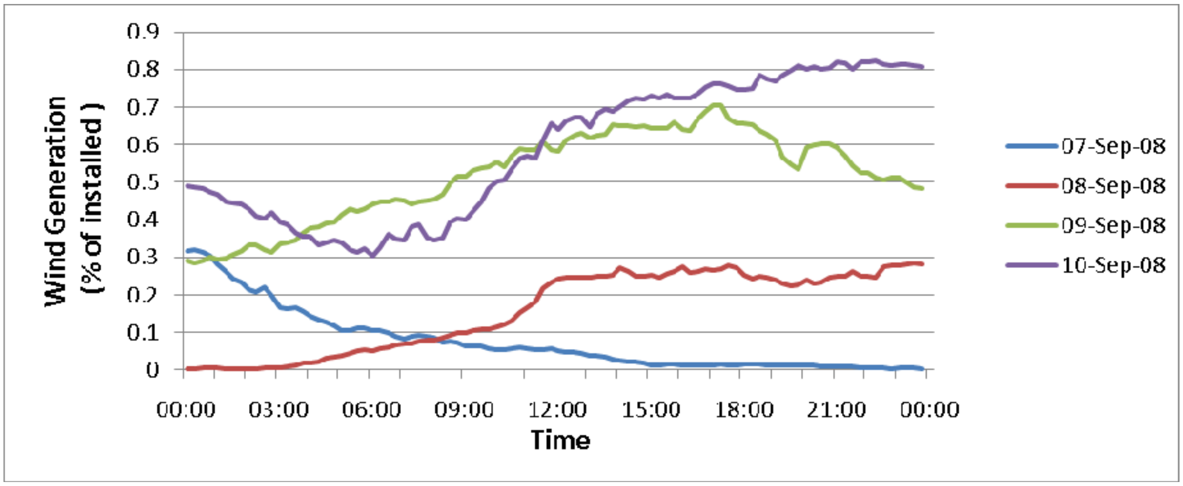
This section begins by describing the specific characteristics of wind energy that present integration challenges (7.5.2). The section then discusses how these characteristics impact issues associated with the planning (7.5.3) and operations [TSU: operation?] (7.5.4) of power systems to accommodate wind electricity, including experience in systems with high wind energy supply. 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 energy penetration.

7.5.2 Wind energy characteristics

The integration of wind energy into power systems is largely based on the same planning and operating mechanisms that are used to ensure the reliable operation of power systems without wind energy, as described in Chapter 8. Several important characteristics of wind energy are different than conventional generation, however, and these characteristics must be considered in the integration [TSU: of] wind energy into power systems.

First, the quality of the wind energy resource and, therefore, the cost of generating wind energy, are location dependent. Sites with high average wind speeds can generate power at much lower cost than sites with lower-quality wind resources, and the regions with the best wind energy resources may not be situated near high demand regions, increasing the need for additional transmission infrastructure to bring wind energy from the best wind resource sites to electricity demand centres.

Second, wind energy is weather dependent and therefore variable. The output of a wind project varies from zero to its rated capacity depending on the prevailing weather conditions; Figure 7.14 illustrates this variability by showing the output of wind projects in Ireland over four consecutive days. The most relevant characteristics of wind energy variability for power system *operations* is the rate of change in wind project output over different time periods; apparent in Figure 7.14 is that wind energy changes much more dramatically over longer periods (multiple hours) than it does in very short periods (minutes). The most relevant characteristic of wind variability for the purpose of power sector *planning*, on the other hand, is the correlation of wind energy output with the periods of time when power system reliability is at greatest risk, typically periods of high electricity demand. This correlation affects the capacity credit assigned by system planners to wind projects, as discussed further in Section 7.5.3.3.



Source: www.eirgrid.com

Figure 7.14. Wind energy supply as a proportion of installed wind capacity in Ireland on four consecutive days.

Third, in comparison with conventional generation, wind energy has lower levels of predictability. Forecasts of wind energy production over longer periods (multiple hours to days) allow for more opportunities to manage variability. Forecasts, however, are less accurate over longer forecast horizons than for shorter periods (Giebel et al., 2006); Figure 7.15 illustrates different forecasting errors over a horizon of up to 36 hours, based on several different forecasting methods.

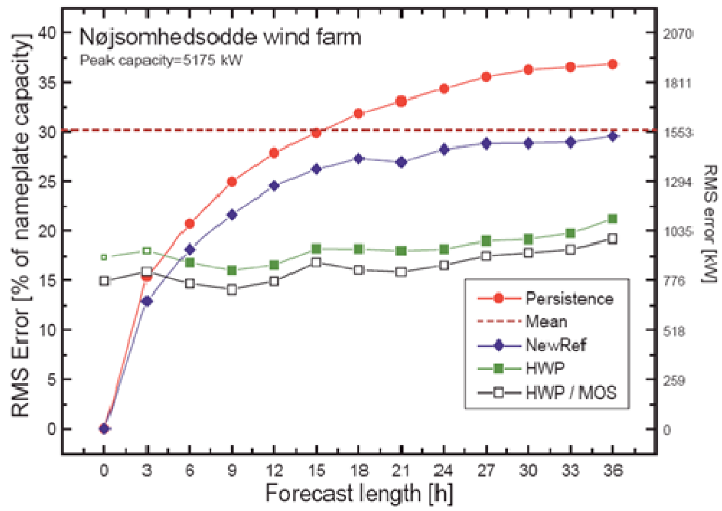


Figure 7.15. Root Mean Square (RMS) error of wind power forecasts for different forecast horizons using different forecasting methods (Giebel *et al*., 2006).

The variability and predictability of wind energy in aggregate depends, in part, on the degree of correlation between geographically dispersed wind projects. This correlation, in turn, depends on the geographic deployment of wind projects and the regional characteristics of wind patterns. Generally, the output of wind projects 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) (Wan *et al.*, 2003; Holttinen, 2005; Sinden, 2007). The decrease in correlation with distance leads to much less variability (smoothing effect) and much more accurate forecasts of aggregated wind projects over a region than the scaled output of a single wind project (nonetheless, in absolute terms, variability and forecast errors increase with increasing quantities of wind energy). The prevailing weather patterns of a region will have a large influence on all these characteristics: variability, forecasting, and the impact of geographical dispersion.

Finally, the electrical characteristics of some wind generators differ from the synchronous generators found on most conventional power projects. The variable speed wind generation technologies being installed in most wind projects (doubly fed induction generators (DFIG) and synchronous generator with a full power convertor) essentially decouple the rotating masses (turbine and generator) from the electric power system. This decoupling typically results in no inertial response (Mullane and O'Malley, 2005). Additional control capability, however, can be added to these generators to provide inertial response (Morren *et al.*, 2006). As discussed in later sections, the lack of inertial response without specific additional controls is an important consideration for system planners since less overall inertia increases the challenges related to maintaining stable system operation (Gautam *et al*., 2009).

7.5.3 Planning power systems with wind energy

Ensuring the reliable operation of power 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 (see Chapter 8). Three issues deserve attention when considering increased reliance on wind energy: the need for accurate power system models of wind projects, the creation of interconnection standards (i.e., grid codes) that account for the characteristics of wind energy, and consideration of new wind [TSU: energy] generation in evaluating transmission and generation resource adequacy.

7.5.3.1 Power system models

Power system models are used extensively in planning to evaluate the ability of the power system to accommodate new generation, changes in demand, and changes in operational practices. An important role of power system models is to demonstrate the ability of a power 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 power system and all its components behave during system events or contingencies. Similar generic models of wind generators and wind projects 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. There has been considerable progress in this area. This process is not complete, however, and the continued development of wind energy [TSU: technology] will require improved and validated models to allow planners to assess the capability of power systems to accommodate additional wind projects (Coughlan *et al.*, 2007; NERC, 2009).

7.5.3.2 Grid codes

Interconnection standards, or grid codes, are put in place to prevent equipment or facilities that interconnect with a power system from adversely affecting reliability. These grid codes are developed by power system planners, regulators, and power system operators depending on the jurisdiction. Grid codes may also specify minimum requirements that facilities or equipment must meet to help maintain power system operation during normal operation and contingencies. Power system models and operating experience are used to develop these requirements. In some cases, the unique characteristics of specific generation types are addressed in grid codes. The unique characteristics of wind turbines, for example, have resulted in dedicated “wind” grid codes in some locations (Singh and Singh, 2009).

Grid codes often require “fault ride-through” capability, or the ability of a project to remain connected and operational during brief but severe changes in power system voltage. The addition of fault ride-through requirements for wind projects in grid codes was in response to the increasing penetration of wind energy and the significant size of individual wind projects in many systems. When wind turbines are only interconnected with the power system as single turbines or in small numbers, systems can typically maintain reliable operation if these wind turbines shut-down or disconnect from the power system for protection purposes in response to fault conditions. As project sizes and the penetration of wind energy has increased, however, system planners have specified that wind projects should continue to remain operational during faults and meet minimum fault ride-through standards similar to other large conventional projects. Reactive power control to help manage voltage is also often required by grid codes. Wind turbine inertial response to increase system stability after disturbances is less common, but is beginning to be required in some grid codes (e.g., Hydro-Quebec TransEnergie, 2006).

7.5.3.3 Transmission infrastructure and resource adequacy evaluations

The addition of large quantities of wind energy to the power system will require upgrades to the transmission system. Accurate transmission adequacy evaluations must account for the locational dependence of wind resources, the relative smoothing benefits of aggregating wind over a large area, and the transmission capacity required to manage the variability of wind energy. As described in more detail in Chapter 8, one of the primary challenges with transmission expansion is the long time it takes to plan, permit, and construct new transmission relative to the time it takes to add new wind projects. Enabling high penetration of wind energy will therefore likely require proactive rather than reactive transmission planning. The need for additional transmission investment to enable wind energy supply is discussed further in Chapter 8.

Generation resource adequacy evaluations routinely assess the capability of generating resources to reliably meet electricity demand. Planners evaluate the long-term reliability of the power 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 generation 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 generation output is tightly correlated with periods of time when there is a high risk of generation shortage. For example, a 100 MW project that is assigned a capacity credit of 90% adds 90 MW to the total ability of the system to serve demand. The capacity credit of a generator is 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 toward long-term reliability can be evaluated using standard approaches, and wind generators are typically found to have a capacity credit of 5-40% of name-plate capacity (Holttinen *et al.*, 2009). The correlation between wind energy output and electrical demand is an important determinant of the capacity credit of an individual wind generator, as is the correlation between the output of different wind projects. In many cases, wind resources are uncorrelated or are weakly negatively correlated with periods of high electricity demand, reducing the capacity credit of wind projects; this is not always the case, however, and wind generation in the UK has been found to be weakly positively correlated with periods of high demand (Sinden, 2007). These correlations are highly system specific as they depend on the diurnal and seasonal characteristics of both wind generation and electricity demand.

A final important characteristic of the capacity credit for wind energy is that its value decreases as wind penetration levels rise (see figure presented in Chapter 8). This characteristic is driven by the correlation between wind project output; the higher the correlation between the output of individual wind projects the lower the capacity credit as wind energy penetration levels increase. Aggregating wind projects over larger areas reduces the correlation between wind project output and can slow the decline in capacity credit, though adequate transmission capacity is required to aggregate wind projects over larger areas in this manner (Tradewind, 2009).[12]

7.5.4 Operating power systems with wind energy

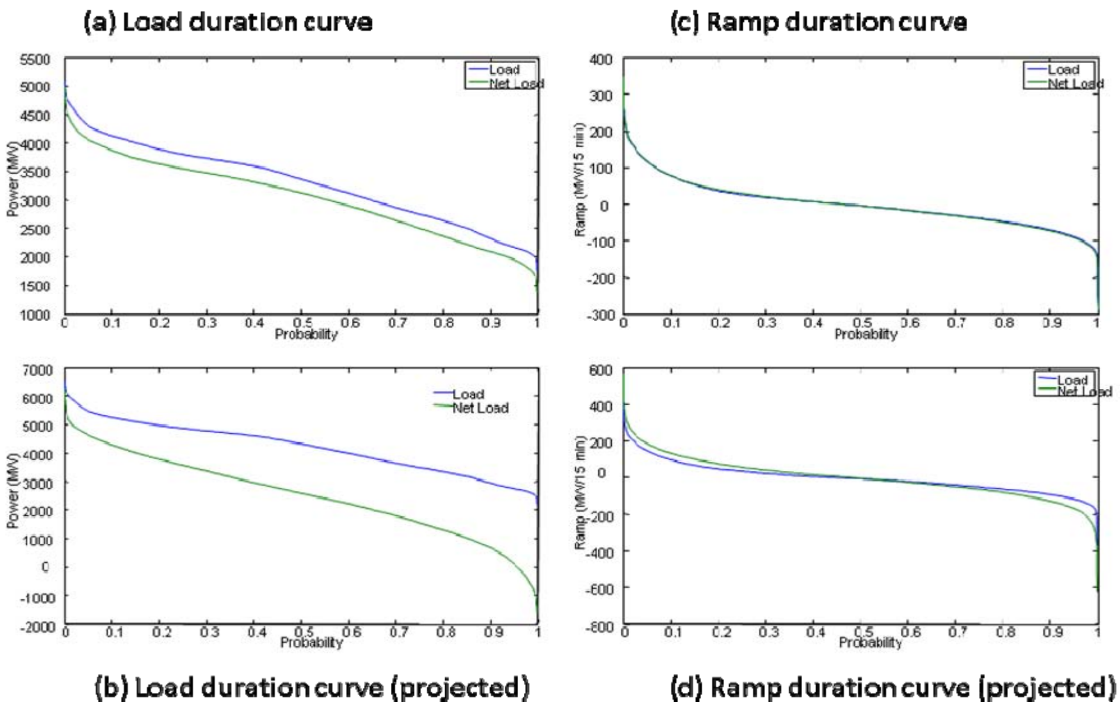
7.5.4.1 Integration, flexibility, and variability

Because wind energy is produced with a near-zero marginal cost, wind energy is typically used to meet demand when wind power is available, thereby displacing the use of conventional generators that have higher marginal operating costs. Power system operators therefore primarily dispatch conventional generators to meet demand minus any available wind generation (net demand).

As wind energy penetration grows, the variability and limited predictability of wind energy will result in an overall increase in the magnitude of changes in net demand and a decrease in the minimum net demand. Figure 7.16 shows that, at relatively low levels of wind energy penetration, the magnitude of changes in *net demand*, as shown in the ramp duration curve, is similar to the magnitude of changes in *demand* (Figure 7.16(c)), but at high levels of wind energy penetration the changes in net demand are greater than changes in total demand (Figure 7.16(d)). The figure also

[12] Generator resource adequacy evaluations are also beginning to include the capability of the system to provide adequate flexibility and operating reserves to accommodate more wind generation (NERC, 2009). The increased demand from wind for operating reserves and flexibility is addressed in Section 7.5.4.

shows that, at high levels of wind energy, the magnitude of net demand across all hours of the year is lower than total demand, and that in some hours the net demand is near or below zero (Figure 7.16(b)).



Source: www.eirgrid.com

Figure 7.16. Load and ramp duration curves for Ireland in (a,c) 2008, and (b,d) projected for high wind energy penetration levels[13].

As a result of these trends, increased wind energy will require that conventional generating units operate in a more flexible manner than required without wind energy. In the near term, it is expected that the increase in minute-to-minute variability will be relatively small and therefore inexpensive to manage in large power systems. The more significant operational challenges relates to the variability and commensurate increased need for flexibility to manage changes in wind generation over 1 to 6 hours. Incorporating state-of-the-art forecasting of wind energy over multiple time horizons into power system operations can reduce the need for flexibility and operating reserves and has been found to be critical to economically and reliably operating power systems with high levels of wind energy. Even with high-quality forecasts, however, additional start-ups and shut-downs, part-load operation, and ramping will be required from conventional units to maintain the supply/demand balance (Göransson and Johnsson, 2009; Troy and O'Malley, 2010).

Though this additional flexibility comes at a cost, proper incentives can ensure that the operational flexibility of conventional generators is made available to system operators. Many regions, for example, have day-ahead, intra-day, or hour-ahead markets for energy as well as markets for reserves and balancing energy. In these circumstances, any increase in the demand for flexibility and reserves caused by increased levels of wind energy will create enhanced incentives for generators and other resources to allocate available flexibility or capacity to the system. The creation of robust markets for such flexibility services will therefore reduce the cost impacts of

[13] Projected penetration level curves are based on scaled of 2008 data (demand is scaled by 1.27 and wind is scaled on average by 7). Ramp duration curves show the cumulative probability distributions of 15-minute changes in demand and net demand.

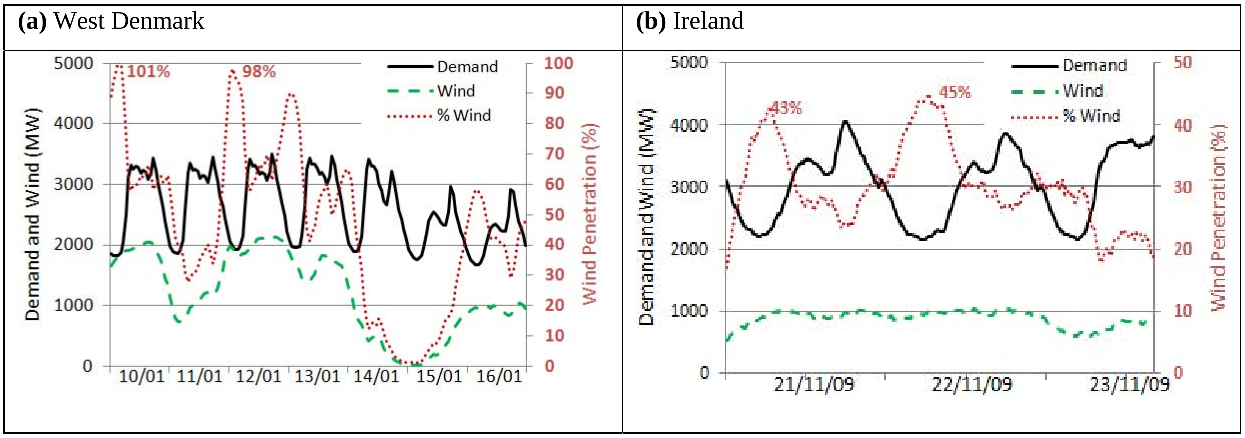
integrating wind generation (Smith *et al.*, 2007b). System operators can also increase access to this existing flexibility through shorter scheduling periods: sub-hourly, or fast energy markets, provide more access and lower costs to accommodate wind energy than do markets based on hourly schedules (Kirby and Milligan, 2008b). Hydropower units, electrical storage units, and various forms of demand response can all be used to further facilitate the integration of wind energy. Additionally, systems with high penetrations of wind energy may need to ensure that new conventional plants are flexible enough to accommodate expected wind production. Wind projects, meanwhile, can provide some flexibility by curtailing output. Though curtailment of wind output is a simple and often times readily available source of flexibility, it is also expensive because wind projects have low operating costs; as a result, wind output curtailment is not likely to be used extensively at low levels of wind energy supply.

7.5.4.2 Practical experience in integrating wind energy

Actual operating experience in different parts of the world demonstrates that wind energy can be reliably integrated into power systems (Söder *et al.*, 2007). The three examples reported here demonstrate the challenges associated with this integration, and the methods used to manage the additional variability, uncertainty, and transmission system impacts associated with wind energy. Naturally, these impacts and management methods vary across regions for reasons of geography, power system design, and regulatory structure.

Denmark has the largest wind energy penetration of any country in the world, with wind energy supplies of 20% of total annual electrical demand (Figure 7.17). The Danish example demonstrates the value of access to markets for flexible resources and strong transmission connections to neighbouring countries. The Danish transmission system operator operates its system without serious reliability issues in part because Denmark is well interconnected to two different synchronous electrical systems. Those markets help the operator manage wind energy output 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 increased its wind energy supply (EA Energianalyse, 2007).

In contrast to the strong interconnections of the Danish system with other systems, Ireland has a single synchronous system; it is of similar size system to the Danish system but interconnection capacity is limited to a single 400 MW link. Wind capacity installed at the end of 2009 was capable of generating 11% of Ireland’s electricity, and the Irish system operators have successfully managed that level of wind energy supply. The large daily variation in electricity demand in Ireland, combined with the isolated nature of the Irish system, has resulted in a very flexible electricity 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 energy supply of over 40%. Nonetheless, it is recognized that as wind penetration levels increase further, many new challenges will arise. Of particular concern is the possible lack of inertial response of wind turbines without additional turbine controls (Doherty *et al.*, 2010), 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 7.17 illustrates the high levels of wind penetration that exist in Ireland and West Denmark.



Source: (a) www.energinet.dk; (b) www.eirgrid.com

Figure 7.17. Wind energy, electricity demand, and instantaneous penetration level in (a) West Denmark for a week in January 2005, and (b) Ireland for three days in November 2009.

The Electric Reliability Council of Texas (ERCOT) operates a synchronous system with a peak demand of nearly 65 GW, and with a wind penetration level of more than 5% at the end of 2008. 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 energy output of 1,500 MW over a three hour period, roughly 30% of the nameplate capacity of installed wind 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 generation 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 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

A number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed around the world. These studies typically quantify the costs and benefits of integrating wind into power systems. The costs include the need for transmission and estimates of the change in operating costs required to accommodate the increased variability and unpredictability caused by wind generation. The benefits include reduced fossil fuel usage and CO_2 emissions. The results of these studies demonstrate that the cost of integrating 10% to 20% wind into the power system is, in most systems, modest but not insignificant.

There are a plethora of wind integration studies with a wide variety of methodologies (Gross *et al.*, 2007; Smith *et al.*, 2007a; Holttinen *et al.*, 2009). As there are many different impacts, positive and negative, each study includes some combination of the following:

- reduction in operating costs because of reduced fossil fuel usage
- additional operational costs from system balancing
- increase in reserve requirements for wind energy
- capacity credit of wind energy
- reinforcements/extensions needed in the transmission grid

- impacts of wind energy on the stability of the transmission system
- impacts of different measures to mitigate variability and uncertainty
- impacts of wind energy on the operation of conventional power plants
- impacts of wind energy on CO_2 emissions

Addressing all impacts requires several different simulation models that operate over different time scales, and most studies therefore focus on only a subset of the potential impacts. The results of wind integration studies will also inherently differ from one power system to another simply due to pre-existing differences in system designs and regulatory environments. Important differences include generation capacity mix and the flexible [TSU: flexibility] of that generation, the variability of demand, and the strength and breadth of the transmission system. Study results also differ because no accepted standard methodology has 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 data at high-time-resolutions for a chosen future wind energy penetration level and for a sufficient duration for the results of the analysis to be statistically reliable. The data are then used in a power system simulation to mimic system operations. Simulations can be used to quantify the costs, emissions savings, and the need to build transmission under a high-wind-energy future. 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 energy, from the day-ahead time scale to some hours ahead of delivery (Barth *et al.*, 2006). Increasingly, integration studies are simultaneously simulating high wind scenarios in entire synchronized systems (not just individual, smaller balancing areas) (NREL, 2010; EWIS, 2010).

Notable examples of wind integration studies include those conducted in Ireland and the U.S. state of Minnesota. In Ireland, the All Island Grid Study (AIGS, 2008) evaluated five energy supply portfolios with penetration levels of up to 42% RE (34% wind) across a large set of parameters including cost and emissions. The findings confirmed that up to 42% RE is feasible, but that a multitude of technical issues would need to be overcome. Perhaps most important was the need to build significant amounts of new high-voltage transmission; additional transmission investment costs were estimated to be approximately US$178 (2005$) per kW of wind. Other issues that would need to be addressed include reactive power control and system inertia. The cost of the portfolio with the highest wind energy penetration (34%) was modestly more expensive (7% more) than the portfolio with the lowest level of wind penetration (16%). At the same time, the portfolio with the highest wind penetration had 25% less CO_2 emissions than the portfolio with low penetration.

In Minnesota, a detailed wind integration study was completed in 2006 (EnerNex Corp., 2006). This study looked at the operational integration costs associated with wind energy, assuming that integration occurred within the context of a well-developed energy market operating in the Midwest Independent System Operator (MISO) territory. The MISO territory covers parts of 14 states, with a peak electricity demand in excess of 115 GW. The assumed Minnesota demand of 21 GW in the year 2020 was served by up to 6 GW of wind capacity. The study results show that 25% wind electricity in Minnesota can be reliably accommodated by the power system, if adequate transmission is available. The highest incremental cost of wind integration associated with this future was estimated to be $4.40/MWh of delivered wind energy, including the cost of additional reserves. Balancing area consolidation within Minnesota, the overall size of the MISO market, and wind project output forecasting were shown to reduce wind integration costs and challenges.

The costs reported by these two studies broadly agree with the results of other significant integration studies conducted in the U.S. and Europe. The estimated increase in short-term reserve requirements in eight studies summarized in an IEA report (Holttinen *et al.*, 2009) has a large range: 1-15% of installed wind energy capacity at 10% wind energy penetration and 4-18% of installed wind energy capacity at 20% wind energy penetration. The higher results are generally from studies that assume that day-ahead uncertainty or four-hour variability of wind energy output is handled with short-term reserves; markets that are optimized for wind energy will generally not operate in this fashion. Notwithstanding these variations in results and methods, the studies find that, in general, a wind energy penetration of up to 20% can be accommodated with increased system operating costs of roughly 1.4–5.6 US$/MWh of wind energy produced, or roughly 10% or less of the levelized generation cost of wind energy.

In addition to these increased operating costs, several broad assessments of the need for and cost of transmission for wind energy have found modest, but not insignificant, costs. The transmission cost for 300 GW of wind in the United States was estimated to add about 10-15% to the levelized cost of wind energy (U.S. DOE, 2008). Similar cost estimates were reached from a much more detailed assessment of the transmission needs of a 20% wind energy scenario for the Eastern Interconnection of the U.S. (JCSP, 2009). 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 for wind energy in Europe lead to 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. (Mills *et al.*, 2009). Holttinen *et al.* (2009) review wind energy transmission costs from several European national case studies, and find those costs to range from 3-13% of the levelized generation cost of wind energy. Finally, a European-wide study identified several transmission upgrades between nations and between high quality off-shore wind resource areas that would reduce transmission congestion and ease wind integration for a 2030 scenario. The study highlights the benefits that a DC [TSU: abbr.] network of off-shore transmission would provide rather than building radial lines between individual off-shore wind farms and on-shore connection points (Tradewind, 2009).

7.6 Environmental and social impacts

Wind energy has significant potential to reduce GHG emissions, together with the emissions of other air pollutants, by displacing fossil fuel-based electricity generation. Because of the relative maturity (Section 7.3) and cost (Section 7.8) of the technology, wind energy can be immediately deployed on a large scale (Section 7.9), enabling significant reductions in emissions in the short- to medium-term. As with other industrial activities, however, wind energy also has the potential to produce some negative 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 more specifically 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

The environmental benefits of wind energy come primarily from a reduction of emissions from conventional electricity generation. However, the manufacturing, transport, and installation of wind turbines induces some indirect negative effects, and the variability of wind generation also impacts the operations and emissions of conventional plants; such effects need to be subtracted from the gross benefits to find the net environmental 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 result from displacing electricity generation from conventional, fossil-fuel powered electricity generators, as the operation of wind turbines does not directly emit greenhouse gases or other air pollutants such as SO_2, NO_x, CO, NMVOCs, particulates, or heavy metals. Estimating the emissions reduction benefits of wind is complicated by the operational characteristics of the electricity system and the investment decisions that are made in new 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, new generating plants may be needed, and the presence of wind generation will influence what types of power plants are built (Kahn, 1979; Lamont, 2008). Depending on the characteristics of the electricity system into which wind energy is integrated, and the amount of wind energy generation, the reduction of air emissions may be substantial. For example, in the largely coal-based German electricity system, the installed wind energy capacity of about 22 GW in 2007 produced roughly 40 TWh of electricity, leading to a reduction in GHG emissions of 34 Mt CO_2 (Federal Ministry for the Environment, 2008), around 10% of the total GHG emissions of the German power sector (Umweltbundesamt, 2009).[14]

In addition to reducing GHG and air pollutant emissions, wind energy also reduces cooling water demands from the operation of conventional power plants. Wind energy can avoid the need for cooling water that would otherwise be used by electricity production from conventional steam generators; in addition, waste ash produced from coal generation will be avoided, as can some of the adverse impacts from coal mining and natural gas drilling.

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 energy systems (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 LCA studies for wind energy 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)
DWTMA (1997)	0.6 MW	on-shore	n/a	0.25	n/a
Schleisner (2000)	0.5 MW	on-shore	43.5%	0.26	9.7
Voorspools (2000)	0.6 MW	on-shore[1]	n/a	n/a	27
Jungbluth et al. (2005)	0.8 MW	on-shore	20%	n/a	11

[14] Total electricity demand in Germany in 2007 was 541 TWh (with 138 GW of installed capacity), and total power-sector CO_2 emissions were 386 Mt (Bundesministerium fuer Wirtschaft und Technologie, 2009).

Pehnt (2006)	1.5 MW	on-shore	n/a	n/a	10.2
Martínez et al (2009)	2.0 MW	on-shore	23%	0.40	n/a
Elsam (2004)	2.0 MW	on-shore	n/a	0.65	7.6
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
Jungbluth et al. (2005)	2.0 MW	off-shore	30%	n/a	13
Elsam (2004)	2.0 MW	off-shore	n/a	0.75	7.6
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
EPD 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 energy payback (in years) and carbon intensity (in gCO_2/kWh) 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 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 project, 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 increase 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 decrease the efficiency of the plants and therefore create a fuel efficiency and GHG emissions penalty relative to a fully-loaded plant. Analyses of the emissions benefits of wind do not always account for this effect.

The UK Energy Research Centre performed an extensive literature review of the costs and impacts of variable generation; 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[15] of wind generation that account 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 in four studies that explicitly addressed the issue was negligible to 7%, for up to 20% wind electricity penetration (Gross *et al.*, 2006). In short, for moderate levels of wind 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).

[15] Because CO_2 emissions are generally proportional to fuel consumption for a single plant, the CO_2 emissions penalty is similar to the fuel efficiency penalty.

7.6.1.4 Net environmental benefits

The overall net balance of positive and negative environmental and health effects of wind energy is documented by the difference in estimated external costs for wind energy and other electricity production options, as shown in Figure 7.18 for Germany. This figure is based on the results of Krewitt and Schlomann (2006), and contains monetized figures for climate change damages, human health impacts, material damages, and agricultural losses. 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. As such, though the figure does not include all ecological effects, it shows the overall significance of the difference between the environmental benefits and the environmental burdens of wind energy. Similar results are found in the externalities literature of other countries, e.g. in the ExternE project of the E.U. comparing the external costs of different fuel cycles and different countries (Bickel and Friedrich, 2005).

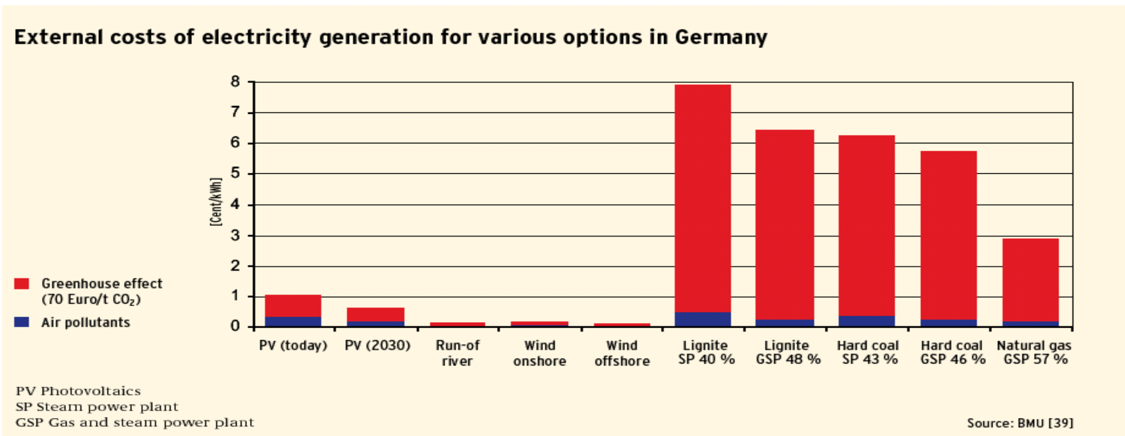


Figure 7.18. External costs of electricity generation for various options in Germany (Federal Ministry for the Environment, 2008, based on Krewitt and Schlomann, 2006).

7.6.2 Ecological impacts

Though the external costs of wind energy are low compared to other forms of electricity generation (Figure 7.18), there are ecological impacts that need to be taken into account when assessing wind energy. Following the National Research Council of the U.S. National Academies (NRC, 2007) and Michel *et al.* (2007), the primary ecological impacts from on-shore wind projects include direct bird and bat fatalities, and the disruption of ecosystem structure. For off-shore wind projects, impacts on benthic resources, fisheries, and marine life more generally must also be considered. Finally, the possible impacts of wind project development on the local climate have also been the focus of some study.

7.6.2.1 Direct bird and bat fatalities

Direct bird and bat fatalities are among the most recognized ecological impact categories for on-shore wind projects (e.g., NRC, 2007; EWEA, 2009). Though these impacts have generated a high level of interest, they are highly site specific and need to be put into the context of other bird fatalities caused by human activities. Erickson *et al.* (2005), for example, estimated that over 680 million annual bird fatalities are due to collisions with human-made structures in the United States, and 150 million from other anthropogenic causes. That study concluded that wind generation in the U.S. is responsible for 0.003% of anthropogenic avian mortality; for the year 2003, about 17,500 wind turbines in the U.S. led to 20,000 to 37,000 avian fatalities. It has also been very-roughly estimated that wind projects cause 0.28 avian fatalities per GWh, while nuclear power generation causes about 0.42 and coal based electricity causes about 5.2 fatalities per GWh; the strongest impact is due to effects of climate change on bird life (Sovacool, 2009).

The U.S. National Research Council found a wide range of bird fatality estimates reported in the literature on U.S. wind projects (NRC, 2007). Bird mortality estimates from these studies range from 0.98 to 7.7 per turbine and year, while the range per MW of installed capacity is even wider, from 0.95 to 11.67 bird fatalities per MW and year (NRC, 2007). Erickson *et al*. (2005), meanwhile, report 2.11 avian deaths per wind turbine in the U.S., while a study by EHN (2003) conducted on 18 wind projects in Navarra, Spain showed an annual mortality of 0.13 birds per wind turbine. Though most of the bird fatalities reported are of songbirds (Passeriformes), which are the most abundant bird group in terrestrial ecosystems (NRC, 2007), raptor fatalities may be of greater concern as their numbers tend to be relatively small. Raptor fatalities have been reported separately in many U.S. studies. Compared to songbird fatalities resulting from wind turbines, raptor fatalities are relatively low, with zero to 0.07 fatalities per turbine and year being reported (NRC, 2007). As should be clear from the data presented here, bird fatality rates are highly project-specific, and vary with site characteristics, turbine design, and turbine size (NRC, 2007).

Bat fatalities have not been researched as extensively as bird fatalities connected to wind energy development, and data allowing reliable assessments of bat fatalities are limited (NRC, 2007). Studies for the U.S. show a wide range of results, with observed bat fatalities ranging from 0.8 to 41.1 bats per MW (per year) (NRC, 2007). The specific role of different influences such as site characteristics, weather conditions, turbine design, and turbine size remain uncertain due to the lack of extensive and comparable studies; additional research is therefore being conducted to better assess these impacts, and their possible mitigation. In the U.S., for example, the Bats and Wind Energy Cooperative was formed in 2004 to address this issue. Results of one study demonstrated that curtailing operation of wind turbines during low wind situations resulted in bat fatality reductions averaging 73% (and ranging from 53% to 87%) compared to fully operational turbines; these results indicated that changing the cut-in speed of turbines can contribute to significant reductions in bat fatalities (Arnett *et al.*, 2009). Similar results have been found at studies conducted in Canada and Germany.

7.6.2.2 Ecosystem structure impacts

Ecosystem impacts, and in particular impacts on habitats of various species, depend largely on the ecosystem into which wind energy facilities are integrated. Wind projects are often installed in agricultural landscapes or on brown-field sites. In such cases, relatively few ecosystem structure impacts are to be expected. In some regions, wind projects are increasingly being sited on forested ridges; in these instances, the construction of access roads and forest clearings for turbine foundations and power lines may have substantial impacts. The existing literature largely focuses on impacts on these forest ecosystems, even though most wind project development has not occurred in such landscapes. The construction of wind energy facilities in largely undisturbed forests may lead to habitat fragmentation for some species. Some species living a minimum distance from the forest edge, for example, may lose habitat due to the so called depth-of-edge influence (NRC, 2007). On the other hand, habitat for other species may actually increase with the increasing amount of edge (NRC, 2007). Research is also being conducted on the possible impacts of wind projects on grassland species. For example, research has been initiated in the United States to investigate the impacts of habitat fragmentation on prairie chickens. In addition, a multi-stakeholder collaborative is being formed to support research on potential habitat impacts to sage grouse in the Pacific Northwest sage brush habitat. Because ecosystem impacts are highly site specific, they are often addressed in the project permitting process (NRC, 2007). Concerns for ecological impacts have also led to ordinances in some countries prohibiting the construction of wind facilities in ecologically sensitive areas.

The impacts of wind projects 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 projects, numerous studies on possible impacts 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 impacts of off-shore wind energy development depend greatly on site-specific conditions, and can be both negative as well as positive (Michel *et al.*, 2007; Punt et al., 2009; Wilson and Elliot, 2009). Potential negative impacts involve underwater sounds, electromagnetic fields, and physical disruption. On the other hand, the physical structures may create new breeding grounds or shelters like artificial reefs. From existing studies no final conclusions can be drawn on the impacts of off-shore wind parks in general as the time spans covered and the numbers of wind projects studied are insufficient for such conclusions. In some countries, however, concerns about the impacts of off-shore wind projects on marine life and migrating bird populations have led to national off-shore zoning efforts that exclude the most-sensitive areas from development.

7.6.2.3 Impact of wind project development on the local climate

The possible impact of wind projects on the local climate has also been the focus of some research. Wind projects 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. Some studies have sought to quantify the effect by treating large wind projects as a block of enhanced surface roughness length or an elevated momentum sink in regional and global models. These studies have found changes in local surface temperature of up to 1°C, and in surface winds of several meters per second (Keith *et al.,* 2004; Kirk-Davidoff and Keith, 2008). Such effects could have both ecological and human impacts. However, the numerical simulations used may not be an ideal analogy for the actual mechanism by which wind turbines interact with the atmosphere. These approaches assume (incorrectly) that the turbines act as an invariant momentum sink; 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 really the case. The results must therefore be viewed with caution.

Observed data and models indicate that large off-shore wind projects 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 projects are no longer discernible in near-surface wind speeds and turbulence intensity at approximately 20 km downstream (Christiansen and Hasager, 2005; Christiansen and Hasager, 2006; Frandsen *et al.*, 2009). 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, as well as the GHG reduction benefits of wind energy.

7.6.3 Impacts on humans

In addition to ecological impacts, wind project 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 projects can encompass a large area (5 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 project, allowing agriculture, ranching, and certain other activities to continue within the project area. Some forms of land use may be precluded from the project 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.

The impacts of wind projects on aviation, shipping, communications, and radar must also be considered, and depend on the placement of wind projects and wind turbines. Where airplane landing corridors and shipping routes are avoided, interference of wind projects with shipping and aviation can be kept to a minimum (Hohmeyer *et al.*, 2005). Integrated marine spatial planning (MSP) and integrated coastal zone management (ICZM) 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 (e.g., Murawsky, 2007; Ehler and Douvere, 2009; Kannen and Burkhard, 2009). Electromagnetic interference (EMI) associated with wind turbines can come in various forms. In general, wind turbines can interfere with detection of signals through reflection and blockage of electromagnetic waves including Doppler produced by the rotation of turbine blades. Many EMI effects can be avoided by not placing wind projects in close proximity to transmitters or receivers (Hohmeyer *et al.*, 2005). Moreover, in the case of military (or civilian) radar, reports have concluded that radar systems can be modified to ensure that aircraft safety and national defence are maintained in the presence of wind energy facilities (BWEA, 2003; Butler and Johnson, 2003; Brenner *et al.*, 2008), though there is a cost to such modifications.

7.6.3.2 Visual impacts

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. In addition, wind turbines have consistently grown in hub height and blade swept area. Moreover, as wind energy installations have increased in number and geographic spread, projects located in a wider diversity of landscapes (and seascapes) – including more highly valued landscapes – have begun to be explored. Taken together, these factors often elevate visual impacts to one of the top concerns of communities considering wind energy facilities (Firestone and Kempton, 2007; NRC, 2007; Wolsink, 2007; Wustenhagen et al., 2007; Firestone et al., 2009; Jones and Eiser, 2009), of those living near existing wind facilities (Thayer and Hansen, 1988; Krohn and Damborg, 1999; Braunholtz and Scotland, 2003; Warren et al., 2005), and of institutions responsible for overseeing wind energy development (Nadaï and Labussiere, 2009). As a result, some contend that a thorough rethinking of what a "landscape" means – and therefore what should be protected – is required (Pasqualetti et al., 2002; Nadaï and Labussiere, 2009).

7.6.3.3 Noise, flicker, health, and safety

A variety of proximal "nuisance" effects are also sometimes raised with respect to wind development. Noise from wind turbines can be a problem, either for those within a very close range of a typical turbine or farther away when turbines are not well designed or maintained. Typically, the sound level of a modern wind turbine at the tip of the rotor blade is around 100 dB at a distance of one meter, depending on the type of turbine and the wind speed at which the sound is measured (Hohmeyer *et al.*, 2005). Directly under the turbine the noise level is reduced to about 70 dB due to the vertical distance to the tip of the rotor blades; though 100 dB is equivalent to the noise of a steam hammer, 70 dB is equivalent to the noise of a roadway at a distance of about 30 meters. Noise effects diminish with distance (roughly a 6 dB reduction with each doubling of the distance from the source), and a sound pressure level of 35-45 dB can be reached with modern wind turbines at a distance of roughly 350 meters (EWEA, 2009); this is the level of a person speaking with a normal voice at a distance of one meter. Rotating turbine blades can also cast moving shadows, 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), and in some countries the use of such operation control systems is mandated by licensing authorities. As discussed above, EMI impacts can take many forms, including impacts on TV, GPS, and communications systems. Where these impacts do exist, they can be managed by appropriate siting of wind projects and through other technical solutions. Finally, although wind turbines can shed parts of blades, or in exceptional circumstances 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), to 2001 there had been no cases of people being injured as a result of such incidents (DTI, 2001).

7.6.3.4 Property values

The aesthetic concerns discussed above, real or perceived, 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 energy facilities (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, often find that effects can fade at distances of 100m (Kroll and Priestley, 1992; 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. Kroll and Priestley, 1992; 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 announcement, but fade over distance and time after a wind energy facility is constructed.

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). That said, translating this broad support into increased deployment (closing the “social gap” – see e.g., Bell *et al*., 2005) often requires the support of local host communities and/or decision makers. To that end, a number of concerns exist that might temper the enthusiasm of these stakeholders, such as visual, proximal, or property value impacts (Jones and Eiser, 2009). In general, research has found that public concern is greater after the announcement of a wind energy facility but before construction, but that acceptance increases after construction when actual risks can be quantified (Wolsink, 1989; Braunholtz and MORI Scotland, 2003; Warren *et al*., 2005; Eltham *et al*., 2008). Additionally, those most familiar with existing wind facilities, including those who live closest to them, have sometimes been found to be more accepting (or less concerned) than those further away (Krohn and Damborg, 1999; Warren *et al.*, 2005), though this support paradigm has sometimes been found to break down at very close distances (Kabes and Smith, 2001) and when turbines are sitting idle

(Thayer and Freeman, 1987). A number of authors have found that a lack of support before the facility is erected can alter perceptions later. For example, those opposed to wind facilities found those facilities to be considerably noisier and more visually intrusive that those in favour of the same facilities (Krohn and Damborg, 1999; Jones and Eiser, 2009). Additionally, some research has found that concerns can be compounding. For instance, those who found turbines to be visually intrusive found their noise to be more annoying (Pedersen and Waye, 2004). In many cases, it is likely that "beauty is in the eye of the beholder" (Warren *et al.*, 2005, p. 14), as aesthetic perceptions have been found to be the strongest single influence for support and opposition of wind development (Pasqualetti *et al.*, 2002; Warren *et al.*, 2005; Wolsink, 2007).

7.6.5 Minimizing social and environmental concerns

Regardless of what type and degree the local concerns are, and how they are tempered, addressing them directly is an essential part of any successful siting process. This might, for example, include conducting ecological impact studies, performing visual simulations of alternative facility designs, and establishing wide set-back requirements. Similarly, involving the community in the siting process will likely improve outcomes. Public attitudes have been found to improve when the development process is perceived as being transparent and involving public comment (Wolsink, 2000; McLaren Loring, 2006; Gross, 2007), especially when community involvement begins before a final facility location is chosen (Nadaï and Labussiere, 2009). Further, experience in Europe suggests that increased community involvement in and even ownership of local wind projects can improve public attitudes towards wind development (Gross, 2007; Wolsink, 2007; Jones and Eiser, 2009). Finally, broader concepts, such as the rethinking of "landscape" to incorporate wind turbines will continue to be of use (e.g., Wustenhagen et al., 2007; Nadaï and Labussiere, 2009).

Proper planning for both on-shore and off-shore wind can also help to minimize social and environmental impacts, and a number of siting guideline documents have been developed (Minister für Soziales, Gesundheit und Energie, 1995; Nielsen 1996; NRC, 2007; AWEA, 2008). The appropriate siting of wind turbines can minimize the impact of noise, flicker, and electromagnetic interference. Appropriate siting will generally avoid placing wind turbines too close to dwellings, streets, railroad lines, and airports, and will avoid areas of heavy bird and bat activity. Habitat fragmentation caused by access roads and power lines can often be minimized by careful placement of wind turbines and facilities, and by proactive governmental planning for wind deployment. Examples of such planning can be found in many jurisdictions across the world, both for on-shore and for off-shore wind.

Even if the environmental impacts of wind energy are minimized through proper planning procedures and community involvement, some impacts will remain. 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 makes it clear 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).

7.7 Prospects for technology improvement and innovation

Over the past three decades, innovation in the design of utility-scale wind turbines has led to significant cost reductions, while the capacity of individual turbines has grown markedly. The "square-cube law"[16] suggests a natural "size limit" for wind turbines. To date, engineers have

[16] The "square-cube law" 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) increases as the cube of the rotor diameter, all else being equal [TSU: sentence unclear]. As a result, at some size, the cost of a larger turbine will grow faster than the resulting energy output and revenue, making further scaling uneconomic.

successfully engineered around this relationship 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 the 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 cost reductions in wind-generated electricity (7.7.2), component-level opportunities for innovation in wind technology (7.7.3), and opportunities to improve the scientific underpinnings of wind 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.[17]

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 production 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 $200 million (2008$), or 1.5% of all energy R&D funding. 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) and Carbon Trust (2008a) find that the ratio of turbine manufacturer R&D expenditures to net revenue typically ranges from 2% to 3%.

Wind energy research strategies have been developed through government and industry collaborations in the U.S. and in Europe. 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, gird integration of wind energy, and siting and environmental concerns (U.S. DOE, 2008). The European Wind Energy Technology Platform (TPWind) similarly describes a long series of research and development targets (E.U., 2008). 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 cumulatively bring about a 30% to 40% improvement in the delivered cost of wind energy over the next two decades.

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. Many studies of advanced wind turbine concepts have identified a number of areas where technology advances could result in changes to the capital cost, annual energy production, reliability, O&M, and grid integration of wind energy. Scaling studies

[17] 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 utility 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.

exploring the system-level impacts of advanced concepts were 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), including a number of additional detailed component-level studies. Ultimately, component-level advances are 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 cost of material as well as impacts on installation costs associated with larger cranes. Sophisticated design approaches are required to systematically evaluate advanced wind turbine concepts.

The U.S. DOE (2008) report summarizes the range of potential impacts on energy production and capital costs from a number of these advances; these ranges are shown in Table 7.4. Though not all of these potential improvements may be achieved, there is sufficient potential to warrant continued research and development. 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 are the baseline for the estimates in Table 7.4).

Table 7.4. Areas of potential technology improvement from a 2002 baseline wind turbine (U.S. DOE 2008)*

		Increments from Baseline (Best/Expected/Least, Percent)	
Technical Area	**Potential Advances**	**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).*

The European Wind Energy Technology Platform has also developed a roadmap that is being discussed with E.U. member countries (E.U., 2008; E.C., 2009). The roadmap (Figure 7.19) is expected to form the basis for the future development of European wind energy research and development strategies, with the following areas of focus: new turbines and components; off-shore structures; grid integration; and wind resource assessment and spatial planning.

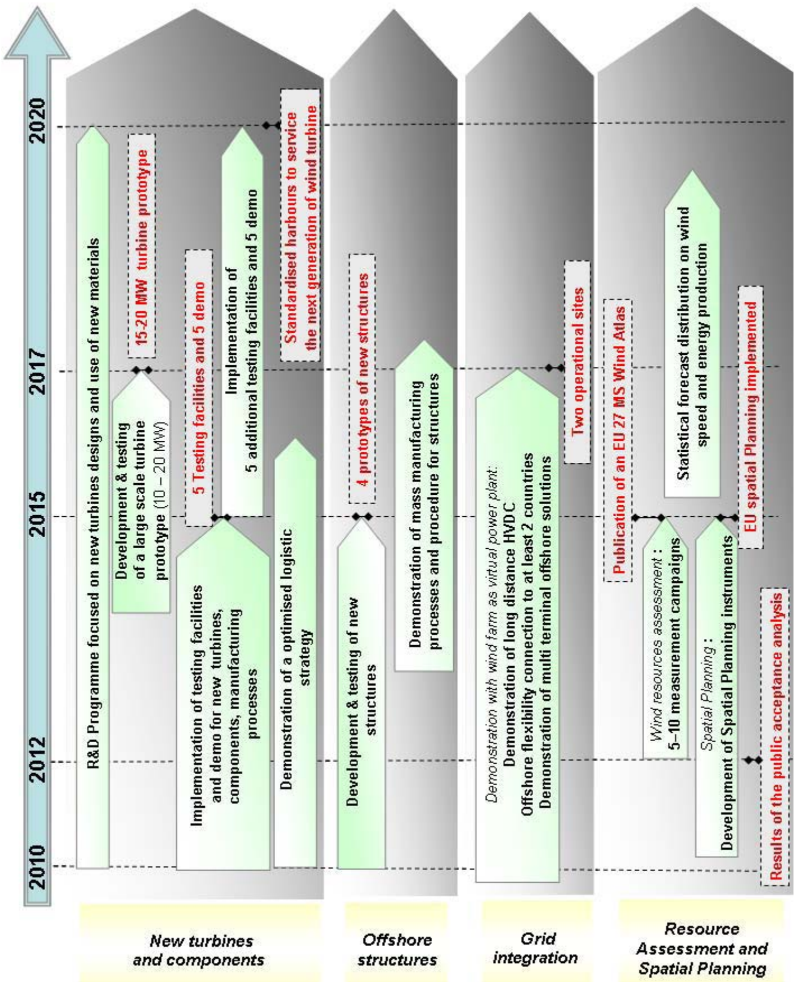


Figure 7.19. European wind initiative R&D roadmap (E.C., 2009).

7.7.3 Component-level innovation opportunities

The potential areas of innovation outlined in Table 7.4 deserve further description, as do two additional topics: advanced turbine concepts and off-shore technology advancement.

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; however, the cost of large cranes and transportation 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. (For more information, see GEC, 2001; Malcolm, 2004; Lanier, 2005; and Native American Technologies, 2006).

7.7.3.2 Advanced rotors and blades

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, 2004). The significance of this development is that wind turbine blades have become lighter for a given length over time (Figure 7.20).

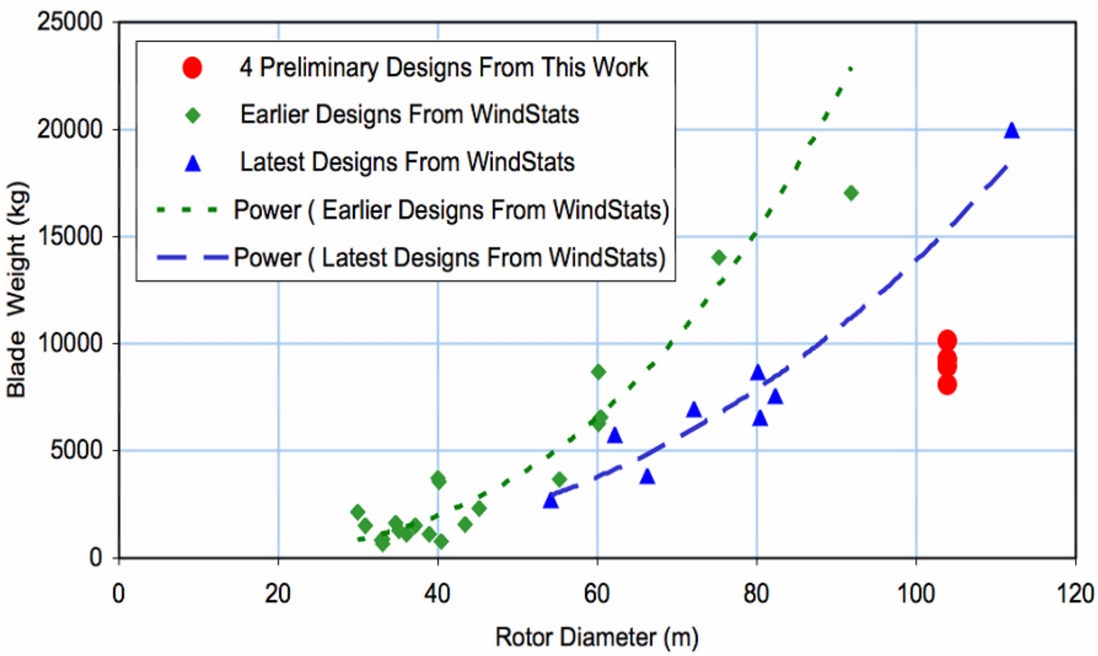


Figure 7.20. Reduced growth in blade weight due to the introduction of new technology (T.P.I. Composites, 2004).

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 the blade needs the most support, producing inherently better structural properties, while allowing less material to be used in other segments of the blade. To date these thicker airfoil shapes in the blade root area have sacrificed too much aerodynamic performance. 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 which 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; Buhl *et al*, 2007; Lackner and van Kuik, 2009). Devices such as trailing edge flaps and micro-tabs are being investigated, but new sensors may need to be developed 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). Basic understanding and mathematical modelling of wind turbine aeroelastic (Section 7.7.4.1), aerodynamic (Section 7.7.4.2), and aeroacoustic (Section 7.7.4.3) responses that are associated with such complicated blade motion, as well as control algorithms to incorporate these sensors and actuators in wind turbine operation schemes (Section 7.7.4.4), must be developed to achieve these new designs. Several of these innovative concepts are being developed in U.S. and European research projects, in conjunction with industry, raising the possibility of significant reductions in fatigue loads on the blades.

Concepts such as on-site manufacturing and segmented blades are also being explored to help reduce transportation costs. In UpWind, for example, one of the goals is to develop a segmented blade. Some manufacturers, meanwhile, are investigating production methods that would enable segmented moulds to be moved into temporary buildings close to the site of major wind installations so that the blades can be made close to or at the wind project site.

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. Advanced controllers are envisioned to be able to control the turbine through turbulent winds, monitor and adapt to the wind conditions, and anticipate and protect against damaging wind gusts. Condition-monitoring systems of the future are expected to track and monitor ongoing conditions at critical locations in the turbine system and report incipient failure possibilities and damage evolution, so that outages and downtime can be minimized. For example, advanced fibre optic sensors can continually and reliably measure blade strains and damage accumulation, although it should be noted that greater uniformity of the quality of blade manufacturing is required to make the application of such techniques effective. Other sensors can monitor the chemical and particulate conditions in the gearbox lubricant, while accelerometers measure vibration and shock loads in the drive train and on other key structural components. By tracking wind conditions and power output, the blade pitch can be adjusted to maximize energy output, even when the blades are soiled. The development and evolution of advanced control and monitoring systems of this nature will take years of operational experience, and optimization algorithms will likely be turbine-specific; the general approach, however, will be transferrable between turbine designs and configurations.

7.7.3.4 Advanced drive trains, generators, and power electronics

Several unique designs are under development to reduce drive train weight and cost while improving reliability (Poore and Lettenmeier, 2003; Bywaters *et al*., 2004; EWEA, 2009), including the use of direct-drive generators (removing the need for a gearbox). 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 decrease in cost and increase in availability of rare-earth permanent magnets is expected to significantly affect the size and cost of future direct-drive generator designs. Permanent-magnet designs tend to be more compact and potentially lightweight and reduce electrical losses in the windings.

A hybrid of the direct-drive approach that offers promise for future large-scale designs is the 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. Another approach that offers promise is the distributed drive train, where rotor torque is distributed to multiple smaller generators, reducing overall size and weight (Clipper Wind Technology, 2003).

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 and the corresponding increased power output is helping to spur interest in larger power electronic component ratings, as well as innovative higher-voltage circuit topologies. In the future, it is expected that wind turbines will use medium-voltage generators and converters (Erdman and Behnke, 2005), and make use of new high-voltage and higher-capacity circuits and transistors.

7.7.3.5 Manufacturing and learning curve

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 technology). Though turbine manufacturers already are beginning to operate at significant scale, as the industry expands further, additional cost savings can be expected. Increased automation and optimized manufacturing processes contribute to cost reductions associated with learning by doing.

7.7.3.6 Advanced turbine concepts

Almost all commercial wind turbines are three-bladed, upwind machines. However, there has been a long-running debate about optimum turbine design and configuration, with early designs including one-, two-, and three-bladed turbines. Some believed that a two-bladed turbine configuration was the minimum cost architecture, particularly for very large turbines of the multi-megawatt class. Nonetheless, a key advantage of the three-bladed turbine, which eventually led to its dominance, is that the dynamic equations of motion are simpler because rotor inertia is symmetric, making the engineering design simpler. In addition, there was very little cost penalty for the three smaller blades of the early turbines, and because the rotor speed was lower they also emitted less noise, as well as having a more pleasing aesthetic during operation.

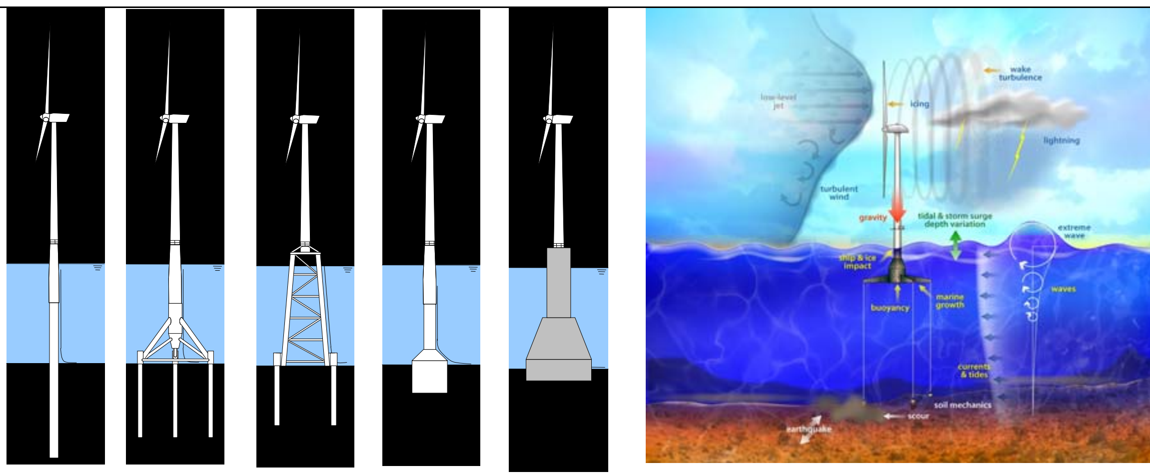
With current turbine designs operating at lower speeds, and offshore developments being less limited by issues of noise, the advantages of a three-bladed turbine may no longer be valid. In addition, the state-of-the-art in low-noise airfoils has advanced such that targeted R&D may reduce the previous noise penalty for one- and two-bladed turbine designs. As a result, two-bladed downwind wind turbines are being investigated off-shore applications. However, the large existing wind turbine manufacturers hesitate to develop alternative designs, due to the high degree of risk involved in shifting away from longstanding design concepts combined with a long and expensive path to commercialization. As a result, significantly different off-shore turbine designs are unlikely to be commercialized before 2020 (Carbon Trust, 2008a).

7.7.3.7 Off-shore research and development opportunities

The larger, lighter, more-flexible turbines envisioned for off-shore applications, perhaps 10 MW in size or even larger, can benefit from many of the advances described previously. The development of large turbines for off-shore applications remains a significant research challenge, however, that requires 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 technology.

Additional R&D opportunities exist in foundation design, and foundation structure innovation offers the potential to access deeper waters, thereby increasing the potential wind resource available. Off-shore turbines have historically been installed on a mono-pile structure that is essentially an extension of the tower and is appropriate in relatively shallow water under 30 m in depth. To more cost-effectively access deeper water locations, concepts with space-frame structures or tension-leg mooring designs, as well as floating wind turbines, are under exploration and development. Floating wind turbines and floating platforms, in particular, increase the complexity of turbine design due to the additional motion of the base, but can – if cost-effective – offer access to significant additional wind resource potential, though the cost of off-shore transmission infrastructure will be a deterrent to moving too far from shore. Figure 7.21(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 deeper-water applications in the longer term.

(a) Near-term off-shore foundation concepts **(b)** Floating off-shore turbine concept



Source: UpWind.eu *Source: National Renewable Energy Laboratory*

Figure 7.21(a,b). Off-shore wind turbine foundation designs

High waves and strong winds can make accessing off-shore wind turbines difficult. This challenge, coupled with slow transport time from land and the relatively low reliability of early off-shore turbines, are some of the factors that make off-shore wind energy more expensive than on-shore projects. In an effort to decrease this cost differential, additional research is expected to be focused on achieving higher reliability, fewer scheduled and unscheduled O&M visits, and higher availability than off-shore turbine models deployed thus far have experienced.

Advancements in off-shore installation and manufacturing techniques are also possible, in part learning from the off-shore oil and gas industries. For example, off-shore wind turbines could be constructed and assembled in or near seaport facilities, thereby eliminating the need to ship large components over roadways. Off-shore turbines could also be designed such that installation of those turbines consists of floating the assembled turbines to their final locations, and therefore erecting the structures with minimal off-shore crane requirements.

7.7.4 The Importance of underpinning science

Wind turbines operate in a challenging environment, and are designed to withstand a wide range of conditions with minimal attendance. 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. Research in a number of areas of fundamental science will improve the physical understanding of this operating environment, which in turn can lead to more-precise design requirements. To develop the innovative components described in Section 7.7.3, the reliability and accuracy of the mathematical and experimental basis underlying turbine design methodologies becomes more critical. Research in areas of aeroelastics, unsteady aerodynamics, aeroacoustics, advanced control systems, materials science, and atmospheric science has yielded improved design capabilities in the past 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 innovation of wind turbine and wind project design.

7.7.4.1 Aeroelastics

The wind industry relies extensively on the use of comprehensive dynamics models for wind turbine performance, loads, and stability analyses.[18] The integrated modelling of these physical phenomena is important for design optimization (Quarton, 1998; Rasmussen *et al.*, 2003). The minimum features required of the aeroelastic tools and experimental verification when applied in the design process are dictated by international wind turbine design and safety standards. The design process illustrated in Figure 7.8(a) requires an accurate prediction of extreme and fatigue loads over a range of operational conditions, including normal operation, start/stop sequences, and parked/idling conditions (IEC, 2005; IEC, 2008c). Limitations and consequent inaccuracies in the aeroelastic tools and the experimental verification of those tools limit advancements of wind turbine technology, and overcoming these limitations is critical to the successful long-term improvement of performance, operation, and reliability of wind turbines.

Overcoming the existing limitations of these tools and experimental verification methods becomes even more important as turbines grow in size, incorporate novel load control technologies together with more-advanced condition monitoring systems, and are installed off-shore. For example, as turbines grow in size and are optimized, the structural flexibility of the turbines will increase, causing more of the turbine’s vibration frequencies to play a prominent role in the system’s response. 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). Future aeroelastic tools may also need to incorporate higher fidelity drive train dynamics models, including detailed models of gears, shafts, and bearings, to properly account for the couplings between the drive train and rotor (Peeters *et al.*, 2006; Heege *et al.*, 2007). The application of novel load-mitigation control technologies, such as can be applied to blades, or advanced sensors and embedded actuators for active control (e.g., deformable trailing edges), will require analysis based on aeroelastic tools that are adapted for these architectures (Buhl *et al.*, 2005; GEC, 2005). Off-shore wind applications 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. The modelling capabilities required will depend on the type of off-shore foundation (Passon and Kühn, 2005; Jonkman, 2007). Analysis of downwind two-bladed rotors, which may ultimately become more-prevalent off-shore, will benefit from improved downwind tower wake models (Butterfield *et al.*, 2007; Zahle *et al.*, 2009).

Because aerodynamic models are the least-accurate component of aeroelastic tools, improving them will produce the greatest benefit. Currently, aerodynamic models rely upon Blade-Element Momentum (BEM) methods (Spera, 2009) to calculate the aerodynamic forces along the span of the

[18] The fundamental models are comprehensive “aero-hydro-servo-elastic” tools (herein, “aeroelastic tools”), meaning that they incorporate integrated models for aerodynamic loads, hydrodynamic loads (for off-shore systems), control system (servo) behavior, and structural-dynamic (elastic) loads (e.g., gravitational, inertial, centrifugal, and gyroscopic loads) (see Figure 7.21 (b)).

blade; these methods provide computational efficiency but also result in a simplistic representation of the blade aerodynamics. Model improvements include developing improved corrections to these (BEM)-based models and replacing BEM-based models with higher fidelity models such as prescribed and free wake models or three-dimensional Computational Fluid Dynamics (CFD) models (Snel, 1998; Snel, 2003), as described in Section 7.7.4.2 below. More research should also be directed towards the rotor wakes' influence on the aeroelastic response of turbines in wind project arrays (Larsen *et al.*, 2008). Finally, the accuracy of design calculations will be improved with verification (model-to-model) (Simms *et al*., 2001) and validation (model-to-wind-tunnel experiments and full-scale field tests) of the aeroelastic tools (Schepers *et al.*, 2002; Schreck, 2002). As aeroelastic tools are upgraded, they must be further verified and experimentally validated to ensure their accuracy.

7.7.4.2 Aerodynamics

As wind energy gained momentum in the early 1980s, turbine aerodynamics emerged as a central research issue. To address energy capture shortfalls and establish a threshold capability for load predictions, initial work concentrated on steady, two-dimensional blade flow fields. This effort produced airfoil (blade) designs optimized for wind turbine applications and enabled significantly increased energy capture (Tangler and Somers, 1995; Timmer and van Rooij, 2003; Fuglsang *et al.*, 2004). At the same time, basic BEM-based design codes were developed, which facilitated early wind turbine designs (Spera, 2009).

Comparisons between wind tunnel and rotating blade data implied that three-dimensional effects figured prominently in rotating blade flow fields (Butterfield, 1989; Madsen and Rasmussen, 1994; Madsen *et al*., 2010). The underlying cause was later identified as rotational augmentation, which has now been quantified in detail (Schreck and Robinson, 2003) and found to be significantly unsteady (Schreck, 2007). Analytically based rotational augmentation models have been formulated to include this effect in BEM codes (e.g., Eggers and Digumarthi, 1992; Snel *et al.,* 1992; Du and Selig, 1998). In addition, early rotating blade measurements for yawed rotor operation revealed prominent load oscillations linked to dynamic stall (Butterfield, 1989), which later was characterized for a broad range of operating conditions (Schreck *et al*., 2000, 2001). Various empirical models for dynamic stall that were originally constructed for rotorcraft applications have been adapted for wind turbine BEM codes (e.g., Bierbooms, 1992; Yeznasni *et al*, 1992), with the Leishman-Beddoes model (Leishman, 2006) most widely employed. As turbines become larger and more flexible, these unsteady effects become more important and improved unsteady aerodynamic models will be required; this will require a combination of fundamental and experimental research.

As blade-flow field modelling complexity has grown, so too has wake model sophistication. The equilibrium wake inherent in basic BEM models lacked fidelity under time-varying inflow conditions, and so was replaced with analytically based dynamic wake representations of low order (Pitt and Peters, 1981; Suzuki and Hansen, 1998) and then of higher order (Peters *et al.*, 1989; Suzuki and Hansen, 1999). Characterization of the wake itself and resulting accuracy enhancements can be realized at the cost of increased computational intensiveness with prescribed and free wake models (Snel and Schepers, 1992). BEM models augmented with analytically and empirically based models as summarized above remain the industry standard for much of wind turbine design. However, the first principles nature of high-performance CFD codes and the prospects for greater predictive accuracy is prompting broader application (Hansen *et al.*, 2006). As turbine aerodynamics modelling advances, the crucial role (e.g., Simms *et al.*, 2001) of research-grade turbine aerodynamics experiments (Hand *et al*., 2001; Snel and Schepers, 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 flow field at levels approaching the theoretical maximum, improved understanding of aerodynamic phenomena will allow more accurate calculation of loads and thus the development of more precise design criteria and greater certainty of wind turbine power production and reliability.

7.7.4.3 Aeroacoustics

Aeroacoustic noise (i.e., the noise of turbine blades passing through the air) is a limiting factor on the performance of wind turbines, and most turbines' rotational speeds are limited because of noise constraints. With quieter gearbox and generator designs, aeroacoustic noise is now considered the dominant noise source for wind turbine operation (Wagner *et al*., 1996). The physical mechanisms and basic modelling techniques for aeroacoustic noise from wind turbines were identified by Lighthill (1952), Curle (1955), and Ffowcs *et al*. (1969). These have led to semi-empirical methods for airfoil noise prediction that are used in many different industries (e.g., Amiet, 1975; Brooks *et al*., 1989). These semi-empirical methods have been modified and applied to a number of different wind turbine noise prediction codes (Wagner *et al*., 1996; Moriarty and Milgiore, 2003; Zhu et al., 2005). More advanced computational aeroacoustics tools have also been developed (Shen and Sørensen, 2007; Zhu *et al*., 2007) that may see greater use in the future as computational constraints are relaxed.

Measurement of wind turbine noise has traditionally required single microphone techniques (IEC, 1998) to quantify overall sound pressure level and satisfy noise ordinances. In more recent years, acoustic arrays (Oerlemans *et al*., 2007) have been developed to help identify the locations of noise sources. This research has found that, on traditional blade designs, the noisiest part of the wind turbine is the outer 25% of the downward passing blade, with the noise source originating at the trailing edge of the blade (Oerlemans *et al*., 2008).

Reducing aeroacoustic noise can be most easily accomplished by slowing down rotor speed. Noise can be reduced without sacrificing aerodynamic performance by using aeroacoustic airfoil design techniques (Migliore and Oerlemans, 2004; Lutz *et al*., 2007). Often, this process involves changing the airfoil shape to minimize the boundary layer thickness at the airfoil trailing edge. Some initial research has shown small reductions in noise based on tip shape (Wagner *et al*., 1996; Fleig *et al*., 2004), but measurements have been inconclusive (Migliore, 2009). Trailing edge modifications such as serrations (Howe, 1991) have shown promise for noise reduction. Field testing of different mitigation methods shows small reductions from optimally shaped airfoils and larger reductions for trailing edge serrations (Oerlemans *et al*., 2008). In addition to blade shape, upwind rotors – as is now standard – are generally less noisy than downwind designs, because in downwind machines the interaction between the blades and the downwind tower wake create a large impulsive noise source (McNerney *et al*., 2003). Understanding trade-offs in airfoil design for structural efficiency or load mitigation as described in Section 7.3.3 and resulting aeroacoustic noise requires further development of these models and field testing to validate analytic results.

Noise propagation is important, as the condition of the atmosphere (van den Berg, 2008) and the local terrain (Prospathopoulos and Voutsinas, 2005) influence how noise travels to observer locations. Prediction methods for propagation include simple ray tracing (Prospathopoulos and Voutsinas, 2005) and more-complicated methods (Cheng *et al*., 2006).

7.7.4.4 Advanced control concepts

Control systems are critical to wind turbine operation; their goal is to maximize power capture, reduce structural loads, and maintain safe turbine operation. Commercial wind turbines are becoming larger, with lighter, more-flexible components. Designing controls to meet multiple control objectives for these large, dynamically active structures is a major challenge. To date, most commercial turbine controllers are designed using classical control design approaches. These approaches result in numerous single-input single-output control loops, but this approach can destabilize the turbine if not carefully designed. More advanced state-space control methods can meet multiple control objectives in a single control loop to assure stability of the turbine system. Progress in the design of advanced controls includes the implementation of periodic control gains to regulate power production and blade loading (Stol and Balas, 2003). Disturbance accommodating control methods developed by Johnson (1976) also show promise for reducing turbine loads while maintaining power production levels (Wright 2004; Hand and Balas, 2004). Many of these more advanced methods rely upon linear wind turbine models. An alternative control technique is to account for the non-linear behaviour of a wind turbine through adaptive control, in which the control gains “adapt” to changing conditions (Johnson *et al.*, 2004; Johnson and Fingersh 2008; Frost *et al.*, 2009). Continued development of modern control methods that are able to incorporate more-advanced sensor inputs and achieve multiple control objectives will contribute to reduced fatigue loading (see Section 7.7.3.2) and improved energy capture (see Section 7.7.3.3).

Most control algorithms depend on measured turbine signals in the control feedback loop for load mitigation, yet these turbine measurements are often unreliable or too slow. A significant advantage in load mitigating capability might be attained by measuring complex wind phenomena ahead of the turbine and preparing the controls in advance to mitigate the resulting loads. Research by Harris *et al.* (2006) investigated the use of Light Detection and Ranging (LIDAR) and Larsen *et al.* (2004) explored pressure probe measurements ahead of the blade to provide the controller with advanced wind-speed measurements; such approaches show promise for more sophisticated control strategies that allow for greater load reduction.

7.7.4.5 Materials science

Wind turbines are designed to survive at least 20 years, which corresponds to more than one-hundred million load cycles on the blades. Because blades can be stiffness or fatigue driven, material testing is very important to provide designers with an array of candidate blade materials that are fully characterized. Comprehensive databases are maintained to characterize these materials (Mandell and Samborsky, 1997; Brøndsted *et al.*, 2005; Brøndsted *et al.*, 2008; Mandell and Samborsky, 2008). Variations in materials include different fibre reinforced composites (using glass and carbon fibres and combinations), different laminate fabrication processes, material forms, orientations, polyester epoxy and other resins, fibre contents, and structural details. Additional characterizations are planned for thermoplastics, thick adhesives, and thick core materials.

Fibreglass has been the primary reinforcement for wind turbine composite blades. Carbon fibre has tremendous potential for use in large blades in areas where loads are acute. As research is showing, carbon fibre also has an advantage when incorporated into passive load control concepts whereby carbon fibres are placed strategically to provide enhanced bend-twist coupling, which will help shed turbulent loads (Lobitz and Veers, 2003). The extent of future use of carbon fibre is uncertain, however, because of supply and cost concerns. Some companies use carbon selectively, whereas other companies do not see enough of a performance benefit relative to the incremental cost to add it to their designs.

7.7.4.6 Atmospheric science

Accurate, reliable wind measurements and computations across scales ranging from microns to thousands of kilometres (Schreck *et al*., 2008) can improve the understanding of the wind turbine operating environment. Though the physics are strongly coupled, the problem can be subdivided into four spatio-temporal levels to facilitate explanation: 1) external design wind conditions for individual wind turbine dynamics, 2) wind project siting and array effects (wind resources and wake effects on design wind conditions), 3) mesoscale atmospheric processes, and 4) global and local climate effects. External design wind conditions affecting the individual wind turbine dynamics encompass detailed characterizations of turbine flow fields including turbulence structures needed to achieve aerodynamics load predictions accurate enough for machine designs. This area is addressed using an incremental approach involving hierarchical computational modelling (Araya *et al.*, 2006) and detailed measurements, e.g. wind tunnel and field experiments (Simms *et al.*, 2001), wherein the isolated turbine is considered initially, and then inflow including the wake trailed from an upwind turbine is undertaken. Wind project siting and array effects focus on improved wake models (Thomsen and Sørensen, 1999; Frandsen *et al.*, 2007) for more reliably predicting energy capture underperformance and exacerbated fatigue loading in large, multiple-row wind projects. Planetary boundary layer research is important for accurate determination of wind inflow structure and turbulence statistics in the presence of various atmospheric stability effects and complex land surface characteristics. Work in mesoscale atmospheric processes aims at improved fundamental understanding of mesoscale and local flows (Banta *et al.*, 2003; Kelley *et al.*, 2004) and developing enhanced wind forecasting methods optimally suited for wind energy production forecasts and wind energy resource assessments. Modelling approaches for resolving spatial scales in the 100-m to 1000-m range, a notable gap in current capabilities (Wyngaard, 2004), could occupy a central role in future research. In global and local climate effects, work is needed to identify and understand historic trends in wind resource variability to increase confidence for future planning and validation. Similar research is needed to better predict future changes in the mean and variability of wind climate and resources (Pryor *et al.*, 2005). Also important are characterizations of large wind project influences on local/regional/global climates.

To make additional progress in many of the above areas will require interdisciplinary work to exploit previously untapped synergies. Also crucial is the need to apply experiments and observations in a coordinated fashion with computation and theory. The models that are developed as a result of this work are essential for improving 1) wind turbine design resulting from turbulent inflow, 2) wind project performance estimates, 3) wind resource mapping that identifies likely locations for projects, 4) short-term forecasting that efficiently integrates wind generation into electric systems, and 5) estimates of the impact of large-scale wind technology deployment on the local climate, as well as the impact of potential climate change effects on wind resources.

7.8 Cost trends[19]

The cost of wind energy has declined significantly since the beginnings of the modern wind industry in the 1980s and, in some circumstances, the cost of wind energy is cost-competitive with fossil generation (e.g., Berry, 2009; IEA, 2009b). Continued technology advancements in on- and off-shore wind are expected (Sections 7.7), which will support further cost reductions. Because the degree to which wind energy is utilized globally and regionally will depend largely on the economic performance of wind compared to alternative power sources, this section describes the factors that affect the cost of wind energy (7.8.1), highlights historical trends in wind project cost and performance (7.8.2), summarizes data and estimates the levelized cost of energy from wind in 2008 (7.8.3), and forecasts the potential for further cost reductions into the future (7.8.4).

7.8.1 Factors that affect the cost of wind energy

The cost of wind energy is affected by four fundamental factors: annual energy production, installation costs, operating costs, and financing costs / project operating life [TSU: unclear]. These factors affect both on-shore and off-shore wind projects, but differently. Available policy incentives can also influence the cost of wind energy, as well as the cost of other generation options, but these factors are not addressed here.

[19] All cost data are presented in real, 2005 U.S. dollars (US2005$)

The quality of the wind resource at a given site largely determines the annual energy production from a prospective wind project, and is among the most important economic factors. Precise micro-siting of wind projects 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, and has also allowed wind projects in lower resource areas to become more economically competitive over time. Off-shore wind projects will, generally, be exposed to a higher wind resource than will on-shore projects.

Wind projects are capital intensive and, over the life of a project, 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 project 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 capital cost components for modern, utility-scale wind energy projects, with the turbines comprising more than 70% of installed costs for on-shore wind projects. The remaining costs are highly site-specific. Off-shore projects 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 for on-shore projects (see also, Junginger *et al*., 2004).

Table 7.5. Installed cost distribution for on-shore and off-shore wind projects (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 operation and maintenance [TSU: please use abbr. O&M] costs of wind projects 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. Operation and maintenance [TSU: please use abbr. O&M] costs comprise approximately 20% of total wind project expenditure (Blanco, 2009), with roughly 50% of total operation and maintenance [TSU: please use abbr. O&M] costs associated directly with maintenance, repair, and spare parts (EWEA, 2009). Off-shore project operation and maintenance [TSU: please use abbr. O&M] costs are higher than on-shore costs 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 project. 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*., 2009a). Other research has found that the stability of policy measures supporting wind can also have a sizable impact on financing costs, and therefore the ultimate cost of wind (Wiser and Pickle, 1998; Dinica, 2006; Dunlop, 2006; Agnolucci, 2007). Because off-shore projects are still relatively new, with greater performance risk, higher financing costs are experienced than for on-shore projects (Dunlop, 2006; Blanco, 2009), and larger firms tend to dominate off-shore wind development and ownership (Markard and Petersen, 2009).

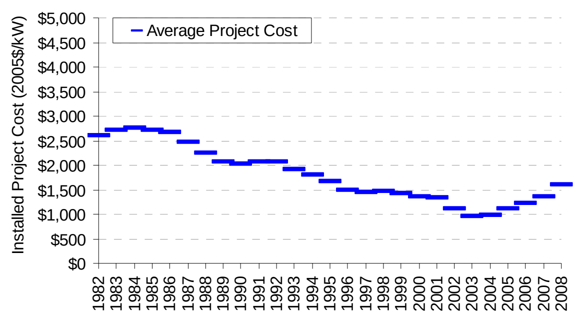
7.8.2 Historical trends

7.8.2.1 Installed capital costs

From the beginnings of commercial wind deployment to roughly 2004, the installed capital cost of on-shore wind projects 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 7.22(a,b). From 2004 to 2008, however, capital costs increased. Wind project costs in Denmark and the U.S. in 2008 averaged $1,600/kW and $1,800/kW, respectively, up by approximately 50% from the earlier low. Some of the reasons behind these increased costs are described in Section 7.8.3.

(a) Wind project costs in Denmark (James-Smith and Bang, 2010)	**(b)** Wind project costs in the United States (Wiser and Bolinger, 2009)



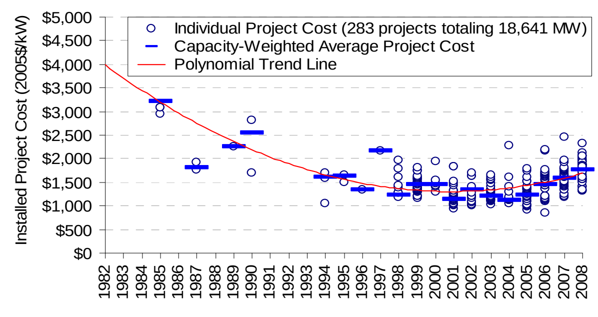


Figure 7.22. Installed cost of wind energy projects in (a) Denmark and (b) the United States

The installed costs of off-shore wind projects are highly site-specific, but have historically been 50% to more than 100% more expensive than on-shore projects (IEA, 2008; EWEA, 2009). Due to the small sample size and short historical record, a trend toward reduced costs over time is not clearly discernable. Off-shore wind project costs have also been influenced by the same factors that caused rising on-shore costs from 2004 through 2008, as described in Section 7.8.3.

7.8.2.2 Project performance

Wind project performance is primarily governed by local wind conditions, but is also impacted by wind turbine design optimization, performance, and availability, and by the effectiveness of operation and maintenance [TSU: please use abbr. O&M] procedures. Improved resource assessment and siting methodologies developed in the 1970s and 1980s played a major role in improved wind project productivity. Advancements in wind technology, including taller towers and larger rotors, have also contributed to increased energy capture (EWEA, 2009).

Data on capacity factors[20] achieved in 2008 for a large sample of on-shore wind projects in the U.S. show a trend toward higher capacity factors for projects built more recently, although variation in

[20] A wind project's capacity factor is only a partial indicator of wind project performance (EWEA, 2009). Most turbine manufacturers supply variations on a given drive-train platform with multiple rotor diameters and hub heights. In general, for a given drive-train platform, increasing the hub height, the rotor diameter, or the average wind speed will result in increased capacity factor. When comparing different drive-train platforms, however, it is possible to increase annual energy capture by using a larger generator, while at the same time decreasing the wind project's capacity factor.

performance among projects built in a single year can be quite large (Figure 7.23). Higher hub heights and larger rotor sizes are primarily responsible for these improvements in energy capture, as the more recent projects in this time period were sited in increasingly lower wind resource regimes.

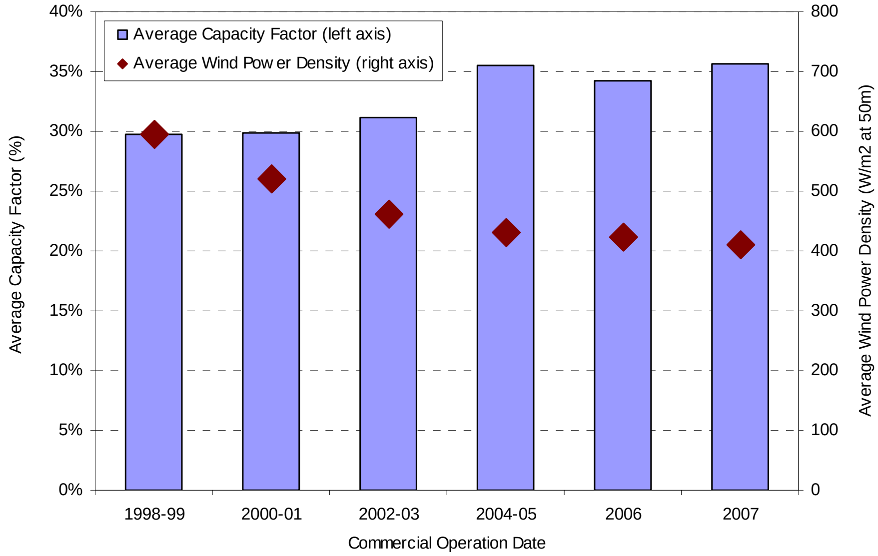


Figure 7.23. Wind project capacity factors in the U.S. (Wiser *et al.,* 2010)

Using a different (and arguably more appropriate) metric for wind project 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). Data from the U.S. also suggest some improvement in this metric from 1998 through 2007, though not at the 2-3% per year level (Wiser *et al.*, 2010).

7.8.2.3 Operation and maintenance

Modern turbines that meet IEC standards are designed for a 20-year life, and project lifetimes may even exceed 20 years if O&M costs remain at an acceptable level. However, few wind projects were constructed 20 or more years ago, and therefore there is limited experience in project operations over this entire time period. Moreover, those projects 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 projects only offer limited guidance for estimating operation and maintenance [TSU: please delete] (O&M) costs for more-recent turbine designs.

In general, operation and maintenance [TSU: please use abbr. O&M] costs during the first couple [TSU: of] years of a project'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 operating costs than older models, with maintenance costs increasing as projects age (Blanco, 2009; EWEA, 2009; Wiser and Bolinger, 2009). New technologies, such as condition monitoring equipment, could lead to lower O&M costs over the life of a project than might otherwise occur. Off-shore wind projects have historically incurred higher operation and maintenance [TSU: please use abbr. O&M] costs than on-shore projects (Junginger *et al.*, 2004; EWEA, 2009; Lemming *et al.*, 2009).

7.8.3 Current conditions

7.8.3.1 Installed capital costs

The cost for most on-shore wind projects in Europe ranged from roughly $1,500/kW to $2,000/kW in 2008 (Milborrow, 2009), while projects installed in the United States in 2008 averaged $1,750/kW (Wiser and Bolinger, 2009). Costs in certain developing markets are somewhat lower: for example, average wind project costs in China in 2008 were around $1,100/kW in real 2005$, driven in part by the dominance of several Chinese turbine manufacturers serving the market with low-installed-cost wind turbines (Li and Ma, 2009).

Overall, wind project costs rose from 2004 to 2008 (Figure 7.22), an increase primarily caused by the rising price of wind turbines (Bolinger and Wiser, 2009), which has 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.*, 2009b). 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, aluminum, 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 have traditionally been provided by only a small number of suppliers. Moreover, because many of the global 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 price increases in certain countries (Bolinger *et al.*, 2009b).

Turbine manufacturers and component suppliers responded to the tight supply by expanding or adding new manufacturing facilities. Coupled with somewhat weakened demand for wind turbines and 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. Wind turbine cost reductions of as much as 25% were reported by mid-2009, relative to the mid-2008 high point (Wiser and Bolinger, 2009).

Due to the relatively small number of off-shore wind installations, cost data are sparse. Off-shore wind project costs are considerably higher than those for on-shore projects, and the factors that have increased the cost of on-shore projects have similarly affected the off-shore sector. The limited availability of turbine manufacturers supplying the off-shore market, and of vessels to install such projects, has exacerbated cost increases. Off-shore wind projects over 50 MW, either built between 2006 and 2008 or planned for 2009-10, have installed costs that range approximately $2,000/kW to $5,000/kW (IEA, 2008; IEA, 2009b; Milborrow, 2009; Snyder and Kaiser, 2009), with most estimates in a narrower range of $3,200/kW to $4,600/kW (Milborrow, 2009).

7.8.3.2 Project performance

On-shore wind project performance varies significantly even within an individual country, primarily as a function of the wind resource, with capacity factors ranging from below 20% to more than 50% depending on the local resource conditions. Among countries, variations in average project performance again reflect differing wind resource conditions: the average capacity factor for Germany's installed wind projects has been estimated at 20.5% (BTM, 2009); European country-level average capacity factors range from 20-30% (Boccard, 2009); and the average capacity factor for U.S. wind projects is nearly 34% (Wiser and Bolinger, 2009). Off-shore wind projects often experience a narrower range in capacity factors, with a typical range of 35% to 45% for the European projects installed to date (Lemming *et al.*, 2009).

Because of these variations among countries and individual projects, which are primarily driven by local wind energy resource conditions, estimates of the levelized cost of wind energy must include a range of energy production estimates. Moreover, because the attractiveness of off-shore projects is enhanced by the potential for greater energy production than for on-shore projects, performance variations among on- and off-shore projects must also be considered.

7.8.3.3 Operation and maintenance

Though fixed operation and maintenance [TSU: please use abbr. 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). operation and maintenance [TSU: please use abbr. O&M] costs vary by project, region, project age and the availability of a local serving infrastructure, among other factors. Levelized on-shore wind operation and maintenance [TSU: please use abbr. O&M]costs are often estimated to range from $0.012/kWh to $0.023/kWh (Blanco, 2009): these figures are reasonably consistent with costs reported in IEA (2008), EWEA (2009), and Wiser and Bolinger (2009), and represent a relatively small fraction of the total delivered cost of wind energy.

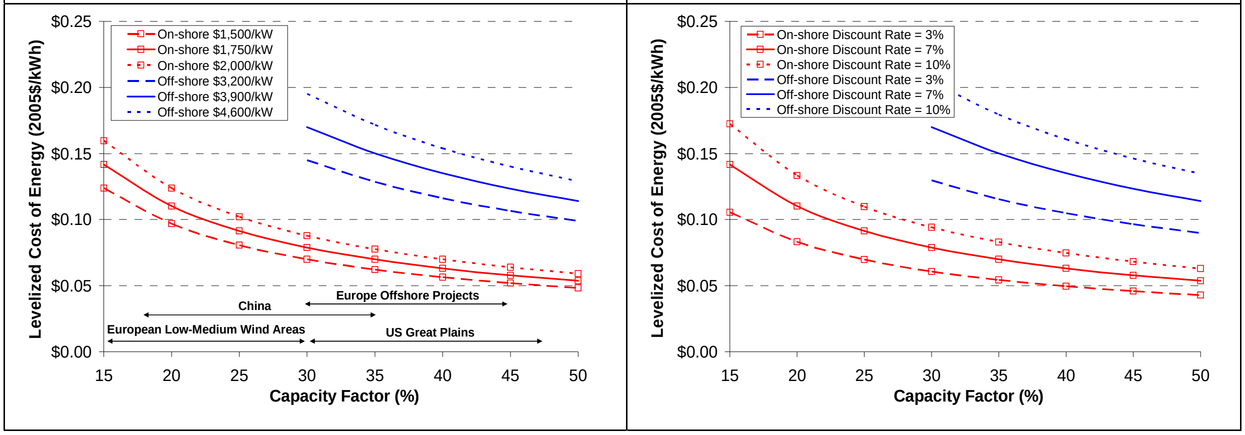
Limited empirical data exist on operations costs for off-shore projects, due in large measure to the limited number of operating projects and the limited duration of those projects' operation. Reported or estimated O&M costs that are available for off-shore projects installed since 2002 range from $0.02/kWh to $0.04/kWh (EWEA, 2009; IEA, 2009b; Lemming *et al.*, 2009; Milborrow, 2009).

7.8.3.4 Levelized cost of energy estimates

Using the methods summarized in Chapter 1, the levelized cost of wind energy for projects built in 2008 is presented in Figure 7.24(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 $1,500/kW to $2,000/kW (mid-point of $1,750/kW); installed costs for off-shore projects range from $3,200/kW to $4,600/kW (mid-point of $3,900/kW). Levelized operation and maintenance [TSU: please use abbr. O&M] costs are assumed to average $0.016/kWh and $0.03/kWh over the life of the project for on-shore and off-shore projects, respectively. A project 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 the levelized cost of energy calculations.

(a) Cost of wind energy as a function of project performance and capital cost*

(b) Cost of wind energy as a function of project performance and discount rate**



* Discount rate assumed to equal 7%

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

Figure 7.24. Estimated levelized cost of on-shore and off-shore wind energy, 2008

The levelized cost of on- and off-shore wind energy in 2008 varies substantially, depending on assumed capital costs, energy production estimates, and discount rates. For on-shore wind, levelized costs can exceed $0.10/kWh in lower resource areas, and be as low as around $0.05/kWh in the highest wind resource regimes. Off-shore wind is generally more expensive than on-shore wind, with levelized costs that can range from $0.10/kWh to $0.20/kWh.

7.8.4 Potential for further reductions in the cost of wind energy

The modern wind industry has developed over a period of 30 years. Though the dramatic cost reductions seen in the 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 applications; however, given the relative immaturity of off-shore wind technology, 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 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 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 (Table 7.6). There is a wide range of calculated learning rates, from 4% to 32%. 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 presented in Table 7.6 cannot easily be compared.

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%	USA	US (turbine cost)	1981-1996
Neij 1999	8%	Denmark	Denmark (turbine cost)	1982-1997
Wene 2000	32%	USA **	USA (production cost)	1985-1994
Wene 2000	18%	European Union **	European Union (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
Taylor et al. 2006	23%	Global	California (installed cost)	not reported
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
Kahouli-Brahmi 2009 *	27%	Global	global (installed cost)	1979-1997
Nemet 2009	11%	Global	California (turbine cost)	1981-2004

* Indicates a 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 in the use of such models to forecast future costs. First, learning curves model how costs have decreased with increased production in the past, but do not explain the reasons behind the decrease. If learning curves are used to forecast future cost trends, one must assume that the factors that have driven costs in the past will be sustained into the future. 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 is arguably the levelized cost of energy, as wind energy production costs are affected by both installed costs and energy production (EWEA, 2009; Feroli *et al.*, 2009). Unfortunately, only two of the published studies calculate the learning rate for wind 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 installations or production in individual countries or regions; because the wind industry is global in scope, however, it is likely that most learning is occurring based on cumulative global installations. Finally, from 2004 through 2008, the installed cost of wind projects 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 energy production increases.

These models have been used to estimate the impact of potential technology improvements on wind project capital costs and energy production, as highlighted earlier in Section 7.3 (based on U.S. DOE, 2008). Given these possible technology advancements, the U.S. DOE (2008) estimates that installed on-shore wind costs may decline by 10% by 2030, while energy production may increase by roughly 15%. Combined, these two impacts correspond to a reduction in the levelized cost of energy from on-shore wind of 17% by 2030.

Given the relative immaturity of off-shore wind technology, there is arguably greater potential for technical advancements in off-shore wind than in on-shore wind, particularly in foundation design, installation, electrical system design, and operation and maintenance [TSU: please use abbr. O&M] 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, 2008a; Lemming *et al.*, 2009).

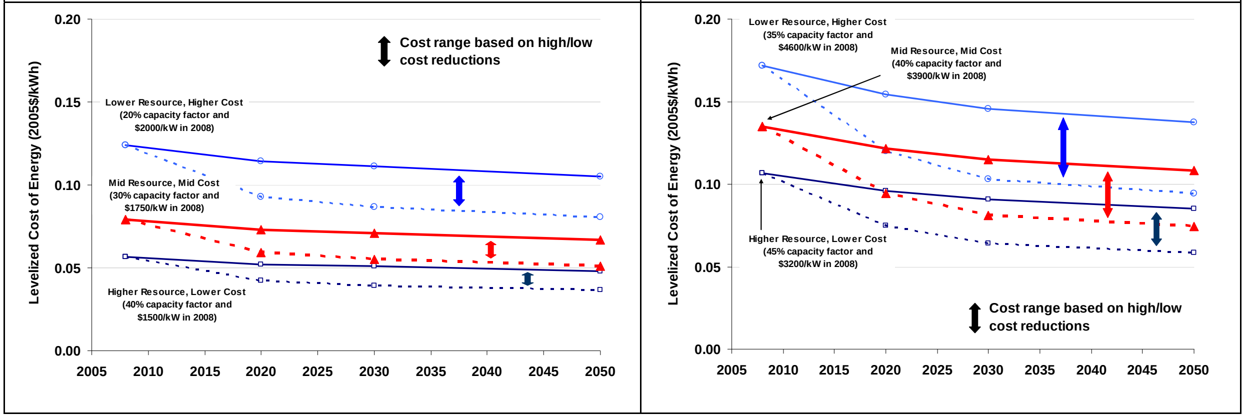
7.8.4.3 Projected levelized cost of wind energy

A number of studies have estimated the cost trajectory for on-shore and off-shore wind based on learning curve estimates and/or engineering models (Junginger *et al.*, 2004; Carbon Trust, 2008a; GWEC 2008; IEA, 2008; Neij, 2008; U.S. DOE, 2008; Lemming *et al.*, 2009).

Using the estimates and assumptions for the percentage cost reduction expected from these studies, a range of levelized cost trajectories have been developed for representative future on-shore and off-shore wind projects (Figure 7.25(a, b)). In each of the graphics, a high, low, and mid-level starting point for the levelized cost of energy is calculated using various combinations of project-level capacity factor and installed cost assumptions, representing a reasonable range of 2008 values. These levelized cost estimates for 2008 are the same as presented earlier in Figure 7.24.

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 7.5-25% by 2020 and 15-35% by 2050, and for off-shore wind of 10-30% by 2020 and 20-45% by 2050.

(a) On-shore* **(b)** Off-shore*



Starting-point O&M costs are assumed to equal $0.016/kWh (on-shore) and $0.03.kWh (off-shore); a 7% discount rates is used throughout

Figure 7.25. Projected levelized cost of (a) on-shore and (b) off-shore wind energy, 2008-2050

Based on these assumptions, the levelized cost of on-shore wind could range from roughly $0.04-0.11/kWh in 2050, depending on the wind resource, installed project costs, and the speed of cost reduction. Off-shore wind is likely to experience somewhat deeper cost reductions, with a range of expected levelized costs of $0.06-0.14/kWh in 2050.

Significant uncertainty exists over future wind technology costs, and the range of costs associated with varied wind resource strength introduces even greater uncertainty. As installed wind capacity levels increase, 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 will depend on the amount of deployment. This “supply-curve” affect is not captured in the estimates presented in Figure 7.26: those projections present potential cost reductions associated with wind projects 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, 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 energy capacity installed by the end of 2008 delivers roughly 1.5% of worldwide electricity supply, and global wind electricity supply 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 is a mature technology that is already being deployed at a rapid pace (see Sections 7.3 and 7.4), therefore offering an immediate option for reducing carbon emissions in the electricity sector. In good wind resource regimes, the cost of wind can be competitive with other forms of electricity generation (especially where environmental impacts are monetized: see Section 7.8), and no fundamental technical barriers exist that preclude increased levels of wind penetration into electricity supply systems (see Section 7.5). Continued technology advancements and cost reductions in on- and off-shore wind are expected (see Sections 7.7 and 7.8), which will further improve 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.

7.9.1 Near-term forecasts

The rapid increase in global wind capacity from 2000-2008 is expected by many studies to continue in the near- to medium-term (Table 7.7). From the roughly 120 GW of wind capacity installed at the end of 2008, the IEA (IEA, 2009a) and U.S. Energy Information Administration (U.S. EIA, 2009) reference-case forecasts predict growth to 295 GW and 249 GW by 2015, respectively. Wind industry organizations predict even faster deployment rates, noting that past IEA and EIA forecasts have understated actual wind growth by a sizable margin (BTM, 2009; GWEC, 2009). However, even these more-aggressive forecasts estimate that wind energy will contribute less than 4% of global electricity supply by 2015. Asia, North America, and Europe are projected to lead in wind 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(2009a)	295 GW	2015	2.8%
U.S. EIA (2009)	249 GW	2015	2.2%
GWEC (2009)	332 GW	2013	not available
BTM (2009)	343 GW	2013	3.4%

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 (U.S. DOE, 2008; Neuhoff *et al.*, 2008). The resulting differences among studies of the long-term deployment of wind 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 could contribute 7% of global electricity supply by 2030, or 2,200 TWh/yr (~ 8 EJ) (IPCC, 2007). This figure is higher than some commonly cited business-as-usual, reference-case forecasts, since the IPCC estimate is not a business-as-usual case. The IEA's World Energy Outlook reference-case, for example, predicts 1,535 TWh/yr of wind by 2030, or 4.5% of global electricity supply (IEA, 2009a). The U.S. EIA forecasts 1,214 TWh/yr of wind energy in its 2030 reference case projection, or 3.8% of net electricity production from central producers (U.S. EIA, 2009).

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 [TSU: in/by] Chapter 10. Focusing specifically [TSU: on] wind energy, Figure 7.26 and Figure 7.27 present modelling results on the global supply of wind energy (in EJ and as a percent of global electricity demand, respectively); refer to Chapter 10 for a full description of this literature. 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 (reference cases), 440-600 ppm (Categories III and IV), and 300-440 ppm (Categories I and II).

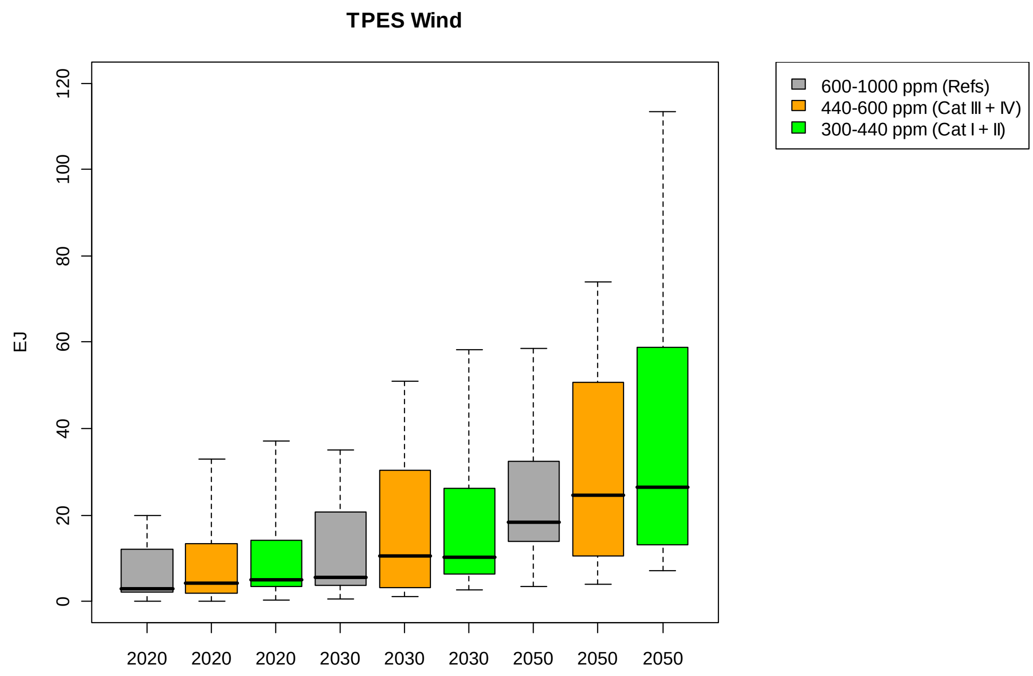


Figure 7.26. Global supply of wind energy in carbon stabilization scenarios (median, 25th to 75th percentile range, and absolute range)

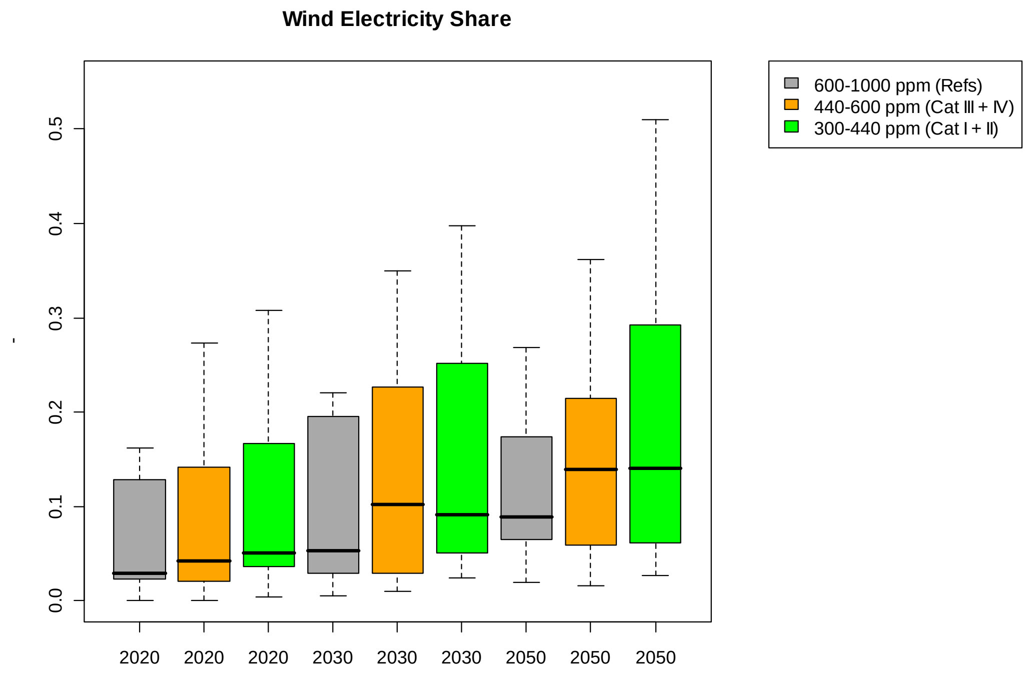


Figure 7.27. Wind electricity share in total global electricity supply (median, 25th to 75th percentile range, and absolute range)

The reference-case projections of wind energy's role in global energy supply span a broad range, but with a median of roughly 3 EJ in 2020, 6 EJ in 2030, and 18 EJ in 2050 (Figure 7.9.1). 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 1.5% in 2008 to 8.9% in 2050 (Figure 7.9.2). 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 (~10% of global electricity supply) in the 440-600 and 300-400 ppm-CO_2 stabilization ranges, increasing to 25-27 EJ by 2050 (~14% of global electricity supply).[21]

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 (median of 18 EJ), 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 (median of 27 EJ), equivalent to 3-51% (median of 14%) of global electricity supply.

Despite this wide range, the IPCC (2007) estimate for potential wind energy supply of roughly 8 EJ by 2030 (which was largely based on literature available through 2005) appears somewhat conservative compared to the more-recent scenarios literature presented above. Other updated forecasts of the possible role of wind energy in meeting global energy demands confirms this assessment, as the IPCC (2007) estimate is roughly one-third to one-half that shown in GWEC/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; 450 ppm case).

Though the literature summarized in Figures 7.9.1 and 7.9.2 shows an increase in wind energy supply 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 relatively 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 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 around 25 EJ, increasing to 50 EJ at the 75th percentile, and to more than 100 EJ in the highest scenario. To achieve this contribution requires wind energy to deliver around 14% of global electricity supply in the median case, or 25% at the 75th percentile. Other scenarios generated by wind and RE organizations are consistent with this median to 75th percentile range; GWEC/GPI (2008) and Lemming *et al.* (2009), for example, estimate the possibility of 32-37 EJ of wind energy supply by 2050.

Even the highest estimates for long-term wind energy production in Figure 7.9.1 are within the global resource estimates presented in Section 7.2, and while efforts may be required to ensure an adequate supply of labour and materials, no fundamental long-term constraints to materials supply, labour availability, or manufacturing capacity are envisioned if policy frameworks for wind energy are sufficiently attractive (e.g., U.S. DOE, 2008). To enable the necessary investment over the long

[21] In addition to the global scenarios literature, a growing body of work has sought to understand the technical and economic limits of wind 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 dena, 2005 (Germany); EC, 2006 (Europe); Nikolaev *et al*., 2008, 2009 (Russia); and U.S. DOE, 2008 (United States).[21] In general, these studies confirm the basic findings from the global scenarios literature: wind deployment to 10% of global electricity supply and then to 20% or more are plausible, assuming that cost and policy factors are favourable towards wind deployment.

term, however, economic incentive policies intended to reduce carbon emissions and/or increase renewable energy supply of adequate economic attractiveness *and* stability would likely be required (see Chapter 11). Additionally, four other challenges would likely need to be addressed to reach the levels of wind energy supply discussed in this section.

First, 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 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, 2009a). Under higher-penetration scenarios, however, a greater geographic distribution of wind deployment is likely to be needed. Scenarios from GWEC/GPI (2008), EREC/GPI (2008), and IEA (2008), for example, suggest that North America, Europe, and China are most-likely to be the areas of greatest wind energy deployment, but a large number of other regions are also significant contributors to wind energy generation growth in these scenarios (Table 7.8).[22] Enabling this level of wind 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, 2009b).

Table 7.8. Regional distribution of global wind energy generation (percentage of total worldwide wind generation)

Region	**GWEC/GPI (2008)*** **2030** ***Advanced***	**EREC/GPI (2008)** **2050** ***Energy Revolution***	**IEA ETP (2008)** **2050** ***BLUE***
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 GWED/GPI (2008), percentage of worldwide wind capacity is presented.

Second, due to resource and siting constraints, some regions would likely rely heavily on additions to off-shore wind energy, particularly Europe. Estimates of the proportion of total wind energy supply likely to be delivered from off-shore developments in 2050 range from 18-30% (EREC/GPI, 2008; IEA, 2008; Lemming *et al*., 2009), while the IEA forecasts a 20-28% share by 2030 (IEA, 2009a). Increases in off-shore wind of this magnitude would require technological advancements and cost reductions given the state of the technology. Though continued and expanded R&D is expected to lead to important cost reductions for on-shore wind energy technology, enhanced R&D

[22] Many of these other regions have lower expected electricity demands. As a result, some of the regions with a small contribution to global wind energy generation are still projected to obtain a sizable fraction of their electricity supply from wind in these scenarios.

expenditures by government and industry may be especially important for off-shore wind energy given the less mature state of off-shore wind technology and development (see Section 7.7).

Third, technical and institutional solutions to transmission constraints and operational integration concerns will need to be implemented. Analysis results and experience suggest that power systems can operate with up to roughly 20% wind energy with relatively modest integration costs (see Section 7.5 and Chapter 8) and, while few studies have explored wind electricity supply in excess of 20% in detail, there is little evidence to suggest that an inherent technical limit exists to wind energy's contribution to electricity supply.[23] Nevertheless, concerns about operational integration and power systems 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. Given the locational dependence of the wind energy resource, substantial new transmission infrastructure both on- and off-shore would also be required under even the more modest wind deployment scenarios presented above. Both cost and institutional barriers would need to be overcome to develop the needed transmission infrastructure (see Section 7.6 and Chapter 8).

Finally, given concerns about the social and environmental impacts of wind projects summarized in Section 7.6, 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 wind energy deployment. Though community and scientific concerns need to be addressed, streamlined planning, siting, and permitting procedures for both on-shore and off-shore wind may be required to enable the capacity additions envisioned under these scenarios.

Overall, the evidence suggests that wind 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 production to ultimately reach or exceed 20% of global electricity supply, and that these levels of wind energy supply would be economically attractive within the context of global carbon mitigation scenarios. The degree to which wind energy is utilized in the future will largely depend on: continued economic performance [TSU: improvements] of wind energy compared to alternative power sources; national and regional 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 electricity networks.

[23] Some studies have looked at wind energy penetrations in excess of 20% in certain regions, often using a somewhat-less-detailed analysis procedure 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 energy (e.g., Grubb, 1991; Watson *et al*., 1994; Lund and Münster, 2003; Kempton and Tomic, 2005; Lund, 2006; Black and Strbac, 2006; DeCarolis and Keith, 2006; Denholm, 2006; Cavallo, 2007; Greenblatt *et al*., 2007; Hoogwijk *et al*.. 2007; Benitez *et al.*, 2008; Lamont, 2008; Leighty, 2008; Lund and Kempton, 2008). These studies confirm that there are no insurmountable technical barriers to increased wind energy supply; instead, as deployment increases, grid 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 also become increasingly valuable at high 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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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 8 has been allocated a total of 102 pages in the SRREN. The actual chapter length (excluding references & cover page) is 125 pages: a total of 23 pages over target. Expert reviewers are kindly asked to indicate where the Chapter could be shortened in terms of text and/or figures and tables.

Reviewers are also asked to note that a number of references in the text are not yet reflected in the reference list.

In addition, all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 8: Integration of Renewable Energy into Present and Future Energy Systems

CONTENTS

EXECUTIVE SUMMARY

For the world to achieve an atmospheric stabilisation level below 450 ppm CO_2 equivalent, renewable energy (RE) will have to make a significant contribution to heating, cooling, electrical and mobility services. In order to achieve this, percentage growth of RE technologies over the next few decades will need to be far more rapid than has been the case to date. Integration of RE with conventional energy supply systems, (dominated by fossil fuels and nuclear energy), is the way to achieve this ambition.

This chapter explores how 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. The many types of RE technologies range from mature to those at the early-concept demonstration stage. They rely on cost-effectiveness, social acceptance, reliability, and political support at national and local government levels in order to gain a greater share of the present energy markets.

RE has the potential in the longer term to provide the major share of global energy. Indeed some towns 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 sufficient resources exist. It could provide the full range of energy services in the future to large and small communities in developed and developing countries. However, the necessary transition to a low carbon, RE future will require considerable investments in new infrastructure, (including energy storage, intelligent electricity grids, novel transport methods and distributed energy systems) and improved energy efficiency of both the supply-side and final consumption.

In the shorter term, integration of RE in the present energy supply system, together with the complimentary use of all RE sources, can enhance system reliability, energy security, electricity and gas network security, greenhouse gas mitigation, sustainable development and access to energy services for all. Integration strategies that increase deployment of RE in both urban and rural areas will depend upon local and regional resources, demand patterns, financing methods and 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 highlighted. Through several case studies, the chapter outlines the options and constraints for RE integration through the optimum combination of technologies and social mechanisms, given the limitations of specific site conditions, RE resources, and local energy demands. Comparative assessments of the costs of RE integration options have not been found in the literature and therefore future research needed to provide data for modeling scenarios was identified. For example, how the projected trend towards decentralised energy supply systems might affect future costs and demand for large, centralised systems has not been fully assessed. Other risks and impacts involving the integration and deployment of RE in a sustainable manner, including use of materials, capacity building, technology transfer, and financing have been discussed separately where appropriate for each of the transport, building, industry and agriculture sectors of the global economy.

To develop a coherent framework in preparation for higher levels of RE penetration requires a good understanding of the current energy supply systems.

- In the electricity sector, international experience of integration of variable RE, mainly wind, shows that high levels of penetration are feasible and economically beneficial for society.

Integration is facilitated by methods and investments that increase flexibility of conventional power supply systems such as system control and operation over the network, demand-side response, energy storage, more flexible thermal power plants and an enabling electricity market framework. Not all RE sources fluctuate and baseload options using hydro, geothermal and bioenergy combined heat and power (CHP) systems are mature technologies. For the electricity sector, it is difficult to standardise on a method for the significant departure from a traditional to highly flexible system as each electricity system, large or small, has its own particular governance, inter-connection, technologies, market and commercial issues to deal with. To increase the penetration of RE resources, stakeholders associated with each "electricity industry" will probably need to determine their own pathway whether the industry serves a village or a continent.

- In the building sector, many successful examples of heating and cooling exist utilising biomass (for domestic cooking, heating, CHP, district heating schemes); geothermal (for high temperature process heat or low temperature, small-scale ground source heat pumps); and solar thermal (for water and space heating as well as cooling at the domestic, community or district scales). 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.
- The industry sector is highly diverse, ranging from very large, energy-intensive basic material industries to small and medium sized enterprises. Energy efficiency, material recycling, carbon dioxide capture and storage and fossil-fuel substitution for CHP generation, are relevant for the integration of RE into present and future energy systems at the large scale. In addition industry could provide demand-response facilities that could achieve greater prominence in future electricity supply systems.
- Agriculture, whether large corporate-owned farms or subsistence farmers, is a relatively low energy consuming sector, with pumping of water for irrigation and indirect energy for the manufacture of fertilisers the greatest contributors. RE sources including 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 the farm.
- Transport presently uses very low inputs from RE, mainly as liquid biofuels blended with petroleum products. The development of advanced biofuels, that are more fungible with today's petroleum fuels and distribution systems, could permit greater penetration. The on-going development of electric- and hydrogen-powered vehicles is advancing and could enable the wider use of a variety of widely available RE sources. However, many uncertainties and cost reduction challenges remain concerning future technologies, source of the energy carriers and the related infrastructure.

Integration of the various transport, electricity, building and industry energy supply systems is conceivable in the future, thereby creating a paradigm shift and a step towards the energy transition being sought.

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.

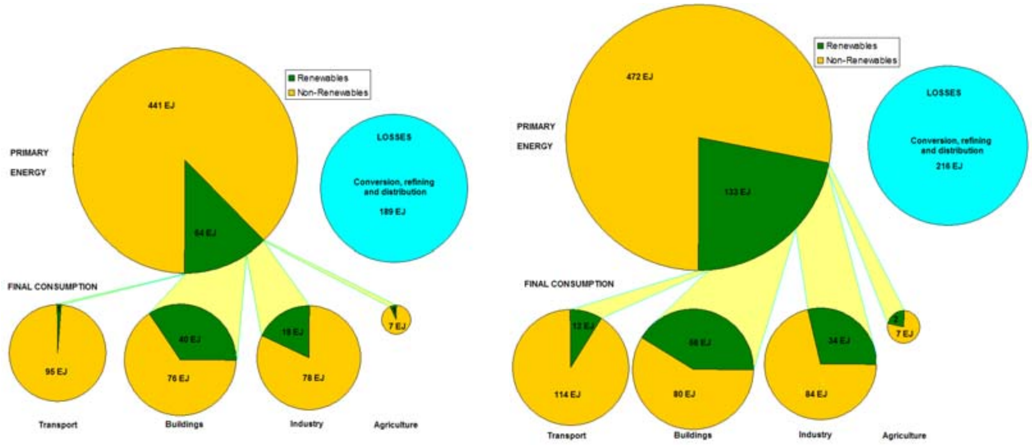
8.1 Introduction

This chapter examines the means by which larger shares of renewable energy (RE) can be integrated into the energy supply system at the national and local levels. Since the 1950s, nations have invested in roads, building and infrastructure designed around the expectation that cheap and available energy supplies would continue. Now that a number of problems with the continued use of conventional fossil fuels and nuclear power have been identified, and many countries are striving to reduce their dependence on imported energy supplies, there is a growing desire to increase alternative energy sources. To enable RE systems to provide a greater share of global heating, cooling, transport fuels and electricity, and thereby displace a portion of fossil fuel supply in the mix, a major transition will be necessary. This will require the adaptation of conventional power supply systems, natural gas grids, heating/cooling schemes, and liquid transport fuel supply and distribution networks, so that they can accommodate greater supplies of RE than at present.

Building on the technology chapters 2 to 7, this chapter outlines the barriers and possible solutions to greater integration. Technologies that can help overcome specific technical barriers to increase deployment of a single technology (such as synchronizing units for wind turbines, co-firing of solid biomass with coal, and back-up requirements for solar water heating systems) have been discussed in the earlier chapters. Here, more general issues, including economic and social barriers, are identified and broad solutions outlined that might overcome them. Differences in the potential uptake of renewables due to their current market status, geographic region, and the varying political ambitions of OECD and non-OECD countries, are also discussed.

Other than the promise of climate change mitigation, RE systems can offer opportunities for sustainable development and improved energy supply security (IEA, 2007c). Energy security is a major challenge facing many nations since prolonged disruptions in supply could cause major economic turmoil. Security risks include the inability of an electricity infrastructure to meet growing load demands; the threat of attack on centralized energy facilities, transmission networks or pipelines; extreme price volatility; or geopolitical actions restricting supplies, particularly oil and natural gas. Diversifying supply by increasing domestic capacity and using a portfolio of local RE sources to meet an increased share of future energy demand growth can make a positive contribution to energy security and reliability (Awerbuch, 2006). Although RE systems can help mitigate supply risks from energy market instabilities, they can carry their own energy security risks such as technical system failure, natural variation in availability, physical threats to infrastructure from extreme weather events, and relatively high costs under some conditions. These issues need to be addressed.

Conventional energy systems are mainly based on oil, coal and gas. To achieve the rapid transition desired to reach a low carbon technology future, the wide range of RE technologies, as outlined in Chapters 2 to 7, will each need to continue to increase market shares. At present, in spite of the long-established contribution to total primary energy supply coming from mature hydropower, modern bioenergy and geothermal technologies, together with the recent impressively high market penetration rates of wind, solar PV and solar water heaters (though all from a low base), the total shares of consumer energy supplied by RE systems remain low (Fig. 8.1). Shares in 2007 were around 16% of global electricity generation from large hydro plants (IEA, 2009a); 2-3% of electricity from wind, geothermal and solar; 1.5% of total transport fuels from biofuels (IEA, 2008a); and 2-3% of total direct heating from solar thermal, geothermal and bioenergy (IEA, 2008a). The latter excludes traditional biomass consumption in rural communities that accounts for around 10% of world primary energy. To make the transition to atmospheric stabilisation of greenhouse gases at 450 ppm CO_2 equivalent will require a rapid ramp up of RE technology deployment (along with energy efficiency, nuclear and CCS) (IEA, 2009a).



2007 **2030**

Figure 8.1: RE shares of primary energy and final consumption in the transport, buildings, industry and agriculture sectors in 2007 and the shares in 2030 under a 450ppm Policy Scenario. (Based on IEA, 2009a).

Notes: Area of circles approximately to scale. Non-renewable energy includes coal, oil, gas and nuclear. Energy efficiency improvements included in 2030 projection.
Building sector RE includes traditional biomass used in developing countries. that is projected to be partly replaced by modern bioenergy by 2030.

Around 1.6 billion people, or 25% of the world's population, mainly living in non-OECD countries, rely on traditional biomass, not always sustainably produced, to provide them with minimal energy services for cooking and keeping warm. Several of these countries, however, are also leading the world in specific RE developments. For example China has over 50% of the world's solar water heaters (SHC, 2007), and Brazil has over 50% of its total transport fuels for light duty vehicles presently supplied from sugar cane ethanol, either blended with gasoline at around 24% by volume or used in higher blends up to 100% in flex-fuel vehicles (Zuurbier & van de Vooren, 2008). Such integration of RE systems with conventional energy systems exemplifies the possible approach needed to achieve further uptake in all regions. Denmark, for example, produced around 19.7% (7180 GWh) of its total power generation in 2007 from wind turbines integrated with other forms of generation (mainly coal- and gas-fired) and with imports/exports of electricity to and from neighbouring countries (DEA, 2009). In Spain, the 2000 Barcelona Solar Thermal Ordnance resulted in over 40% of all new and retrofitted buildings in the area having a solar water heating system installed (EC, 2006). This integrates with the conventional power supply system by reducing demand for electrical heating services. In New Zealand, over 60% of electricity demand has been met from hydropower plants for several decades, but now new back-up, thermal plant capacity has been built to meet demand in recent dry periods.

There are significant regional and local differences in the potentials for RE integration. What is successful in one region may not be so in another, even where conditions are considered to be similar. Integration of RE into the energy supply system and infrastructure of many non-OECD countries today raises challenges that differ from many OECD countries. A paradigm shift is required to supply the millions of people currently with limited access to electricity and other energy services. Integration of variable RE generation into an isolated power supply system is different to integration into a region which already has high shares of RE, or where cross-border transmission options are possible. Many developing country governments place a higher priority on future economic development than on climate change mitigation. The deployment of low-carbon technologies, particularly renewables, could be a win/win solution, but may need political support or external aid funding to gain greater deployment. Small-scale, distributed RE systems may be able to avoid the high capital cost of constructing the infrastructure presently lacking, and hence leapfrog conventional energy systems.

It is anticipated that the current trend to increased urbanisation will continue and that by 2030 cities and towns will house around 60% of the world's population of, by then, 8.2 billion people (UNDP, 2007). There is good potential in many urban environments to capture local RE resources and thereby help meet a growing share of future energy demands (IEA, 2009b). For small towns surrounded by rural areas, this share can be higher than for urban areas contained within mega-cities. Even so, the potential still exists to integrate RE systems into the buildings and infrastructure, as well as to convert municipal and industrial organic wastes to energy. Conversely, existing local planning regulations of some local governments may restrict the potential deployment of such technologies.

As RE systems develop and their market shares increase, competition could result. This is in addition to competition with incumbent fossil fuel-based technologies and other low carbon technologies. Failing to recognise the future competition from other technologies can result in an over-estimation of the potential of any single technology. For example, if an urban-based company encouraged the uptake of solar water heating systems and ground-source heat pumps in the local community by offering good promotion, cheap installation, and future maintenance services, but then the local municipality supported the development of a large biomass-fuelled district heating scheme, the solar and geothermal systems could be made redundant. On a larger scale, should a large nuclear or thermal power plant with carbon dioxide capture and storage (CCS) attached be developed in a region to provide enough power capacity at low carbon emissions to meet future electricity demand for some years (possibly with government support), then this could constrain the development of a proposed nearby wind, solar, geothermal or bioenergy plant for some decades even where good resources exist. Similarly in the transport sector, it is uncertain whether hybrid vehicles using biofuels, hydrogen fuel cells or electric vehicles will become the dominant drive-chain technology in the future, or indeed if all three will compete with each other. Therefore, energy systems need to be flexible enough to cope with the future integration of the range of RE technologies as they evolve.

Hydrogen, as an energy carrier, can be produced in many ways using a range of energy sources including by gasification of coal or biomass, steam reforming of natural gas and other liquid and gaseous fuels, or electrolysis. In Chapter 2, hydrogen production from biomass using a range of processes is discussed. In this chapter, only hydrogen from electrolysis using "green" electricity generated from RE systems is covered, with the hydrogen to be used in either stationary or vehicle applications.

A major objective of this chapter is to determine how problems of integration might affect the future deployment of RE technologies into the conventional energy system. Regardless of the technology, adhering to the national and local planning and consenting processes will involve some costs, but accurately predicting the future acceptance by the general public of a RE plant, (or indeed of a nuclear or CCS plant), in any given location is difficult. Adding to this complexity, some RE technologies are already mature but failing to gain wider acceptance in the market, whereas others, only close-to-market, are enjoying premature integration into the energy supply system due to government support. Relative costs are an important factor, but often other co-benefits exist (such as energy security, employment opportunities, improved health). These can be the driving reason for governments to offer supporting policies (IEA, 2008c). Overall, given these complexities, uncertainties, and a deficit of analysis in the literature, it is not possible to accurately evaluate the future costs of system integration that modellers might wish.

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 (see for example Chapter 11 of IPCC, 2007). Whether reduced energy demand will encourage the greater uptake of RE over and above other energy sources is difficult to determine, but reduced demand could facilitate a greater share for RE of the growing energy market. For example, a building owner should be encouraged to initially invest in energy saving measures 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 (IEA, 2009b). The required capacity, and hence cost, of a RE system will be less if it is designed to meet a lower energy demand.

The transition of the global energy sector away from the present dominance of fossil fuels, needs to include a greater share of RE. This will take time and involve significant investment costs (IEA, 2009a). Other low carbon technologies, particularly nuclear power and CCS linked with coal- or gas-fired power generation, as well as industry applications, will all have a role to play (IPCC, 2007). Many energy models have been produced to project how the various energy supply sources could, together, meet future energy demands (see Chapter 10). It is therefore not the aim of this chapter to attempt to assess the future share of RE as a result of improved integration.

This chapter discusses the integration of RE into centralised, decentralised and off-grid systems to provide desirable energy services (heating, cooling, lighting, communication, entertainment, motor drives, mobility, etc.). Regional differences between the potentials for various systems are highlighted, as are the barriers to deployment depending on the system presently in place. Successful deployment depends upon the local energy resources, current markets, density of population, existing infrastructure, the ability to increase supply capacity, financing options and credit availability. The specific costs of each of the various technologies are covered in Chapters 2 to 7. Since any additional costs relating to integration are complex, site-specific, and not clearly identified in the literature, it was not possible to provide them in this chapter.

8.1.1 Structure of the chapter

Factors such as technology experience cost curves, advances in existing technologies and RD&D developments are discussed in the specific technology chapters (2 to 7). Each of these chapters also examines issues of integration related to their specific technology. However, integration issues relating to RE supplies are more complex. This chapter looks at cross-cutting issues across RE technologies relating to such factors as energy distribution and storage. Non-technology cross-cutting issues are also discussed, including market flexibility, project financing, system reliability, energy balances, energy supply security, system flexibility, transmission of energy carriers, ownership, sense of independence, social acceptance of the technology, the public's awareness and acceptance, and the need for a transition of the energy sector as a major component for mitigation of climate change. External factors such as future carbon and oil prices are covered in Chapter 10.

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 benefits of system design, technology components to facilitate integration, including storage, ownership, operation and maintenance strategies, are discussed. The potential for small-scale distributed energy systems is reviewed on the one hand, along with high voltage, trans-continental, super-grid systems on the other.

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 energy efficiency is included. The current status, possible pathways to enhance increased adoption of renewables, the 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 either OECD or non-OECD countries.

8.2 Integration of renewable energy into supply systems

Conventional energy systems have evolved over many decades to enable cheap and efficient distribution of electricity, gas, heat and transport fuels to end-users. Increasing the deployment of RE systems requires their integration into the existing infrastructure. This section outlines the issues and barriers involved as well as some solutions.

8.2.1 Electric power systems

8.2.1.1 Features and structure of power systems

In order to facilitate a proper understanding of the integration issues and solutions for the electricity sector, the basic features of the structure and operation of power supply systems are first outlined. These concepts, within the context of integration of renewables, are explained in more detail in the literature (see for example, Ackermann, 2005 [TSU: Reference is missing in reference list]; EWEA, 2005; Ummels, 2009).

8.2.1.1.1 Power systems and electricity networks

Renewable energy integration impacts the complete power system, from generation to demand, because some RE resources are exploited on the demand-side (such as roof-mounted PV), and others, on the supply-side for example, in the form of generation based on stochastic, non-storable RE fluxes (e.g. wind or solar energy). The latter are easier to integrate and accommodate using various counter-measures such as end-users with flexible energy services adjusting their demand for energy supply to match the time-varying pattern of the RE flux availability. The characteristics of primary energy resources and their implications must also be carefully considered. Therefore the boundary of an electricity industry must be drawn sufficiently broadly to encompass all relevant primary energy resource and end-use service issues. These will be context-specific. The concept of a power system should therefore consider a range of industry characteristics, including geographical location, state of technological development, social acceptance and innovativeness in its ability to absorb unfamiliar types or levels of RE resources.

Basic characteristics of power systems

Power systems are designed to provide reliable electricity supply while minimizing cost. The stakeholders in the process are system operators, regulators, governments, generators, industry, utilities and users.

Reliable operation requires that demand for electricity is matched in real time by generation (real and reactive) throughout the system. A sustained, substantial imbalance in real or reactive power could eventually lead to catastrophic system failure resulting in blackouts (Novosel et al., 2004) [TSU: Reference is missing in reference list]. The system must also be able to maintain supply-demand balance even with variability and a degree of unpredictability in both demand and generation. For example, the power system must be robust enough to avoid significant contingencies or faults, such as a near-instantaneous, unplanned loss of a large power plant, or the loss of a large transmission line.

Power systems benefit from the aggregation of a large number of different generation resources and types of demand that help to provide reliable operation (Awerbuch, 2006). Systems with access to tens or hundreds of different generation resources can be less expensive than if providing the same level of reliability with only a few power plants. The benefits of aggregation are accessed through a network of transmission/distribution lines and a communication infrastructure that allows for the transfer of power and coordination throughout the network.

8.2.1.1.2 Variable electricity demand

Reliable and least cost operation of the power system is typically ensured through many different mechanisms that can be broadly categorized as planning and operations, depending on the time horizon of interest.

In real-time operations, at time scales from seconds to hours, power systems operate in a way that recovery from significant contingencies can occur virtually automatically without the need for operator intervention. For example, to accommodate rapid changes in power flows that occur after significant faults, system operators can rely on strong transmission connections to neighbouring power systems and margins left between the capacity of transmission lines and the maximum operating point. System operators also rely in part on the inertia of the collective large spinning mass of all on-line and synchronized generation and demand to maintain supply-demand balance even after severe faults.

System operators schedule generation capacity or responsive demand to provide reserves that can be available in a short period to compensate for the possible loss of generation or transmission, inaccurate forecasts or schedules, or to maintain a near-instantaneous supply-demand balance. Flexible resources used to provide these services include partially-loaded thermal plant, transmission interconnections between systems, hydropower units, storage systems, various forms of demand response, and controlling the output of RE plants. Based on short-term forecasts, system operators can provide economic dispatch signals to adjust the output of such resources within minutes subject to their ramp-rate constraints and operating limits. Over longer periods, resources can be started or stopped depending on demand, generation availability, and the minimum start and operating time of individual generators.

System planning enables reliable operation in real time. It encompasses evaluating a system to provide reliable operations in real time over long periods. Power system planners use complex models of the system and its operations to evaluate the adequacy of the transmission infrastructure. They also evaluate the adequacy of the generation resources connected to the system to reliably meet demand, based on the load carrying capability of the power system. Depending on the performance of these resources, planners assign a capacity credit to different resources based on their contribution to the load carrying capability (capacity needs) of the system. The capacity credit of a resource can be broadly defined as the amount of additional demand that can be served due to the addition of the generator, while maintaining the existing levels of reliability (Billinton and Allen, 1996).

Box 8.1: Principles of power balancing in the system

Power system operation covers time scales ranging from seconds to days and, within that timeframe, it is the responsibility of the system operator to ensure that the power balance between generation and consumption is continuously maintained. The essential parameter in controlling the energy balance is the system frequency because it reflects stored kinetic energy. If generation exceeds consumption at a particular moment, both stored kinetic energy and frequency rise; if consumption exceeds generation, both stored kinetic energy and frequency fall.

Small supply-demand imbalances occur all the time. 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. Primary reserve is activated automatically as a result of frequency fluctuations to re-instate the power balance, typically within 30-60 seconds for small disturbances if sufficient primary reserves are available. If not, or in response to very large disturbances necessary, shedding of pre-determined load can also occur automatically within seconds to prevent a system collapse.

Secondary reserve is where active or reactive power is activated manually or automatically in 5 to 15 minutes after the occurrence of a frequency deviation from nominal levels. It backs up the primary reserve and will remain in operation until long-term reserves are brought on line. The secondary reserve consists of spinning reserve (hydro or thermal plants in part-load operation) and standing reserve (rapidly starting gas turbine power plants and load shedding by manual disconnection). Because large supply-demand imbalances are not typically predicted or scheduled in advance, primary and secondary controls should always be available for use.

Consumption of electrical power varies by the minute, hour, day and season. Because the power balance must be continuously maintained, generation is scheduled to match longer term variations. Economic dispatch decisions are made in response to anticipated trends in demand (while primary and secondary controls continue to respond to unexpected imbalances). For example, during the early morning period an increase in load usually occurs from approximately 7:00 am to midday. After the daily peak is reached, the load declines, finally reaching a daily minimum late at night or very early in the morning.

Some generators require several hours to be started and synchronized to the grid. That means that the generation available during the mid-day peak must have been started hours in advance, in anticipation of the peak. In many cases, the shut-down process is also lengthy, and once shut down, thermal generating units may require several hours of cooling and preparation prior to re-synchronizing. Moreover, once started, thermal generating units used for base load should continue to run for one or more days in order to be economic, depending on specific generator characteristics and operational practice. Peaking plants are operated when needed.

In a wholesale electricity market, power producers bid in before any given market interval (ranging from 5 to 60 minutes or even days before dispatching balancing reserve power) and their bid is then accepted or rejected. The system operator manages the balancing task in that market interval. The power system operation of this time scale is called unit commitment, and it can range from several hours to several days, depending on specific generator characteristics and operational practice. This is cost effective, as the deviations of individual producers and loads smooth out when aggregated. Only the net imbalances in the system then need to be balanced to control the frequency. System operators have access to information schedules for production, consumption and inter-connector usage. These schedules are either made by the operators or are provided by the electricity market or other actors involved (producers, balance-responsible players, or programme-responsible parties). Operators can also use on-line data and forecasts of load and RE generation to assist in their operational duty.

8.2.1.1.3 Departure from the traditional model to enable RE integration

A significant departure is necessary in order to efficiently integrate large amounts of RE into conventional power supply systems that are characterized by centralized power plants, limited inter-connection capacity between systems and distribution grids with limited grid management possibilities. Governance of the process is as important as the technical system. The traditional model, (prior to competitive markets introduced in several states and countries) has market arrangements and a market structure that is inhomogeneous and fragmented, with long-term delivery commitments, lack of transparency and limited competition. Conversely, the conceptual design of future power supply systems should include adequate flexibility in generation and demand, a higher degree of inter-connection and long distance transmission, adequate network management, smart distribution grids, as well as an integrated, transparent and fast-operating power market (with support mechanisms needed for near-commercial RE systems; IEA, 2008c).

For grid connection of a large number of decentralized RE generators, new power system architectures could emerge in the future. A promising initiative in this respect is the Danish Cell Controller Pilot Project (Lund, 2007) that investigates how decentralized generation units can be used to support security of supply. If the high-voltage transmission network should fail, then many of the consumers could be supplied from decentralized sources.

A reorientation of power systems for integration of renewables is in line with efforts to deal with other design drivers such as increasing electricity consumption worldwide, replacement of ageing generation and network assets, more economical and efficient power production. Designing power systems that can deal efficiently with variable output renewables will also bring significant benefits to society by more sustainable power production, improved competition from additional generators, and improved sustainability with reduced dependence on fossil fuels.

8.2.1.2 Characteristics of renewable energies

8.2.1.2.1 Differences between renewable power generation and 'conventional' plants.

Although on a system wide level RE plants generate electricity just like any other power plant, many of the generators have distinctive features compared to conventional generation. Understanding these characteristics, and their interaction and impact with the other parts of the power system, is the basis for proper system integration. Bioenergy and geothermal power and CHP plants are more closely allied to conventional thermal power plants as the fuel for combustion and heat can be stored. However, typically, characteristics of other RE systems differ from conventional generation.

- *Variability and predictability.* The power output from RE generation from hydro, wind, solar PV, wave and tidal fluctuates with the variability of the local resource. Fluctuations can be predicted to various levels of accuracy but do not necessarily correlate with the fluctuating power demand.

- *Resource location.* The location of the RE generation is determined by the primary renewable resource location and, particularly at the large scale, cannot be easily relocated to be close to the transmission networks and demand centres.

- *Electrical characteristics.* RE power plant capabilities can be different from conventional thermal and nuclear power plants.

Variability and predictability

A major issue for the integration of RE into a power system is the additional imbalances introduced by variable sources (IEA, 2009). Dealing with variability is an intrinsic quality of power systems (as outlined in 8.2.1.1).

Analyzing RE variability on different time scales is necessary to understand the impact on the power system (EWEA, 2005). RE can be categorized by the variability time-scale of the available natural resource (Fig. 8.2). The variability time-scale for hydro power using dams, biomass, geothermal, ocean salinity and ocean thermal systems ranges from seasonal to decades, whereas, for "variable resources" including small and run-of-river hydro, wind, solar PV, wave and tides, variations occur in shorter time scales from minutes to days, in addition to longer term variations (Holttinen, 2009b). Discussion on variable resources often focuses on wind power because it exhibits variability over a range of time scales. In this respect, it also represents other variable renewables.

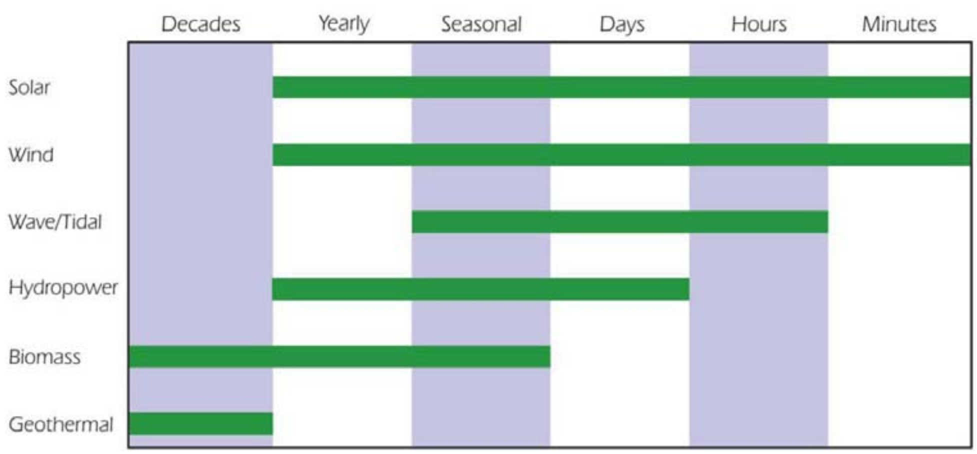


Figure 8.2: Time-scale of the natural cycles of RE sources (IEA, 2008 f).

Geographically dispersed, variable RE systems can be combined to reduce power fluctuations (see for example, case study 8.2.1.6.1). Over large areas, the correlation of output between RE plants is often small due to variations in the RE resource at any given moment (Giebel, 2007). As a consequence the aggregated output of multiple RE generators usually fluctuates less in fractional terms than that of individual plants (Holttinen, 2009b; IEA, 2008f). RE technologies are often referred to as "intermittent", but this term is considered misleading because, when aggregated at the system level, and over different types of RE, the total output does not change instantaneously between zero and full power, but fluctuates at a rate dictated by meteorological and geo-physical effects (IEA, 2008f; EWEA, 2005).

Predictability is the key to dealing with RE variability. The ability to accurately predict a variable RE resource is significant for bulk commercialization, cost reduction and industrial uptake. From the technical perspective, if RE prediction methods are effective, grid integration and accommodation of variable resources in the system becomes more manageable from the technical and economic perspective. For example major improvements in the forecast accuracy of wind power have been accomplished (Lange *et al*., 2009; Kariniotakis *et al*., 2006; Giebel *et al*., 2003; and section 7.5.2.). Aggregated PV generation over a wide geographic area is more predictable using the smoothing effect (see section 3.5.4), and tidal variations are fully predictable being diurnal. Estimation of wave characteristics involves less uncertainty than for wind speeds owing to their slower frequency of variation and direct dependence on wind conditions over the wave fetch.

Resource location

Unlike conventional thermal or nuclear generation where the coal, gas, oil or uranium fuel can be transported to the plant, for most RE systems the power production is strongly dependent on the local availability and power density of the resource, which is not necessarily close to demand or existing networks. This characteristic of RE has consequences for distribution and transmission network infrastructure (see section 8.2.1.3). Small-scale RE systems can often be installed at the location of the demand such as biogas plants and solar PV integrated into buildings. Medium size wind farms and bioenergy CHP plants are often widely dispersed over the network but close to demand centres. Such RE-based distributed generation brings advantages for grids but also poses new challenges mainly requiring better controls, smart meters and intelligent grids (IEA, 2009b). In other cases, the RE resource can be remote such as large scale solar PV and concentrating solar power plants located in deserts, off-shore wind, geothermal, forest biomass and hydro. 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.

Electrical characteristics

Experiences from various projects confirm that RE can make a significant contribution to the support of power system operation. Modern RE electrical conversion systems, especially at high penetration levels, can provide grid services such as voltage and frequency control ancillary services (Cardinal, 2006; Burges, 2003). These capabilities are inherently linked to the specific technologies that can be used where the cost to deliver an ancillary service is an important consideration (Jansen, 2007).

8.2.1.2.2 Energy conversion characteristics

The capacities of conversion technologies to extract energy from RE sources have varying physical dimensions (such as surface area), in order to harness the same amount of energy from selected RE resources (see technology chapters 2 to 7). The primary difference in energy extraction capacity arises from energy density, water being a denser medium than air for example (Fig. 8.3). Some conversion technologies, such as wave energy devices, are capable of extracting the incident energy from an effective surface area many times larger than the actual device.

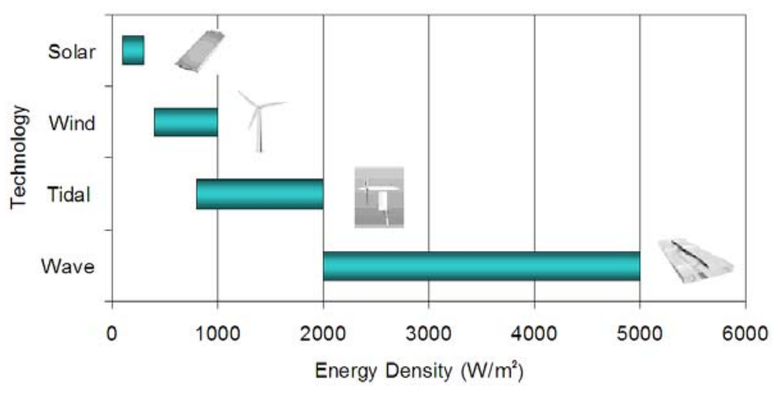


Figure 8.3: Energy density of some variable RE resources (Falnes, 2005).

Conversion technologies for harnessing marine energy conversion technologies for tidal currents are analogous to wind, whereas those for harnessing waves operate on diverse principles and may require cascaded conversion mechanisms (Fig. 8.4).

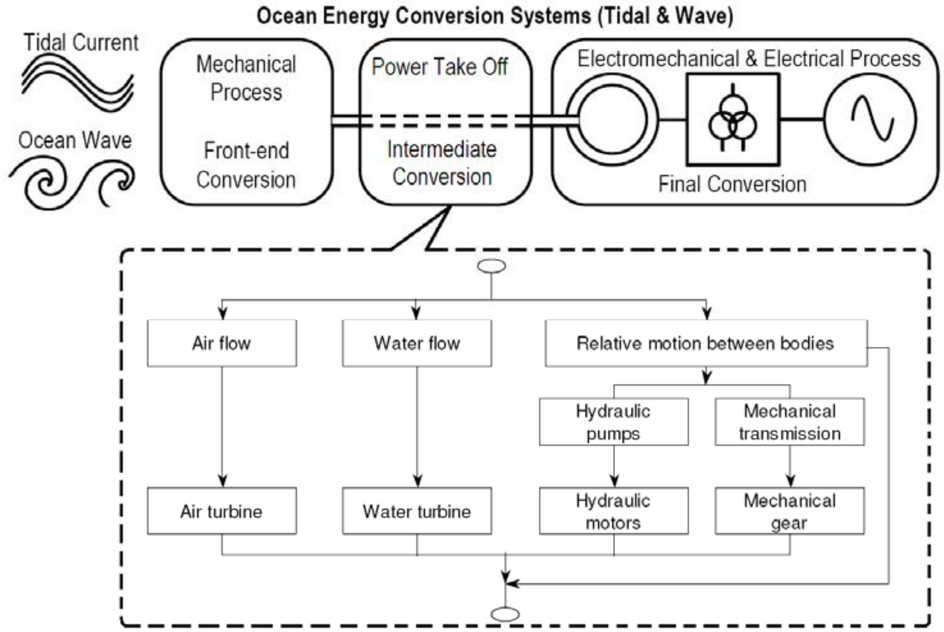


Figure 8.4: Dynamic characterization of wave and tidal current technology conversion systems (Khan et al., 2009).

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 power system need assessing because they determine the evolution and future design of power systems. Impacts are primarily dependent on the penetration level of RE in a given power system that, in the mid-term, may increase to more than 20-30% and in the long-term, up to 100% coverage of total annual electricity demand by renewable electricity. Impacts can be both positive and negative.

Physical impacts on the power supply system regarding control, efficiency, adequacy and planning at the generation, transmission and distribution levels, are due to variability, degree of predictability (affecting, for example, operating system reserves and generation adequacy), power plant characteristics and location of the resource with respect to demand affecting network issues. Furthermore, low marginal costs of RE systems can impact on the economic dispatch merit order of a power system.

Short-term and long-term impacts.

Short-term effects are caused by balancing the system at the operational time scale (minutes to hours), and the interaction of 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.

Local and system-wide impacts.

Locally, RE plants, like any other power station, interact with the grid concerning voltage deviations from the steady-state, power quality, and voltage control at or near the generation sites. Depending on the specific technology, RE plants can provide voltage control and active power control as well as reduce transmission and distribution losses when applied as embedded generation in a demand area. At the system-wide scale, other effects to consider include those impacting on voltage levels and power flows in the network and system stability. These effects can be beneficial to the system, especially when the plants are located near load centres and at low penetration levels. On the other hand, high penetration levels of RE may necessitate additional upgrades in transmission and distribution grid infrastructure, as may be the case when any new power plant is connected to a grid. In order to connect remote high-resource site plants to the load centres, new transmission lines may have to be constructed, (just as it is necessary to build pipelines for new oil and gas reserves or new lines for new conventional power plants).

In order to maximize the smoothing effects of geographically distributed RE, and to increase the level of firm power (also termed "capacity credit" or "capacity value"), the opportunity for cross-border power flows could reduce the challenge of managing a system with high levels of RE.

RE can play a role in maintaining system stability. Different types of RE generators have different stability impacts and possibilities to support the system in normal and system fault situations (time scale seconds to minutes). More specifically this is related to voltage and power control and to fault-ride through capability. RE also contributes to the system adequacy and security of supply (Table 8.1).

Table 8.1: Power system impacts of RE systems with the impacts of wind power generalised to all RE systems (EWEA, 2005).

	Effect or impacted element	**Area**	**Time-scale**	**RE potential contribution**
Short term effects	Voltage management	Local	Seconds to minutes	RE plants can provide (dynamic) voltage support (design dependent).
	Unit commitment and production efficiency of thermal and hydro	System	1-24 hours	Impact depends on how the system is operated and on the use of short-term forecast.
	Transmission and distribution efficiency	System or local	1-24 hours	Depending on penetration level, RE plants may create additional investment costs or benefits. RE can reduce network losses, except for example, off-shore wind and concentrating solar power (CSP).
	Regulating reserves	System	Several minutes to hours	Appropriately designed RE plants can contribute to primary and secondary control.
	Stability	System	Seconds / minutes	Depending on power plant capabilities, RE may support system during fault situations.
Long term effects	System reliability (generation and transmission adequacy)	System	Years	RE capacity can contribute (capacity credit) to power system adequacy depending on the possibility to aggregate over large areas and across types of generation.

RE generation requires measures for regulating (balancing) control just as any other technology. It should not be treated in isolation in the system as it depends on penetration level and local network characteristics and can impact on the efficiency of other generators in the system (and vice versa). In the absence of sufficient intelligent and well-managed power exchange between regions or countries, a combination of (non-manageable) system demands and generation may result in situations where specific variable RE plants have to be curtailed.

Impacts of wind power in different time and geographical scales are relevant for integration studies (Fig. 8.5) (Holttinen, 2009b) and can be classified from local to system-wide and from seconds to year. Relevant for integration is whether the power system can deal with these impacts and to identify the specific challenges that should be addressed.

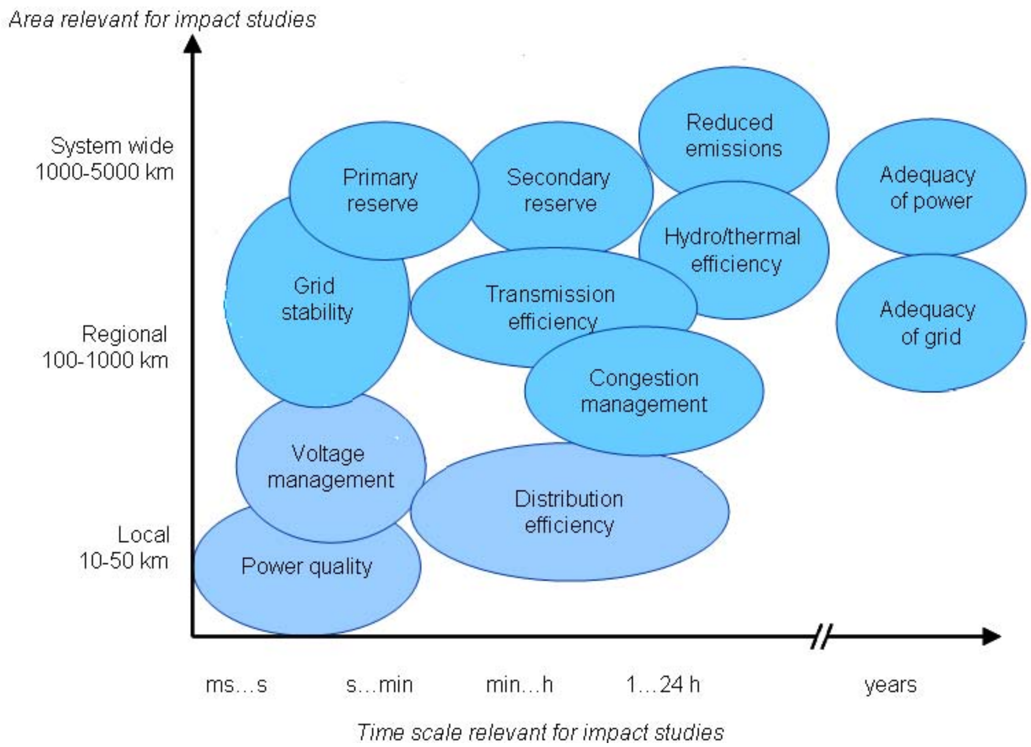


Figure 8.5: Impacts of wind power on power systems by time scale and area (Holttinen, 2009a).

8.2.1.3.2 Issues and challenges

The challenges brought by variable, distributed RE systems, highlight the need to address specific aspects of the power system. Integration issues for high penetration levels have been analysed extensively, primarily for wind power because of the rapid pace of implementation. The experience with wind energy has more general relevance because it represents a "worst design case" for power systems in view of its high variability and relatively high penetration levels.

From experience to date with wind energy (Milligan, 2009; Holttinen, 2009; EWEA, 2005), the main challenges for power systems are:

a. system operation, balancing and the need for additional system reserves;

b. network reinforcement, extension and inter-connection;

c. appropriate connection rules and codes for RE;

d. system adequacy with high penetration of renewables due to the low capacity credit of several variable RE technologies; and

e. electricity market design and corresponding market rules.

These challenges have technical, institutional and regulatory and market design aspects.

a. System operation and balancing

- *Increased reserve requirements.* In the absence of a perfect forecast, system balancing requirements and costs are increased by random fluctuations and by forecast errors, both of variable RE and of load demand, since these are generally not correlated. Power balancing requirements in large-scale power systems mainly address reserve power in secondary control time scales that is offered on the balancing market. For wind, these costs have been extensively analysed (Holttinen, 2009b) and there is a modest increased need for additional reserve with growing wind penetration. For an isolated system or one with limited inter-connection, (at various penetration levels up to 10-15% in some areas or higher elsewhere), unpredicted imbalances can be countered with existing reserves (DENA, 2005). Several national and regional specific system studies indicate additional balancing costs in a narrow range (e.g. EUR 0 - 3/MWh for wind) for levels of wind power penetration up to 10% (on an energy basis) despite large differences between systems.

- *Need for forecasting.* Accurate RE power output forecasting is critical to economic operation of RE plants in the system, as confirmed by experience in countries with significant penetration (Denmark, Spain, Germany, Ireland). In the absence of accurate forecasting, uncertainty leads to increasing balancing costs (Lange, 2009).

- *Excess RE production.* Where RE output exceeds the amount that can be safely absorbed while still maintaining adequate reserves and dynamic control in the system, a part of RE generation may have to be curtailed (for example in low demand, high wind situations). However, it may prove more economic to increase demand under ‘demand side management’, for example by additional pumping at pumped storage facilities, use of heat pumps and/or water supply reservoirs. Increased inter-connection and improved power exchange rules between neighbouring countries can avoid wasting RE output in such situations (Beharrysingh, 2009; Ummels, 2009).

- *Ancillary services.* Apart from balancing requirements, the power system requires ancillary services. These range from operating reserve and reactive power through short-circuit current contribution and black start capability. All RE plants can provide part of these services (Burges, 2003; Jansen, 2007; Syczynski, 2009) noting that if reserve is provided with variable RE, this is at the cost of lost production, so it will not be the first or most frequent option to deploy. In addition, appropriate equipment should be maintained in the system to provide the ancillary services that cannot be delivered by RE power plants.

- *System operation at transmission and distribution levels.* RE generation has implications for the operation and management of the network.

    - *Management of congestion and unpredicted flows.* Specific combinations of RE production and demand, in terms of level and geographical location, cause changes in the magnitude and direction of power flows in the transmission grid. The effects of these can be mitigated by accurate forecasting of the renewable generation, combined with monitoring technologies to reduce the impacts using the on-line SCADA (supervisory control and data acquisition) information for the RE plant and WAMS (wide-area measurement systems). Operational issues include congestion management (also termed “connect and manage”), priority access of RE plants and priorities in curtailment in critical situations (for example the combination of low demand and high

RE production). As a positive impact, RE may keep parts of the system operational in the event of transmission failures which otherwise would cause black outs.

- *Management of distribution grids.* Connection of RE generation to distribution grids introduces similar effects as in transmission grids including changing direction and quantity of real (active) and reactive power flows, which may affect operation of grid control and protection equipment. There is less active management of distribution grids than at the transmission level. Nevertheless, distribution grids have to cope with varying distributed generation levels without reducing the quality of supply. Weak distribution grids may be supported by RE and end-users may be better served because RE can contribute to grid voltage and power quality control. Power generated within a local distribution network can go directly to local users, thereby avoiding transmission costs and line losses.

b. Network infrastructure

Upgrading transmission infrastructure to handle large penetration of variable RE is a complex process subject to strategic long term planning which has to proceed through various stages, following the gradually increasing penetration of RE. Transmission systems in several parts of the world have been developed in a compartmental way by being confined within countries or to limited network areas. National transmission system operators (TSO) and regulators deal with grid issues, balancing, and power exchange in a way that is determined by national legislation and the grid topology, geographical situation and historical developments.

Relatively low penetration (< 10%) of variable RE in existing networks could add to existing transmission congestion. The extent to which transmission upgrades are required depends on the effectiveness of congestion management and optimization of the transmission system.

At higher penetration levels, or in order to access new remote resources, new lines have to be added. Planning methods should avoid the classic ‘chicken and egg’ problem by jointly considering RE power projects and the associated transmission network requirements. At very high penetration levels of variable RE, large-scale storage systems may become economically attractive.

Transmission network upgrades are needed for large-scale integration of wind power in many countries (Holttinen, 2009; Lew, 2009; Corbus, 2009; EWIS, 2009). Different studies use various methods of cost allocation, distances, and grid reinforcements assumptions, but, in general, estimated costs in the literature are in the range of USD 100-200 /kW for wind penetration levels up to 50% (though costs vary widely with specific conditions).

Transmission planning

Over planning horizons sufficient to add new infrastructure, planners evaluate the power system using a variety of tools to ensure adequate transmission and generation resources to reliably balance generation and demand. Though these same planning methods can be used to evaluate the adequacy of the system with the addition of significant amounts of RE, planners must also appropriately account for its variable characteristics.

Evaluating the adequacy of transmission capacity with significant additions of wind, for example, needs to account for the locational dependence of wind resources, the relative smoothing benefits of aggregating wind over a large area, and the transmission capacity required to access flexible resources to manage wind’s variability. The locational dependence of wind energy means that, in many regions of the world, new transmission infrastructure will be required to move power from the best wind resource areas to demand centres. The most efficient and economic way of transporting bulk electrical energy over such distanced is via large, high-voltage overhead transmission systems.

In some cases transmission planning practices for conventional generation are not as appropriate when applied to RE. For instance, transmission planning rules that encourage generation to be sited where existing transmission capacity is available ignores the strong dependence of RE resources on location. Additionally, transmission lines are often much less expensive per unit of capacity the larger the line is, and RE plants are often located in regions that can support much more capacity than the size of an individual plant. Increasing transmission capacity and coordination between different parts of an inter-connected system also reduces the total variability in the demand that must be managed by power system operators (Milligan and Kirby, 2008). Finally, transmission lines can take a decade to plan, permit, and construct whereas individual wind plants can be built in a period of a few years. As a result of these factors, transmission capacity expansion is most economic if planned for quantities of RE much larger than the size of individual generation plants, and there is a strong rationale for building transmission proactively in anticipation of growth in RE rather than planning transmission in reaction to individual RE plants (Mills et al., 2009). At the same time, public opposition to transmission lines is expected to be a major factor in the integration of large amounts of wind energy (Vajjhala and Fishbeck, 2007; Vaccaro, 2008).

Various solutions to proactive transmission expansion are being investigated, but solutions will vary depending on geography, the design of the pre-existing power system, and the regulatory environment. In the U.S. efforts focused on proactive transmission planning and Europe is similarly considering ways to proactively plan transmission to integrate RE particularly through improvement of transfer capabilities between transmission system operators (EWEA, 2005; EASAC, 2009). One recent development in Europe is the founding of an organization to coordinate network planning across Europe called the European Network of Transmission System Operators for Energy (ENTSO-E). It should be noted, though, that more research is required to identify the extent to which such new transmission infrastructure would be cost effective.

c. Connection rules for inter-connection of RE generators

TSOs impose grid connection requirements, such as inter-connection regulations and grid codes, on RE plants just like on any other generator. This is to keep good order in the system and to prevent negative impacts on the network. For example, in countries facing significant wind power development, the specific rules for wind power are continually being refined to allow a larger penetration and at the same time maintain an adequate power supply. Grid codes are country and system-specific, resulting in a wide disparity of requirements that equipment manufacturers, developers and RE plant operators face across the globe. Internationally harmonized connection requirements for RE plants would avoid unnecessary costs for manufacturers and operators (EWEA, 2008).

d. System adequacy

Variable RE generation can only replace a minor part of the capacity of conventional plants, which as a consequence have to be retained in the system and gradually replaced with more efficient and flexible resources where necessary. The load carrying capability of variable RE generation can be high at low penetrations but decreases at higher penetration levels. Energy storage can contribute when aiming to realize 100% RE penetration in the long term.

In situations with low wind penetration and high capacity factor at times of peak load, the capacity credit of wind power can be as high as 40%. In high wind penetration, low capacity factor at times of peak load, or when regional wind power output profiles correlate negatively with system load profile, the capacity credit can be as low as 5% (Holttinen, 2009; Boyle, 2007). Aggregation of RE output over larger areas, for example by providing more inter-connection between control zones, is beneficial for aggregated capacity credit (Van Hulle, 2009). Planning the optimum generation mix with high shares of RE requires further research in order to develop probabilistic system adequacy forecast methods.

e. Electricity market design

Technical solutions will not work unless matched by market design enhancements including market aggregation and faster operation. Many electricity markets across the world still have structural deficiencies and inefficiencies in their balancing and settlement procedures. For example, long gate closure times (invented when there was only dispatchable generation) and few balancing means available in smaller markets discriminate against variable-output RE. In addition market characteristics can cause unnecessarily high costs of integration. Therefore, a re-design of corresponding market structures and procedures is considered to be a pre-condition for integrating significant amounts of RE into national and international networks. Changing the rules is a matter of principle rather than physics, and does involve little cost, whereas the benefits would be significant.

8.2.1.4 Options to facilitate the integration of RE into power systems

This section discusses how to manage challenges described in 8.2.1.3 by for example making power system more flexible and better interconnected. The basic technical options to facilitate the integration of RE are more and better networks, changes in the power system with respect to balancing (including generation flexibility, demand side control and storage), and addressing system stability in an innovative way. Non-technical issues also need to be addressed.

Variable RE generation induces power flow fluctuation which needs voltage regulation or power flow control in a transmission/distribution system as well as demand-supply balance in the total power system. The technology options to facilitate RE integration into the power system are categorized as outlined below.

8.2.1.4.1 Technical options

Voltage regulation technology

Traditionally, the terminal voltage control of a generator, tap change control of a power transformer, and switching of shunt power capacitors and shunt power reactors are the major reactive power control measures in a power system. Although their importance will probably be maintained in future, further control measures are possible. Reactive power control technologies are divided into two categories:

- a series device inserted between the nodes of the power system, and
- devices which inject or absorb reactive power at a node such as a static var (volt/ampere reactive) compensator (SVC) and a static synchronous compensator (STATCOM) (Xu et al., 2006).

All voltage regulation technologies are commercialized but their performance can be enhanced with the progress of R&D investment in power electronic devices. Energy storage technologies which are nearby or at the same location as RE generation can compensate for power flow fluctuations and eventually, voltage regulation. Currently, electric energy storage technologies are more expensive than reactive power control technologies so are not selected just to stabilize voltage.

Power flow regulation technology

Large power flow fluctuations on a transmission system can lead to overloading of series components and result in a single outage or cascading outages of a transformer or transmission line. Series control devices such as thyristor-controlled series compensators (TCSC), static, synchronous series compensators (SSSC), and thyristor-controlled, phase-angle regulators (TCPAR) can control the power flow through the modification of voltage phase differences between the nodes to alleviate line overloads. Combined series–shunt controllers, such as unified power flow controllers (UPFC), can control voltage and power flow (Ye and Kazerani, 2006).

Power flow regulation technologies are close to commercialization. The overload of series components can be alleviated through an appropriate combination of power system operation, total power system expansion, and power flow control technologies.

Electrical energy storage technology

There is a difference between dedicated energy storage and system level storage. The latter is usually not an economically attractive option in inter-connected systems until high RE penetration exists (Ummels, 2009; O'Malley, 2008; Holttinen, 2009a). The requirement of energy storage should be decided based on the difficulty of aggregated power supply-demand balance and economy. In essence, in isolated power systems with high RE penetration there is a need for storage whereas in inter-connected systems, storage is not economically viable until RE penetration reaches high levels. There are many varieties of electric energy storage (EES) technologies (Table 8.2).

Table 8.2: Technical characteristics of electric energy storage systems (Chen et al., 2009).

	Power Rating	Discharge time	Self discharge	Cost			Energy Density		Power Density		Life	Cycle life
				Cjarge-Discharge Capacity	Storage Capacity	Cyclic Storage	per Weight	per Volume	per Weight	per Volume		
	(kW)		(%/day)	($/kW)	($/kWh)	(cents/kWhcycle)	(Wh/kg)	(Wh/litter)	(kW/kg)	(kW/litter)	(Years)	(cycles)
Pumped Hydro Storage	100000-5000000	1-24h+	Very small	600-2000	5-100	0.1-14	0.5-1.5	0.5-1.5	-	-	40-60	
Compressed Air Energy Storage	5000-300000	1-24h+	Small	400-800	2-50	2-4	30-60	3-6	-	0.5-2.0	20-40	
Lead-Acid Battery	0-20000	Sec-hours	0.1-0.3	300-600	200-400	20-100	30-50	50-80	75-300	10-400	5-15	500-1000
Nikel Cadmium (NiCd) Battery	0-40000	Sec-hours	0.2-0.6	500-1500	800-1500	20-100	50-75	60-150	150-300		10-20	2000-2500
Sodium Sulphur (NaS) Battery	50-8000	Sec-hours	about20	1000-3000	300-500	8-20	150-240	150-250	150-230		10-15	2500
Sodium Nickel Chloride (ZEBRA) Battery	0-300	Sec-hours	about15	150-300	100-200	5-10	100-120	150-180	150-200	220-300	10-14	2500+
Li-Ion Battery	0-100	Mins-hours	0.1-0.3	1200-4000	600-2500	15-100	75-200	200-500	150-315		5-15	1000-10000+
Metal-Air Battery	0-50000	Secs-24hours	Very small	100-250	10-60	-	150-3000	500-10000				100-300
Vanadium Redox Flow Battery	0-10	Secs-10h	Small	600-1500	150-1000	5-80	10-30	16-33			5-10	12000+
Zink Bromine (ZnBr) Flow Battery	50-2000	Secs-10h	Small	700-2500	150-1000	5-80	30-50	30-60			5-10	2000+
Polysulphide Bromide Flow Battery	1000-15000	Secs-10h	Small	700-2500	150-1000	5-80	-	-	-	-	10-15	
Sperconducting Magmetic Energy Storage	100-10000	msecs-8min	10-15	200-300	1000-10000	-	0.5-5	0.2-2.5	500-2000	1000-4000	20+	100000+
Flywheel	I 0-250	msecs-15min	100	250-350	1000-5000	3-25	10-30	20-80	400-1500	1000-2000	-15	20000+
Capacitor	0-50	msecs-60min	40	200-400	500-1000	-	0.05-5	2-10	-100000	100000+	-5	50000+
Supercapacitor	0-300	msecs-60min	20-40	100-300	300-2000	2-20	2.5-15		500-5000	100000+	20+	100000+

The required EES power ratings range from 10% to 100% of the RE generating capacity. The required energy storage times range from 10 seconds for wind fluctuations to several hours for weather change; 10 hours for daily cycles and 1-3 months for seasonal changes. The shorter storage requirements are for uninterruptible power supply (UPS), power quality and reliability needs, and the longer ones are for energy management or load levelling/shaving.

Pumped hydroelectric storage (PHS), is deployed widely around the world. It is a centralized, site-specific technology that will continue to be deployed when appropriate. Compressed air energy storage (CAES) is another site-specific technology and two plants have been deployed in Germany and the USA.

Other technologies are still under development, with the exception of the lead-acid battery which is widely used as a UPS resource. Electrical energy storage for RE integration has to have good economy but with low environmental/ecological impacts in order to gain broad deployment. This will need large efforts in technology R&D.

Vehicle-to-grid (V2G) is a concept whereby battery-powered electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) can be used as EES to give GWs of capacity. However, their more widespread deployment will only be possible when EVs and PHEVs have batteries with enough durability, economy, and capacity for power control use.

To store electricity, it must first be converted into another form of energy and transformed back when needed. Possible techniques for energy storage include mechanical, chemical, and thermal forms. Many technologies exist, but comparison is difficult because of their different stages of development.

Through the transformation of low-cost primary energy sources used in regular power plants, the intermediate energy obtained from electricity can be stored and used at an appropriate time as a substitute for the expensive primary power used in peak-load power stations, or for the "virtual energy" as a result of a breakdown in supply. There are two modes of energy production for which storage is clearly important:

- conventional energy production where storage could compensate for a temporary loss of production of a generating unit and fulfil a commercial obligation of pre-sold energy supply, and thus avoid penalties; and
- RE production (CSP and PV) where the storage adds value to the supplied current by making this type of energy predictable (e.g., the delivery of electrical power during peak hours). However, the cost of buffer storage should be considered. The stored power could only satisfy a portion of the nominal production capacity, while the energy should be made available as a result of a contractual compromise.

Network imbalance can be caused by temporary production deficits, which could possibly be predicted. Imbalance could also be the result of production failures. Storage and retrieval systems can help provide instant response to demand and, as a consequence, add flexibility to the network in terms of load levelling. Load-levelling also helps to reduce fluctuations to a minimum, making the supply more predictable. Effective load-levelling would make it possible to use the existing transmission and distribution facilities for many years to come.

Demand control technology

The mitigation, modification, or time shifting of demand can improve the power demand-supply balance by responding to variations in RE generation, often referred to as demand response (DR). The demand of residential and commercial sectors may be more responsive than that of industry because industrial demand is heavily linked to its production schedules. In the near future, the power demand of heat pump water heaters and the charging of EVs and PHEVs, could also be responsive, as could that of refrigerators, washing machines, and air conditioners. In order for this to happen, advanced metering infrastructure (AMI), energy management technology, and control interface technology for appliances used in households, commercial buildings and factories, together with information technology (IT) for communication, are all essential. These technologies will realize direct/indirect control of the appliances using a control signal or an incentive signal such as a dynamic pricing of electricity. Once customers set demand response into their energy management controller, the direct/in-direct controls become automatic in accordance with the signal from the power system (NETL, 2008). Distributed generation technologies, such as CHP and PV, can be included in the DR category as an active supply source (Chicco and Mancarella, 2009).

Sub-marine and long-distance transmission

Excluding DC power distribution systems which are in the early stages of evolution, the power system are usually configured as alternate current (AC) systems, with 50 Hz or 60 Hz frequency. Using efficient and economic power transformers and other AC technologies, the power generated at power stations is transmitted and distributed to near-by and remote loads reliably, economically and flexibly. AC transmission and distribution systems are composed of a set of classes of different rated voltages, for example, from 765kV to 120V in North America. For longer distances, transmission as high-rated AC voltage with high performance and capital costs can be adopted, as well as high voltage, direct current cables. AC power transmission is neither economic nor applicable in the following cases:

- large capacity and long distance transmission -for example, 5 GW over >1000 km;
- long distance submarine cable transmission of, for example, >50 km;
- difficulty of power flow control in mesh-structured systems; and
- non-synchronizing inter-connection between incompatible AC power systems such as with different frequencies.

Direct current (DC) transmission technology can be adopted to overcome the above limitations. It uses an AC to DC converter and a DC to AC inverter based on power electronic devices.

Although many traditional HVDC systems are based on current source converters utilizing thyristor devices, the development of a new power electronic device, insulated-gate, bipolar transister (IGBT) has enabled a new HVDC system “HVDC Light” to be developed using a voltage-sourced converter (Jones et al., 2007). The converter, being able to independently control active and reactive power in addition to the essential power transmission, offers effective active and reactive power control of an AC power system (Ruan et al., 2007). It is an attractive future technology for both off-shore and on-shore grids but some technical issues still need to be resolved before multi-terminal HVDC variable speed control can be commercially implemented.

Using HVAC and HVDC technologies, several proposals could realize “super grids” to give large-scale, RE integration into a power system including:

- a conceptual transmission plan to accommodate 400 GW of wind energy (US DOE, 2008a); and
- the trans-Mediterranean grid inter-connecting the best sites for RE use in EU, Middle East and North Africa (DLR, 2005).

Variable RE generation analysis and forecast technologies

Knowledge about the characteristics of variable RE generation is needed for long-term capacity planning and everyday operation as RE penetrates more into the power system. Aggregating RE from larger areas improves its predictability since forecast error decreases with the size of the area. Hence there is need for larger balancing areas, which can be realised by market organisation and inter-connection. Experience with wind generation in regions with high RE penetration implies that the forecasting technology should enable a substantial reduction in balancing costs and improve system security when using a high level of variable RE.

Accurate short-term forecasting is industrial practice today and commonly implemented in control rooms of plant and system operators (see Chapter 7). Day-ahead forecasts now have an error of only around 6% in Germany. There is still room for improvement with wind speed forecasts remaining the most researched and tested.

Various forecasting techniques have been proposed for predicting 1 hour to 1 day-ahead forecasts for a single turbine, a wind farm, or a region with many wind farms (Ramirez-Rosado et al., 2009; Kavasseri et al., 2009). Solar radiation forecasts for PV and solar thermal generation have also been researched (Reikard et al., 2009; Cao and Lin, 2008).

For demand-supply balance of a total power system, the analysis of generation characteristics of aggregated RE becomes more important than those of individual generation. The aggregated generation will have less variation, thus requiring fewer counter-measures, and will reduce the integration cost of investment and operation subject to network flow constraints.

Operating power systems with variable RE does not need to be drastically different than operating power systems without, especially in the near term with moderate levels of RE penetration. Specifically, variability can be managed through scheduling and dispatching conventional resources to maintain a balance between expected generation and demand, whereas uncertainty can be managed through an increase in reserves to accommodate imperfect forecasts. Several modifications to conventional system operations, however, will increase access to flexible resources and reduce the additional uncertainty from variable RE. These modifications include the inclusion of a centralized forecast in the scheduling and dispatch of generation and decreasing the time between generation scheduling intervals.

Reserves are generation or demand capacity that are scheduled to be available to restore the supply-demand balance in the event of an unforecasted demand or generation deviation. Because some variable RE sources are predictable over short periods of time (minutes), the need for providing additional reserve from the fast reserve categories is small. On longer time scales (in the order of hours or more), wind forecast errors grow substantially. Forecast errors over longer periods consequentially increase the need for additional slower reserves (Doherty and O'Malley, 2005). The need for both fast and slow reserves increases with wind penetration levels.

Contingency reserve, a particular category of fast-acting reserves, cater for very sudden changes, typically the loss of a the largest in-feed contingency (generating unit or interconnection to other systems). Unless a RE plant connecting through a single line is the largest in-feed (such as a large off-shore wind farm), RE is not expected to add substantially to contingency reserve requirements. Some severe weather conditions, however, may require scheduling increased reserves. An extreme weather pattern hitting a large concentration of wind plants, for example, will increase the risk that multiple wind turbines will shut down due to high wind speeds.

System operators can manage this risk by incorporating severe weather forecast alerts in system operations and increasing reserves accordingly. Similar actions are often taken by system operators in response to forecasted lighting storms, which increase the risk of transmission line outages (NERC, 2009). Incorporating wind forecasts into the scheduling and dispatch of the system provides more opportunities to accommodate changes in wind generation over all time-frames of interest to power system operators, and therefore can reduce the reliance on reserves. Inclusion of state-of-the-art wind forecasts, for example, has been found to reduce scheduling costs (Smith et al., 2007a). Similarly, operational decisions based on knowledge that forecasts are not perfect, through stochastic unit-commitment, allow for more conservative and lower-cost scheduling decisions (Tuohy et al. 2009).

Centralized/decentralized energy management

Traditionally, a transmission system operator monitors the major status of a power system including frequency, voltage and power flow at central/regional operation centres, as well as controlling on-line/off-line system control devices on the supply side. In order to manage more frequent and wider variations of RE generation outputs, central energy management is required to realize more robust and sophisticated power system control. The deployment of phasor measurement units (PMU) and wide-area measurement systems (WAMS) are emerging technologies to strengthen the monitoring of power systems (Wang et al., 2007). They improve system performance including recovery from various system disturbances (Zhang et al., 2008).

In order to keep the supply-demand balance of the power system with higher penetration levels of variable RE generation, it is necessary to deploy more effective measures. Decentralized energy management can realize optimum demand-side controls for a residential building, commercial building, group of buildings, or an industrial area, can be harmonized with power system operation by information exchange. This scheme is often called a "smart grid" (Litos, 2008). The EU has been investigating smart grid technologies in the European Technology Platform initiative since 2005 (Bouffard and Kirschen, 2008). In the US, smart grids have been incorporated in energy policy by the Energy Independence and Security Act (EISA) 2007, which promotes their development through a matching programme to states, utilities and consumers. The EISA assigns the National Institute of Standards and Technology as a coordinating body for the development and modification of a number of standards that relate to the smart grid.

A virtual power plant (VPP) is a combination of the above-mentioned monitoring and control technologies to give a business model akin to a power utility. Distributed locations of substantial amounts of generation capacity can be virtually regarded as a single generation plant. When they meet a load or a group of loads, their power production and consumption are monitored and the demand-supply balance is managed through an appropriate energy management control (van Dam, 2008).

For rural electrification involving RE generation, it is important to take a long-range view using a comprehensive planning methodology involving the use of geographical information systems (GIS) (Amador and Dominguez, 2006). This includes decisions as to whether a particular district will become integrated into a large power system or remain an off-grid, autonomous system, based on the total life cycle costs of the alternatives (Kaijuka, 2007).

8.2.1.4.2 Institutional aspects facilitating integration

Integrated long-term energy planning is a key to enabling future energy supplies and identifying strategic generation, transmission & distribution infrastructure needs. The first step for an integrated energy planning process is to identify and quantify RE resources and socio-economic benefits from their uptake. Identification of the near- and long-term practical potential of these resources could then be integrated with existing and future electricity infrastructure plans and identifying barriers. Lack of an integrated planning process could cause a significant barrier for the uptake of renewable electricity. A project by project approach would not address cumulative effects nor provide a signal to stakeholders for the best development option. In a competitive electricity industry, these tasks may be delegated to a market that is supported by advisory functions because future costs and benefits may be matters of opinion rather than objective facts.

A systematic approach that accommodates generic electrical system issues in an integrated manner could provide guidance on how best to facilitate uptake of mature and emerging RE resources. Through scenario analysis, coupled with steady state and dynamic network investigations, the challenges and opportunities associated with large-scale integration of renewable electricity could be identified. Current and future power generation characteristics, local distribution & transmission control areas, cross-border networks, load growth, and future network expansion plans should be considered. Outputs from such integrated analysis could provide framework for developing an optimized planning process and appropriate policy instruments to enable cost reductions and market deployment.

An approach to deploy a high penetration of various types of variable RE technologies across a large geographical region has been developed (NERC, 2009).

- Deploy advanced control technology designed to address ramping, supply surplus 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 generation output.
- Adopt more comprehensive planning approaches, from the distribution system through to the bulk power system.
- Explore further possibilities for interconnection to extend the geographical scope of power systems that have high penetrations of variable RE generation.

In Australia, despite the progress that has been made in preparing for RE integration (AEMC, 2009; Outhred and Thorncraft, 2010), the Australian Energy Market Operator (AEMO, 2009) suggests that more needs to be done, often involving institutional aspects, with respect to:

- convergence of electricity and gas markets, particularly gas market evolution;
- efficient utilisation and provision of electricity networks, particularly generator locational incentives and congestion management;
- connecting remote generation, particularly boundary, interaction and coordination issues between dedicated and shared network assets;
- inter-regional TUOS in the context of the National Electricity Market;
- retail market price caps, prudential frameworks and retailer failure risks;
- generation capacity in the short-term, where a single, well structured and coherent set of arrangements is needed;
- system operation with intermittent generation, where AEMO is re-starting its network support and control services review.

European electricity transmission system operators (TSOs) have been engaged in a wind integration study with funding support from the European Commission. Their July 2008 Interim Report (ETSO, 2008) notes that they are already active in addressing issues associated with efficiently accommodating wind into the transmission networks by:

- establishing direct connections to large wind farms both onshore and offshore;
- planning the connections and interfaces with increasingly active distribution networks connecting wind generation;
- reinforcing network pinch-points within and between national networks;
- participating in market developments, such as establishing intraday markets, market coupling, and forming regional markets;

- developing balancing arrangements through enhanced control arrangements and commercial mechanism; and
- developing appropriate grid codes to facilitate large scale wind entry.

The above experiences all point to the need to address institutional aspects of RE integration consistently across the full physical scope of a power system prior to reaching high levels of RE penetration in that power system (AEMC, 2009). Addressing institutional aspects may require close cooperation between multiple jurisdictions. For example, a recent study on optimal wind power deployment in Europe (Roques et al, 2009) highlighted the need for more cross-border inter-connection capacity, greater coordination of European RE support policies, and for support mechanisms and electricity market designs to provide local incentives. Similarly, Van Hulle et al., (2009) that integration of wind power in Europe had been slowed by planning and administrative barriers, lack of public acceptance, insufficient economic incentives for network operators and investors to undertake transmission projects of European interest, and a generally fragmented approach by the main stakeholders.

8.2.1.5 Benefits & costs of large-scale penetration of renewables

In broad terms, the benefits of RE generation arise from:

- the displacement of fossil fuels, with ensuing reductions in fuel costs and external fossil-fuel impacts such as climate change emissions and acid rain;
- reduced reliance on imported primary energy resources with 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.

The operating and investment costs associated with RE generation integration arise from:

- network augmentation and/or extension to accommodate the possibly fluctuating electricity flows associated with RE generation; 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 fluctuating energy flows associated with non-storable RE forms.

RE generation with intrinsic storage, such as biomass or pumped-storage hydro, behave in a similar manner to fossil fuel thermal generation and thus raise no additional technology-specific costs when integrated into power systems. However, the situation is different for variable RE generation without intrinsic storage. Wind energy is the first non-storable RE technology to reach high levels of penetration and most cost-benefit investigations have focussed on the additional technology-specific costs that arise when wind energy is integrated.

For low levels of penetration, the costs and benefits associated with wind energy depend on the pre-existing electric power system (generation, network and load characteristics) and can be estimated by simulation studies that extrapolate from the pre-existing state. Holttinen et al. (2009a) presented and analysed the results from ten studies of this kind in Europe and the USA undertaken under the auspices of IEA Wind Task 25 (www.ieawind.org.AnnexXXV.html[TSU: URLs are to be cited only in footnotes or reference list.]). These studies addressed three key power system issues:

- balancing (managing short-term wind energy fluctuations from seconds to hours by maintaining sufficient generation reserves);
- power adequacy (reliability of supply, often assessed by calculating “capacity credit”); and

- grid (congestion management, system security and grid reinforcement).

Estimates depend on the forecast lead-time. In practice, reserve requirements are highest when wind energy generation is high and thus other, displaced generators should be available to provide reserves, subject to their operating flexibility constraints. Balancing costs due to wind energy are expected to vary with wind penetration (Fig. 8.6).

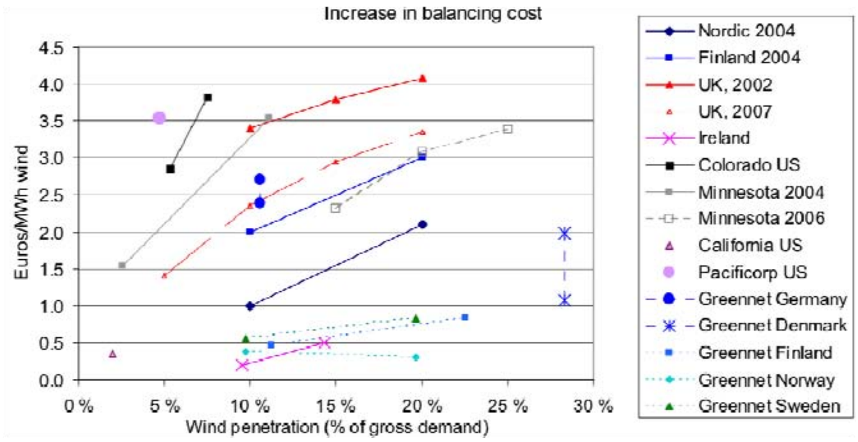


Figure 8.6: At higher levels of wind penetration, the additional balancing costs of the entire power system are higher, as shown by several power supply system studies (Holttinen et al., 2009a).

Holttinen et al., (2009a) concluded that "at wind penetrations of up to 20% of gross demand (energy), system operating cost increases arising from wind variability and uncertainty amount to about EUR 1-4 /MWh [TSU: Also needs to be presented in 2005 US$]", which represents around 10% or less of the wholesale cost of wind energy generation.

With respect to the capacity credit of wind energy generation, Holttinen et al. (2009a) recommended calculating the effective load carrying capability (ELCC), which requires detailed chronological data for wind generation and load and availability information for generators with intrinsic primary energy storage. Figure 8.7 summarises the results from eight studies undertaken in Europe and the USA [TSU: Holttinen et al, 2009a was cited above as covering ten studies across Europe and the USA – discrepancy should be clarified]. The capacity credit estimates (as % of installed capacity) show considerable variation due to the differing nature of the wind regimes and their correlation with electricity demand as well as a general reduction trend with increasing wind penetration.

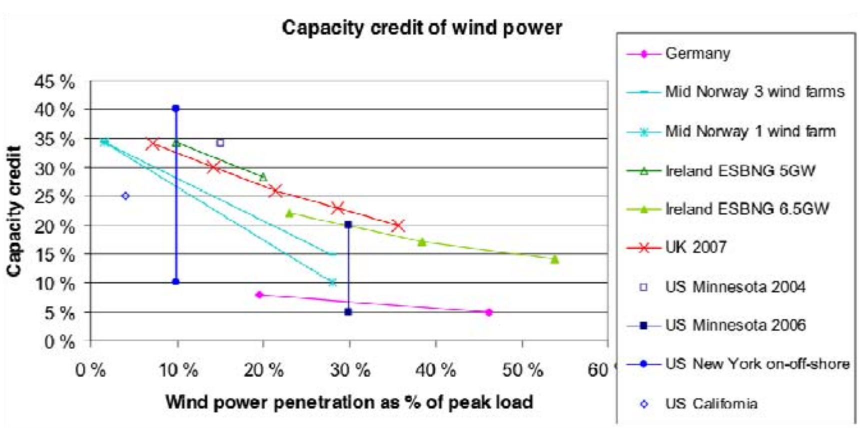


Figure 8.7: Capacity credit declines as wind power penetration increases (Holttinen et al., 2009a).

When moving beyond penetration levels of 20% of wind energy on an annual energy basis, Van Hulle et al., (2009) suggest that new directions need to be followed for both the design and operation of the power system and the electricity markets to give consistent policy decisions. Hence it is critical that the decision-making processes are well thought through, for example, on grid reinforcement, technical standards, market rules etc. A similar conclusion has been reached in Australia, where a holistic approach has been taken since 2003 to integrating non-storable RE resources, including wind energy, into the Australian national electricity market.

Holtinnen et al., (2009) identify large unconstrained transmission regions, flexible complementary resources and efficient intra-day trading, as factors that can help to minimise the costs of wind energy integration. They also suggest that augmenting wind energy with high penetration of PV or ocean power would help to smooth variability and thus reduce, at least in a per-unit sense, overall integration costs.

The EU and Australian experiences are discussed further as case studies below. However carefully chosen policies and commercial incentives will be required to bring forward an appropriate mix of “complementary resources” (generation, network, reversible storage and flexible end-use) and to maximise the benefits that wind energy or other non-storable RE resources can bring whilst minimising the costs. The resulting resource mix, and the effectiveness of such a strategy, will be context-specific and evolve over time.

8.2.1.6 Case studies

8.2.1.6.1 European large-scale wind integration: TradeWind

The TradeWind project (2006-2009) coordinated by the European wind industry association EWEA and sponsored by the European IEE Programme (Van Hulle et al. 2009) was a recent study to investigate the adequacy of European power systems for large scale wind integration (www.trade-wind.eu[TSU: URLs are to be cited only in footnotes or reference list.]).

TradeWind assessed the options for improved interconnection between European member states and the corresponding power market design to enable large-scale wind energy integration in Europe. Optimal power flow simulations were carried out with a Europe wide network model to look into the effects of increasing wind power capacity and more specifically of possible grid dimensioning situations on cross border flow. Future wind power capacity scenarios up to 300 GW in the year 2030 were investigated. The TradeWind simulations show that increasing wind power capacity in Europe leads to increased cross border energy exchanges and more severe cross-border transmission bottlenecks in the future, especially with the amounts of wind power capacity expected in 2020 and 2030. Also the effect of passing storms on cross-border flow was investigated. Wind power forecast errors result in deviations between the actual and expected cross-border power flows on most interconnectors during a substantial part of the time and will further exacerbate these congestions. Significant economical benefits of network upgrades that would relieve existing and future structural congestion in the interconnections have been quantified. More specifically, a staged upgrade at 42 interconnectors would benefit the European power system and its ability to integrate wind power. These upgrades would lead to savings in operational costs of power generation amount of 1500 M€/year[TSU: Also needs to be presented in 2005 US$], justifying investments in the order of €22 billion[TSU: Also needs to be presented in 2005 US$], for wind power scenarios up to 2030 [TSU: Source?].

The project looked also specifically at the benefits of transnational offshore grid topologies for integrating offshore wind power. A meshed offshore grid linking future 120 GW offshore wind farms in the North Sea and the Baltic Sea and the onshore transmission grid compares favourably to a radial connection solution of individual wind farms, due to the higher flexibility and the benefits it offers for international trade of electricity. Such offshore grid supposes further upgrade of the onshore network, which needs to be studied in follow up studies[1].

The European wind power time series were also used to calculate the effect of geographical aggregation on the contribution of wind power to the generation adequacy. It was found that aggregating wind energy production from multiple countries strongly increases the capacity credit of wind power (firm power added in the system by adding wind power capacity). The greater geographic area the grouped countries represent, the higher is the capacity credit (Fig. 8.8). If no wind energy is exchanged between the European countries, the capacity credit of 200 GW wind power in 2020 in Europe would be 8 %, which corresponds to 16 GW firm capacity. When Europe is calculated as one wind energy production system and wind energy is distributed across multiple countries according to individual load profiles, the capacity credit almost doubles to 14 %, which corresponds approximately to 27 GW of firm power in the system.

In addition to transmission needs, TradeWind also evaluated the effect of improved power market rules and quantified these in terms of reduction of the operational costs of power generation. The establishment of intra-day markets for cross-border trade is found to be of key importance for market efficiency in Europe as it will lead to savings in system costs in the order of EUR 1-2 billion[TSU: Also needs to be presented in 2005 US$] per year as compared to a situation where cross-border exchange must be scheduled day-ahead. In order to ensure efficient interconnector allocation, they should be allocated directly to the market via implicit auction.

Intraday rescheduling of the generation portfolio, taking into account wind power forecasts up to three hours before delivery, results in a reduction in operational costs of power generation of EUR 260 M/yr[TSU: Also needs to be presented in 2005 US$] (compared to day-ahead scheduling) thanks to the decrease in demand for additional system reserves. Consequently, the TradeWind analysis concluded that the European electricity market needs intraday rescheduling of generators and trade, a consolidation of market areas, and increased interconnection capacity in order to enable efficient wind power integration.

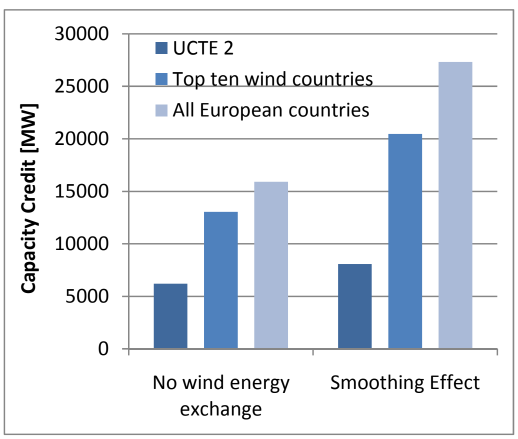


Figure 8.8: Increase of the capacity credit in Europe through wind energy exchange between the countries in the TradeWind 2020 M scenario (200 GW, 12% penetration) (Van Hulle, 2009).

UCTE 2= Union for the Co-ordination of Transmission of Electricity for France, Belgium, Netherlands, Luxemburg, Germany, Switzerland and Austria www.ucte.org [TSU: URLs are to be cited only in footnotes or reference list.]

[1] Based on the findings of TradeWind, EWEA has proposed a long-term plan for offshore grid development (EWEA, 2009). The technical, economic and regulatory options for such an offshore grid delivering 12% of Europe's demand are further researched in the frame of the IEE Offshore Grid project (www.offshoregrid.eu).

8.2.1.6.2 Desertec

The "Desertec Industrial Initiative GmbH" is a consortium of twelve large German and Spanish engineering, financial and energy companies that, in 2009, launched a USD 560 billion [TSU: Needs to be presented in 2005 US$] investment scheme aiming to produce 15% of Europe's electricity demand in 2050 (Global Insight, 2009). The concept was initiated in 2003 by the German Club of Rome global think-tank. It aims to harness solar energy from the desert areas of Middle East and North Africa (MENA) using concentrating solar power (CSP) technologies spread over nearly 17 000 km^2. The electricity will be transmitted to Europe through high voltage, direct current (HVDC) cables, some sub-sea. Interconnections between Europe and MENA (Fig. 8.9) could enable the present 16% share of renewable electricity to rise to 80% in 2050 (Trieb and Műller-Steinhagen, 2007). The venture is in the very early stages of planning with many major technological, fiscal, logistical and political barriers identified as needing to be overcome.

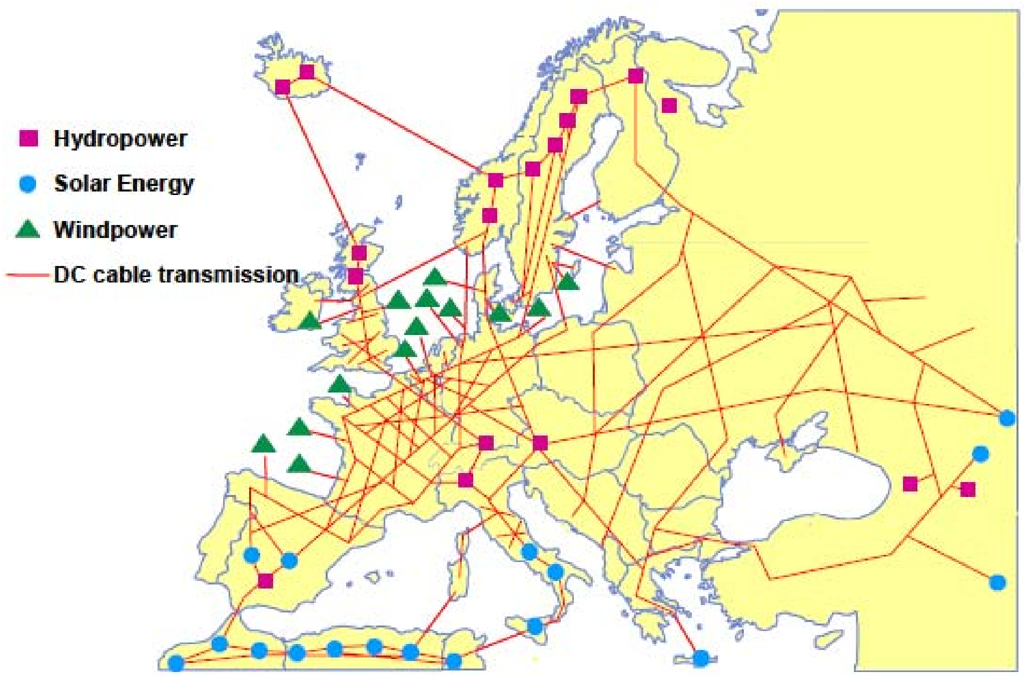


Figure 8.9: The concept of an inter-connected electricity grid between Europe, North Africa and Middle East based on high voltage DC transmission "highways" to connect with the existing AC grid and power plants (Asplund, 2004).

Around 85% of the investment cost will be for the solar power plants and the remainder for the 20 or more transmission cables. The partner Abengoa is already developing integrated CSP installations combined with combined-cycle gas plants in Morocco and Algeria. The two demonstration plants are:

- a USD 212 million[TSU: Needs to be presented in 2005 US$], 472 MW plant in Ain Beni Mathar, Morocco, of which only 20 MW is solar; and
- a 150 MW system in Hassi R'Mel, Algeria, with 35 MW solar.

Some private funding is involved (along with funding from international agencies) but in spite of government facilitation, this has been difficult to attract.

The main barriers anticipated to developing the Desertec project are: possible damage to the solar mirrors from desert sandstorms; public resistance against limited water supplies being diverted for cooling turbines and cleaning the solar mirrors; the need for thermal or fossil-fuel balancing capacity to cover for fluctuations in output; and the challenge to meet the increasing local demand for electricity outweighing the option to export power. For MENA nations that have failed to meet their growing electricity demands in recent years, knowing the demand will rise over three times by 2050 compared with around 1 000 TWh per year today, with a further 500 TWh/yr probably needed for desalination to meet the projected water deficit in 2050 (Trieb and Műller-Steinhagen, 2007), then the concept of exporting power will be difficult to promote. Several North African states already have solar targets in place for the medium term, but establishing commercial-scale CSP facilities has been constrained by their relatively high cost, in spite of feed-in tariffs being in place in Algeria and Morocco. However, CSP generation costs are expected to decline over time to around USD 50/MWh by 2030.

There is unresolved debate whether in Europe, improved energy efficiency measures and the advent of distributed generation (including solar PV) will be a cheaper option than massive investment in the Desertec project infrastructure (Global Insight, 2009). This option would also involve a major upgrade of the existing transmission networks throughout Europe, so further work to assess the combined effects and costs of having a portfolio of all renewables is warranted. The location of the curved solar mirrors, turbines and solar thermal storage systems is also under debate; deep in the Sahara desert and Arabian Peninsula, or closer to populated areas where a supply of water is more readily available are the options.

Close agreement between all stakeholder governments will be needed for the Desertec project to succeed, yet historically this has proved difficult for some of those involved. Exploitation of the local solar resource by foreign-owned companies is already under question. The initial 3 year study led by The German Aerospace Centre, confirmed the feasibility of the project and until 2012 the consortium will concentrate on accelerating the implementation of the Concept by creating of a favourable regulatory and legislative environment and developing a plan for development (Desertec Foundation, 2009). It will have to consider how to manage the political issues, as well as to ensure the technological barriers can be overcome, the CSP plant components can be manufactured at the rate required, and that the inevitable transmission losses can be kept low enough to make the venture profitable.

8.2.1.6.3 ISET renewable combi-plant

This project, a combined RE power plant system, is an initiative of leading German manufacturers of RE technologies. It is supported by partners from the REsector and by the Institute for Solar Energy Supply Systems (ISET) at the University of Kassel, Germany. The objective is to demonstrate the feasibility of RE to cover 100 % of electricity demand and dispel the major arguments against a massive penetration of renewables, including variable generation, poor predictability and lack of controllability (Mackensen et al, 2008a).

The concept is to produce a virtual power plant (VPP) consisting of several decentralized stations, each generating electricity. Photovoltaics, wind turbines, combined heat and power (CHP), and storage devices, are combined plus a central control consisting of system management, forecasting, and a primary control unit (Arndt et al., 2006).

The difference with other VPP projects is that the Renewable Combi-Plant works only with RE technologies. These are all produced in Germany. The grid supply capacity is calculated by adding all decentralized generation including existing renewable power production. The outputs of CHP systems are considered as constant baseload, because their output can not be rapidly varied to follow demand.

The first step to create the scenario for 100% power supply of Germany by RE sources was to estimate the potentials of wind, solar PV and biomass. The resulting electrical power production gave a potential of 448 TWh per year, around 10% higher than the current annual German demand of around 420 TWh. To demonstrate the integration of RE power systems, the VPP was designed to represent a future scenario of supplying the yearly electricity requirements of a small town of 12 000 households. Around 10 000 such VPPs would therefore be needed to supply all of Germany (Mackensen et al, 2008b).

The system aggregates and controls the power generation from three distributed wind farms, 20 solar PV plants, four biogas-fired CHP plants and a pumped storage hydro system (Fig. 8.11) in such a way that the output matches the specified load at all times. The capacities for the system components (Table 8.3) reflect current technology and make it possible to compare the results with real power plant outputs integrated into the Renewable Combi-Plant. The total produced energy is 43.5 GWh/yr including imports/exports and storage.

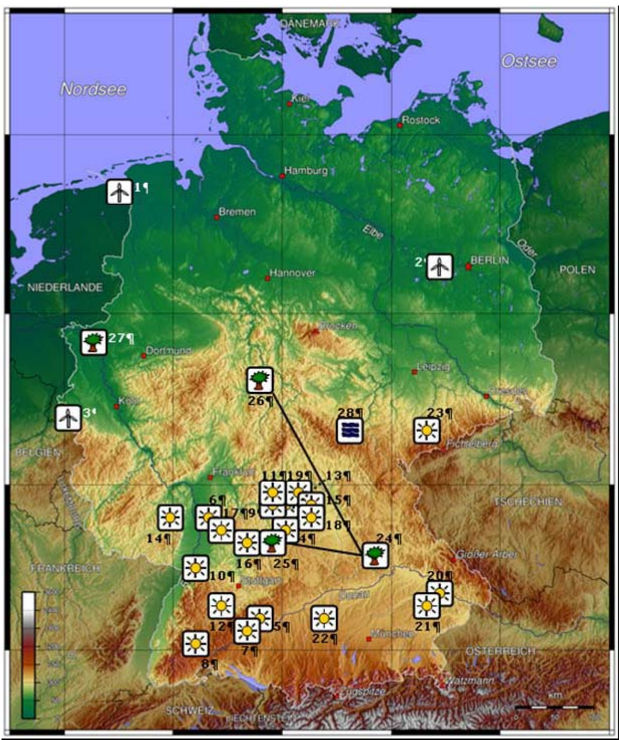


Figure 8.10: Components of the Renewable Combi-Plant depicted by wind (1-3), solar (4-23), biogas (24-27) and pumped hydro (28) (Mackensen et al, 2008b).

Table 8.3: Electrical energy generation and capacity global portfolio of RE technologies (Mackensen et al, 2008a).

	Wind	Solar	Biogas	Reser-voirs	Import/Export	Total
Installed capacity [MW]	12.6	5.5	4.0	1.06	-/1.0	-
Electrical energy [GWh/a]	26.5	6.2	10.8	-0.6	0.02/1.8	41.1 (43.5)
% of Total	60.9	14.3	24.8	-	-	100.0

The wind and solar power components of the combi-plant are geographically spread in order to take advantage of smoothing effects due to different weather conditions in the German regions. These are combined with controllable biogas-fired CHP outputs and the hydro storage reservoir. The plants are real, except for the pumped hydro storage device, with electricity currently being fed into the public grid (Mackensen et al, 2008b).

The use of intelligent control and regulation technology enables the decentralized installations to be linked together so that fluctuations in the amount of electricity fed into the grid can be balanced. The central control unit (CCU, Fig. 8.11) is where the various output forecasts and measurement values are balanced. Based on the data, the control process is carried out in two steps (Mackensen et al, 2008a).

a. Forecast and scheduling

The CCU receives weather and demand forecasts and, based on these, anticipates the necessary amount of power to be produced by wind and solar plants (Rohrig, 2003). To balance out the difference between the actual demand and the electricity generated by wind/solar energy, it calculates and sends a schedule to the biogas plant operators. If there is still a surplus or shortage, this is balanced out by using the pumped storage power plant and, as a last resort, by exporting and importing to and from neighboring grids.

b. Comparison of actual data

The CCU receives feedback from all power plants on the actual current output and compares this data with the immediate demand. Differences compared with the forecast values are balanced through short-term adjustments to the biogas electricity outputs within minutes. The algorithms created for the concept were verified and a prototype has been in operation since May 2007.

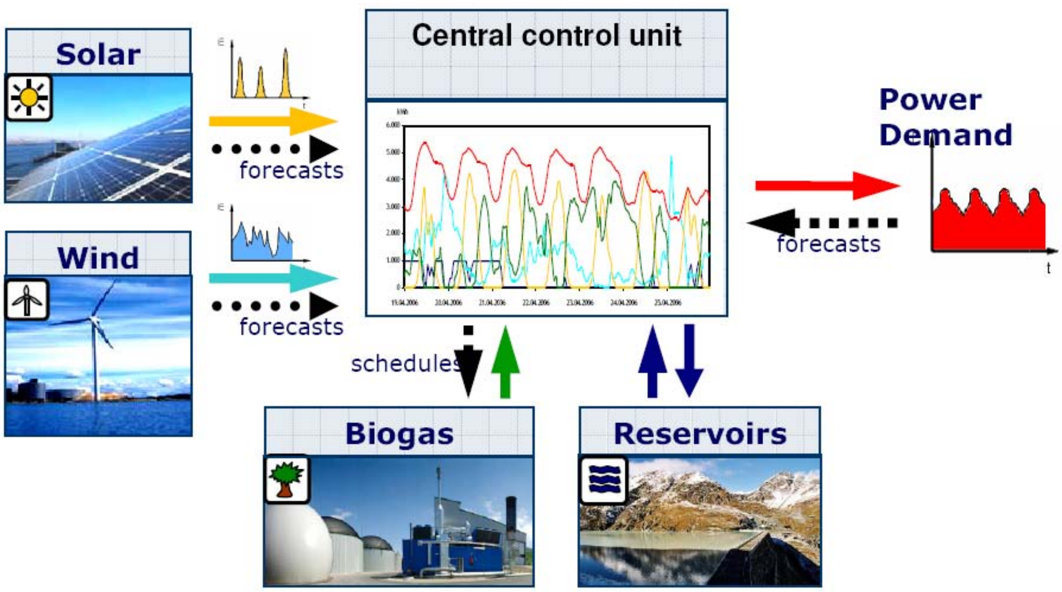


Figure 8.11: Operating principle of the Renewable Combi-Plant (Mackensen et al, 2008a).

To deal with a large portion of fluctuating power, it is necessary to install more total capacity than peak load demand. The Renewable Combi-Plant needs storage capacities to be able to constantly meet the demand. When supply exceeds the demand, the surplus can be shed, stored or exported to neighbours through the Union for the Co-ordination of Transmission of Electricity (UCTE). Exporting energy leads to additional costs for grid reinforcement and expansion. Creating new storage capacity also involves a cost. In addition, storing and transmitting electricity always results in losses.

At higher penetrations of fluctuating energy producers, intelligent integration into the supply system is required to balance production with demand. Integration into the electricity markets requires an adequate payment system as a replacement for the fixed tariffs defined by EEG, the German Renewables Act, 2000. For example a bonus for cogeneration or storage of electrical power would allow transferring the responsibility for compensating for fluctuating power generation to the producers. Under the existing law with a fixed tariff system, neither operators of RE plants nor transmission system operators seek steady energy production, combination with demand side management, or the integration of storage devices. Presently, situations sometimes arise when selling electricity on the free market is valuable, but we can assume that these situations will appear more often because of rising prices and the declining tariffs of the EEG.

This project confirms that it is possible to supply Germany with 100% renewable electricity. To achieve this will depend on the speed of research and development, political will and societal support for the concept.

8.2.1.6.4 Wind integration in the Australian national electricity market

Perhaps uniquely, the Australian national electricity market (NEM) was designed from the outset to accommodate non-storable RE resources. The electricity market design concepts (Schweppe et al., 1980; Outhred and Schweppe, 1980) were incorporated into the Australian NEM. This was partly motivated by an expectation of “increasing exploitation of distributed RE resources often by independent groups that wish to sell excess power to utilities and buy back-up power when needed” (Outhred and Schweppe, 1980). Thus since the NEM commenced in 1998, its centre piece has been a multi-region, real-time energy spot market that implements a competitive security constrained 5-minute dispatch across a power system network that extends over 4000 km, one of the largest in the world. The real-time energy market is supported by co-optimized, real-time ancillary service markets, centralized security management and decentralized derivative markets. These form co-designed, decision-making regimes in an over-arching decision making framework for the stationary energy sector (Outhred and Thorncraft, 2010). In the year to June 2009, wind energy supplied approximately 15% of the 13.1 TWh of electricity consumed in the South Australian region of the NEM. Further increases in wind penetration are anticipated (ESIPC, 2009). While wind penetrations are lower in other NEM market regions, they are also expected to rise.

The Council of Australian Governments (COAG) established a Wind Energy Policy Working Group (WEPWG) in mid 2004 to consider the range of policy level issues associated with the anticipated entry of large amounts of wind generation into the NEM in coming years. In turn, WEPWG requested that the NEM Management Company[2] (NEMMCO) establish the Wind Energy Technical Advisory Group (WETAG) consisting of industry participants to assist the WEPWG with the analysis of technical and policy aspects of wind penetration in the NEM. WETAG identified a number of key tasks (MCE, 2006):

- review technical standards for grid connection;
- manage the impact of “intermittent generation” on network flows;
- investigate wind-farm behaviour in respect of power system operational implications;
- require appropriate information disclosure; and

[2] The National Electricity Market Management Company was absorbed into the Australian Energy Market Operator (AEMO) in July 2009. AEMO is responsible for both electricity and gas markets.

- review cost recovery for regulation frequency control ancillary services.

NEMMCO itself undertook a series of investigations into RE integration. Significant issues identified in NEMMCO (2003) included forecasting, frequency control ancillary services and network management and connection issues. NEMMCO (2004) reported on the issue of forecasting and recommended that steps be taken to create a forecasting capability, with associated obligations on wind farm owners to contribute data.

The Australian Government then funded NEMMCO to specify and implement an Australian Wind Energy Forecasting System (AWEFS). This is now fully integrated into the security and commercial decision-making regimes in the NEM (see www.aemo.com.au/electricityops/awefs.html[TSU: URLs are to be cited only in footnotes or reference list.]).

AWEFS has a set of forecasting horizons from five minutes to two years and draws on SCADA information from all transmission-level wind farms connected to the NEM. Amongst other functions, AWEFS will support recently implemented “semi-scheduled” arrangements whereby wind farms will be required to participate in the dispatch process if an associated network flow constraint appears likely. Further research is underway to ensure that AWEFS has adequate capacity to forecast large, rapid changes in aggregated wind farm output (Cutler et al., 2008). AWEFS will also be used to forecast other RE resources such as solar energy, when justified by their level of penetration.

The Australian Energy Market Commission (AEMC) has recently completed a comprehensive review of energy (electricity and gas) market frameworks in light of climate change policies for the Council of Australian Governments. Its final report (AEMC, 2009) concluded that “subject to implementation of the framework changes we are recommending, the energy market framework is generally capable of accommodating the impacts of climate change policies efficiently and reliably”. The report recommended the following framework changes:

removal of electricity retail price regulation (where still in force) or at least the introduction of flexibility mechanisms to allow timely adjustment of regulated prices;

bringing forward the implementation of a national framework for energy customer protection developing network connection arrangements that achieve efficiency gains from connecting clusters of generators, developed over time, using common network assets;

- introducing transmission charges between market regions of the NEM in recognition of the likely increased importance of fluctuating inter-regional flows increasing the extent to which generator network charges vary by location as well as the extent to which spot market energy prices reflect congestion within market regions;
- regularly reviewing the spot market price cap (presently approximately USD 10,000 /MWh) for adequacy with respect to bringing forward complementary resources to manage fluctuations in the output of generators based on non-storable RE resources; and
- reviewing the effectiveness of reliability intervention powers of the Australian Energy Market Operator (AEMO).

8.2.2 Integration of renewable energies into heating and cooling networks

8.2.2.1 Characteristics

A district heating or cooling system is a piping network that allows multiple energy sources to be connected to many energy consumers by pumping hot or cold water as the energy carrier. Technologies used for district heating and district cooling are can facilitate the use of renewables, especially in dense urban, commercial and industrial areas. The concept creates the opportunity to access a broad spectrum of RE sources to provide heat or cold to a large number of users.

Historically, district heating systems were mainly developed in countries with long, cold winters. After the oil crises in the 1970s, several countries developed district heating systems in combination with combined heat and power (CHP) generation to increase overall energy efficiency. Some countries, in particular in Scandinavia, have a district heating market penetration of more than 50% and in Iceland, the share, using geothermal resources, reaches 96% (Fig. 8.12). Today, district heating is also used in lower latitude countries and district cooling is increasingly being used in many regions of the world, either through the distribution of chilled water or by using the district heating network to deliver heat for heat-driven absorption chillers. The Swedish town of Växjo, for example, uses excess heat from the biomass CHP plant in summer for cooling in one district (SESAC, 2009), and a further 2MW chiller is planned (IEA, 2009b).

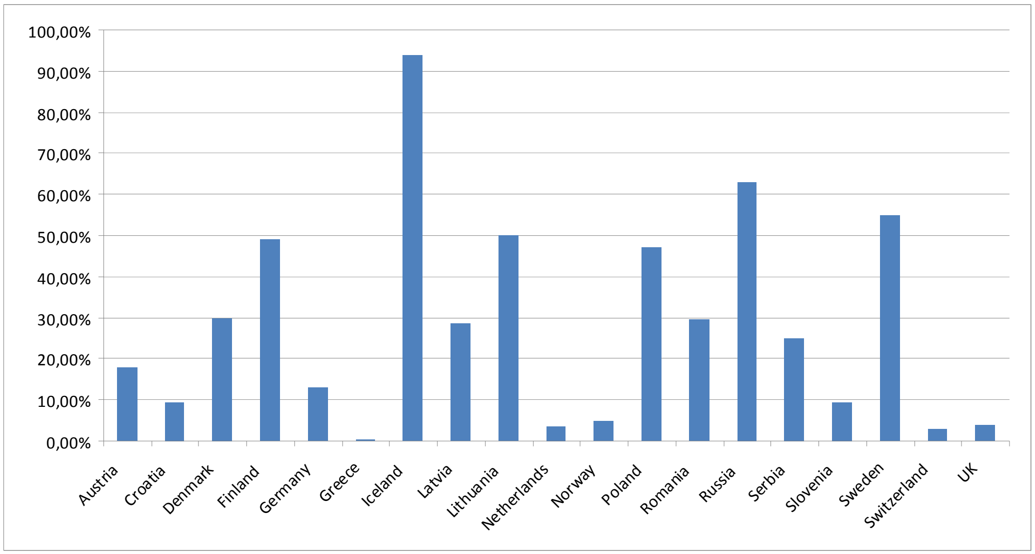


Figure 8.12: Share of district heating in total heat demand in selected countries (Euroheat & Power, 2007).

District heating systems offer benefits both on the demand side and on the supply side (Fig. 8.13) the cost-effective use of large scale geothermal, solar or biomass technologies, and fuel flexibility. In the future, new-low carbon and renewable sources can be integrated as soon as they become available and a network can quickly be extended as appropriate to provide an easy way to supply a larger number of customers. Those connected to a district heating system do not need to care about operation and maintenance of their own individual boilers, but can rely on a professionally managed central heating system.

- In the case of deep geothermal systems, the commercial exploitation of large heat flow volumes is required to compensate for the high drilling costs. In most cases, such a large heat demand is only available through district heating networks. Also enhanced geothermal systems (EGS) usually require to be operated in CHP mode coupled with district heating networks in order to be cost-effective.

- Woody biomass or crop residues can be more efficiently used in a district heating integrated CHP plant than in individual small scale burners. The operation of a centralised biomass CHP plant with lower specific investment costs facilitates the operation of cost-effective emission reduction measures.

- The costs of solar heating of water, space or both can 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 the integration into a district heating system with a sufficiently high heat demand is again a prerequisite.

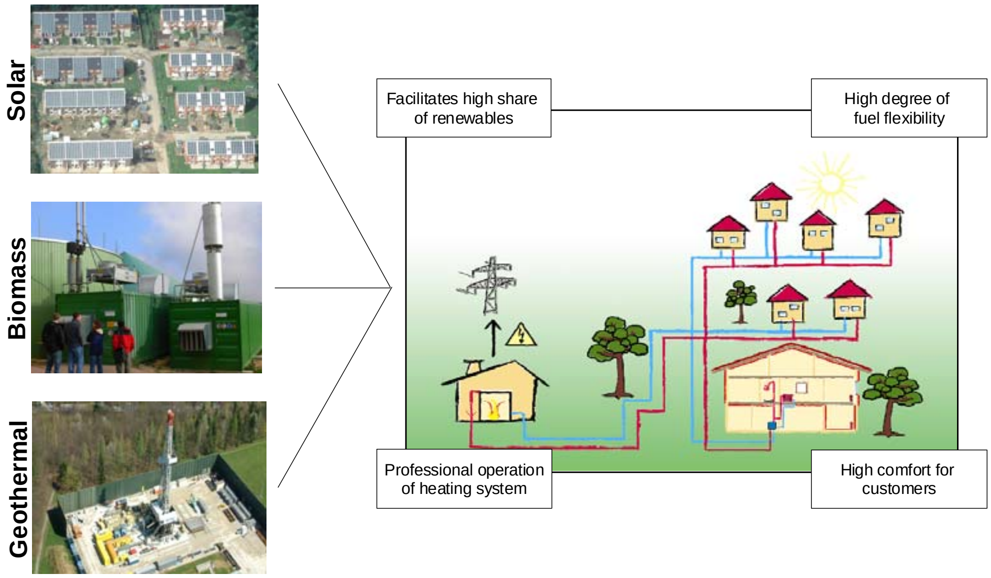


Figure 8.13: A district heating system, often linked with power generation from a CHP plant, offers several benefits for heat users.

By 2007, the more than 200 Mm^2 area of solar collectors installed worldwide produced 146.8 GWth (Weiss et al., 2009). The power output from 1 Mm^2 of flat-plate solar collectors is on the order of 700 MW during the middle of the day (assuming 1,000 W/m^2 incident radiation and 70% collector efficiency). Thus, the peak power capacity of solar water heaters in a number of countries already exceeds 1,000 MW and makes a significant contribution to the energy supply system. The impact of the installation of a large number of solar domestic water heaters to replace electrical heating on the operation of an electricity grid depends on the load management strategies of the utility.

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 fuel 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. Maximum solar water-heater output corresponds with peak summer electrical demand, 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.

Combining biomass and solar thermal energy could provide high capacity factor solutions suited to areas with lower levels of direct-beam, solar radiation due to greater cloud cover. Such areas often have good availability of biomass due to increased rainfall. Since solar technology is more land efficient than biomass (in terms of GJ energy supply per hectare), its use reduces the need for land to grow the biomass and the related transport costs. The optimum ratio of solar thermal to biomass to supply heat would be site-specific.

8.2.2.2 Features and structure

Thermal energy in the form of hot water or steam is distributed by pipelines from central plants to individual buildings. Energy is extracted at the buildings and return pipes bring the water back to the heating plant. In order to be economically viable, the heat demand density must be sufficiently high.

District heating systems are most commonly operated in densely populated urban areas. However, district heating 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). The annual cost to supply around 18 MWh/yr of heat to a single family, Danish house (130 m²) has become around 30% lower for biomass district heating versus an oil-fired central heating system (Fig. 8.14), partly due to the increased oil price (Dansk Fjernvarme, 2007).

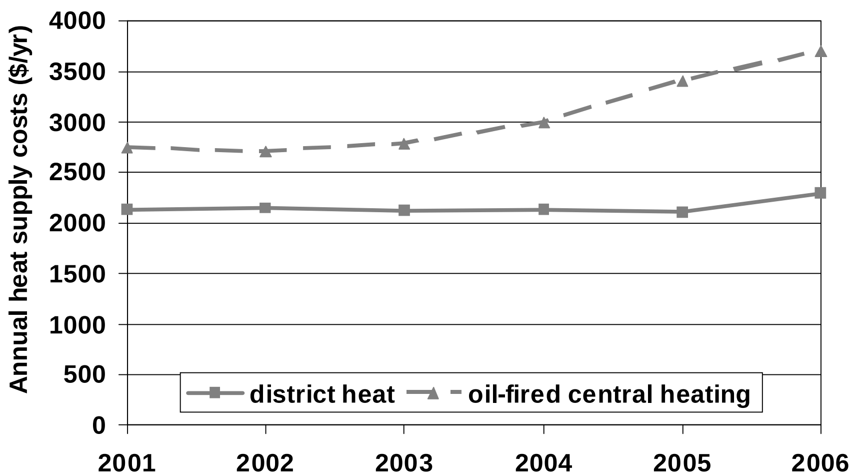


Figure 8.14: Annual heat supply costs for a single family house in Denmark (130 m², 18.1 MWh/yr) supplied either by district heating or by oil-fired central heating (Dansk Fjernvarme, 2007).

8.2.2.3 Challenges caused by integration into heating networks

The cost of district heat supply varies strongly with the heat density of the consumer area. In Denmark, about 80% of the district heating companies face an average heat density within the range of 330 to 1400 kWh per metre of pipeline per year (Bruus & Halldor, 2004). In small towns, the average heat density is typically somewhere between 280 to 550 kWh/m/yr, while centres of large urban areas can have densities above 2800 kWh/m/yr. In Germany, the average economically viable heat density is around 4000 kWh/m/yr as a result of high heating network installation costs due to technical and administrative reasons (although current legislation provides incentives for expanding district heating systems into regions with lower heat densities than this). By comparison, in Denmark the distribution cost component per heating unit is acceptable where heat density is above 550 kWh/m/yr (typical of an urban area with a moderate population density). The total supply cost remains well below the cost of individual fossil-based heating of apartments.

In the future, very energy efficient buildings in new residential areas will have a heat density well below 300 kWh/m/yr.[TSU: Source?] This will flatten the load curve and require only relatively small amounts of heat for space heating during winter and for hot water throughout the year. Heat distribution network investment costs, depending on site specific conditions, are therefore likely to become the predominant part of the total heat supply costs. Heat pumps or other local alternatives could supply much of this baseload heat. Therefore district heating could end up being of interest only for industrial areas or as occasional back-up to meet peak load demands. However, expected reductions in heat distribution costs, through improved design and reduced losses, suggest that the expansion of district heating will become economically feasible to consumer areas with a heat density of only around 150 kWh/m/yr (Bruus & Halldor, 2004). Improved designs includes the co-insulating of smaller diameter forward and reverse flow distribution pipes.

8.2.2.4 Options to facilitate integration into heating networks

8.2.2.4.1 Storage

Thermal storage systems are essential components for system integration, as they can bridge the gap between intermittent, discontinuous or unsynchronised heat supply and demand. The capacity of thermal storage systems ranges from a few MJ up to TJ, the storage time from minutes to months, and the temperature from -20°C up to 1000°C. This is possible only by using different storage materials (solid, water, oil, salt, air) and the corresponding thermal storage mechanisms.

In household applications 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 district heating networks, the development of systems for seasonal heat storage (Fig. 8.15) has made considerable progress and several demonstration plants have been realised. Heat storage systems using latent heat of fusion or evaporation (phase change materials, PCMs), or the heat of sorption, offer higher storage densities. Sorptive and thermo-chemical processes allow thermal storage for an almost unlimited period of time, since heat supply or removal occurs only if 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.

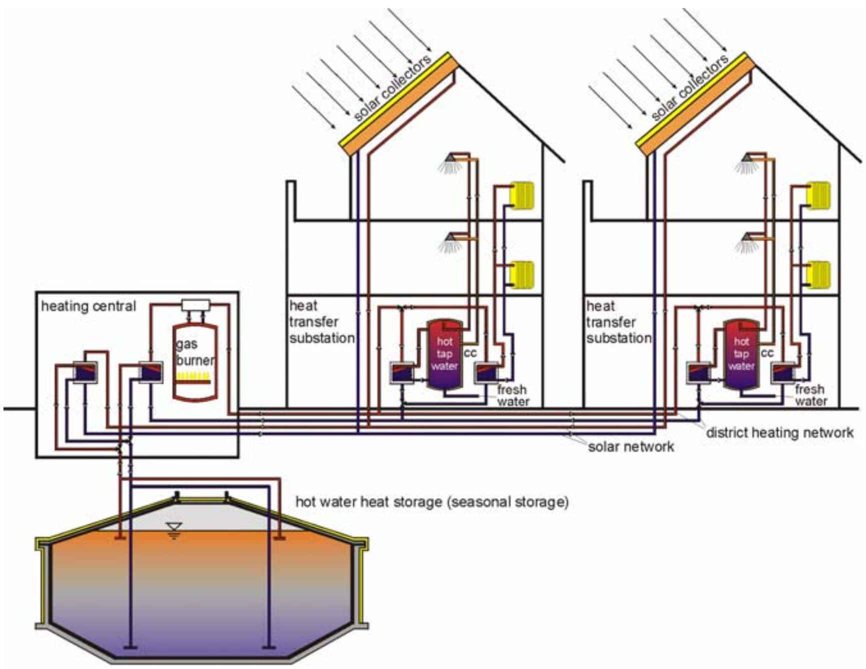


Figure 8.15: Central solar-supported heating plant with seasonal storage connected to a district heating system (Heidemann and Müller-Steinhagen, 2006).

The type of hot water storage system depends on the local geological and hydro geological conditions. Currently four different storage types have been developed (Heidemann and Müller-Steinhagen, 2006).

- A water-filled containment of steel-enforced concrete, partly submerged into the ground, has the widest range of utilisation possibilities, as it can be used independent of local geological conditions. It is usually small, but sufficient to provide heat storage for several days. A glass fibre tank is an alternative option.

- A gravel/water heat storage consists of a pit sealed with a water-proof synthetic foil, filled by a storage medium consisting of gravel and water. No static support structure is necessary.
- In a duct storage system, heat is conducted directly into water-saturated soil via probes. These poly-butane U-tubes are inserted into bore holes with a diameter of 100-200 mm and 20 to 100 m deep. The operational behaviour is slower than for the other heat store types as heat transfer from the store occurs mainly by heat conduction to the heat carrier in the tubes.
- Aquifer heat storage uses naturally existing, closed layers of ground water for storing heat. The ground water is taken out of the store via well bore holes, heated, and then pumped back into the store through other bore holes.

Specific storage costs are a function of storage volume (Fig. 8.16), expressed as "water equivalent" to be able to compare storage technologies. The storage costs, as taken from demonstration and pilot systems built in Germany, significantly depend on specific site conditions. A reduction of costs occurs with increasing storage volume. Investment costs for storage systems with a volume of more than 10,000 m³ are currently between USD 90/m³ and USD 150/m³[TSU: Needs to be presented in 2005 US$/m³] water equivalent. The economic performance of a storage system depends not only on the investment costs, but also on the thermal performance of the storage and the connected thermal system as well as the rate of heat extraction when needed.

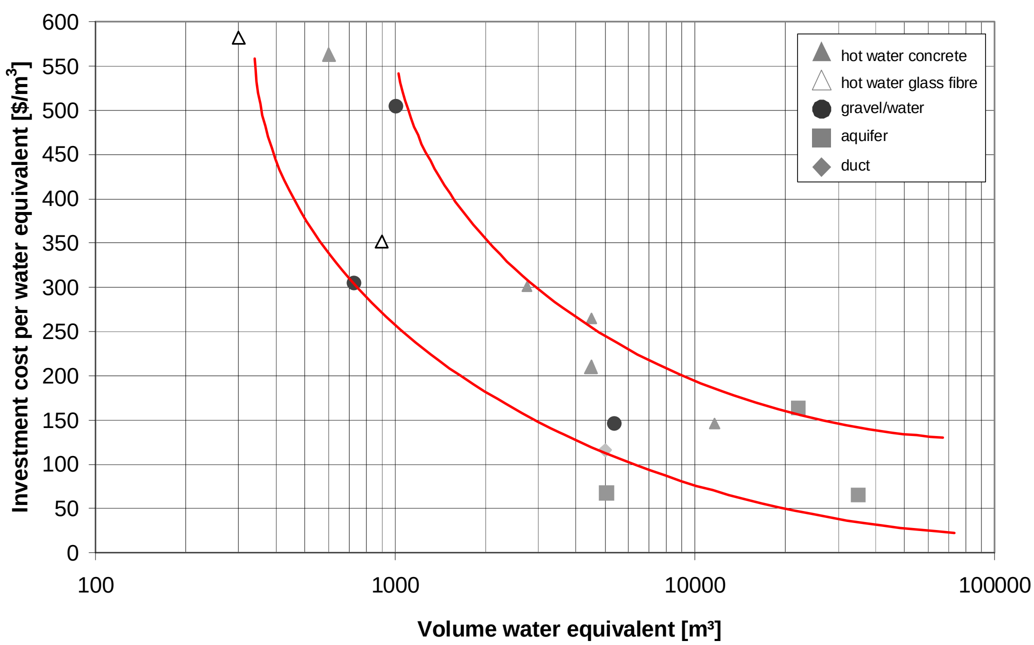


Figure 8.16: Costs of different seasonal heat storage pilot and demonstration systems in Germany (Heidemann et al., 2005).

8.2.2.4.2 Institutional aspects

District heating and cooling is capital intensive mainly due to the piping network. Such schemes have typically been developed in centrally planned economies, Western European countries with multi-utilities, and cities controlled by local municipalities where strong planning powers exist. The liberalisation of energy markets has had a significant impact on district heating operation. Electricity, the direct use of natural gas, and small-scale heat pump, biomass, solar and geothermal systems, are strong competitors to district heating. The introduction of competition in electricity and natural gas markets resulted in price reductions in many countries – at least in the short-term. Lower prices favoured the installation of individual gas or electric boilers so that district heating utilities had to adjust their heat prices downwards to compete. Subsidised gas prices for residential customers in some regulated markets is a key economic barrier hindering the expansion of district heating operations.

In theory, third party access to district heating networks could lead to a more competitive market for heating services, resulting in decreasing heat prices and thus consumer benefits. Markets for district heat by nature are local, contrary to 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 district heating utility, the incumbent utility would then be unable to sell its heat to existing or new consumers, the only choice being to reduce the price or accept lost revenue. In this case, the stranded asset cost can thus be higher than the customer benefit 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 district heating systems however are too small to host that many producers. Thus it remains debatable whether or not third party access in an existing district heating system is financially sustainable and beneficial for the customer.

In the former centrally-planned economies, district heating prices were regulated because of a social policy to sell heat below its market price. Today, in many countries with large district heating schemes, an independent regulatory body ensures appropriate pricing where natural monopolies exist. For instance the Danish district heating law has been a major factor in the development of the sector. This law recognises the ownership of district heating grids and the sale of heat as a monopoly and so provides general regulation regarding pricing and conditions of sale for the heat. A regulatory authority was established to oversee the formation of regulated prices and solve disputes between consumers and utilities (Euroheat&Power 2007). Other countries with a high share of district heating, such as Sweden, do not have price regulation in place, but use tax incentives to support efficient district heating schemes. Tax on fossil fuels has been a strong incentive to switch to renewable heating options, biomass in particular. In Germany, a Market Incentive Programme for renewable energies currently supports investment into new district heating schemes by granting $100/m[TSU: Needs to be presented in 2005 US$/m] in existing settlement areas, and $75/m[TSU: Needs to be presented in 2005 US$/m] in new development areas if the share of renewable energies is above 50% (BMU, 2009). In addition, the district heating system operator receives $2240[TSU: Needs to be presented in 2005 US$] for each consumer connected to the new district heating system (consumer station owned by the system operator).

8.2.2.5 Options to facilitate integration into cooling networks

The design of buildings in hot countries has for centuries provided cooling. With good design and careful planning a building can be designed to be comfortable for people to live and work in, in almost any hot climate by using shading (including by trees), reflection from white surfaces, natural ventilation, orientation to provide a natural breeze, together with suitable materials, thermal mass, earth sheltering, and adequate insulation. For example, the Romans used the sun warming the outside of a tall external "solar chimney" painted black to encourage the more rapid upward convection of hot air and thereby drawing cooler air into the building below. Variations of this passive solar cooling concept are often used in modern building designs. The evaporative cooling tower is another traditional passive cooling concept whereby water at the top of a tower attached to the building evaporates and hence cools the incoming air causing a downdraft of the denser air inside the tower that then cools the associated building space (IEA, 2007a).

Modern district cooling systems from 5 to 300 MW have been operating successfully for some years in cities and towns near to a good water supply. Similar to district heating systems, a network of pipes carries cold water from the supply to a series of buildings where it is passed through simple heat exchange systems. Paris, Amsterdam, Lisbon, Stockholm, and Barcelona use chiller/heat pumps, absorption chillers, compression chillers or a cold water distribution network. Expansion of demand will depend in part on the other options available for cooling building space. Solar energy is not currently utilised at this scale. Sea water can be used but is more corrosive than cold fresh water sources. Where natural aquifers, waterways, the sea or deep lakes are utilised as the source of cold, then this could conceivably be classed as a form of RE. Seasonal storage of cold during winter for use in summer is possible through aquifer, snow or ice storage (see case study below).

National and state building code standards can have an impact on building designs and networks for cooling. Existing apartment buildings, commercial buildings and individual dwellings cannot be easily modified to reduce the solar gain so the addition of air-to-air-conditioning has become the accepted method of cooling[3]. Unit costs have declined over recent years due to mass production. In many countries rapid uptake has led to increased power generation in summer with peak electricity demands occurring. New building codes and developments should be designed with these factors in mind. The principles of passive solar design[4] can also be applied, at least in part, when retrofitting existing buildings.

Cooling demands 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 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.

To use renewable 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 (IEA, 2007a) although this order may often differ by specific local conditions.

1. Energy efficiency and conservation options in buildings and industry sectors.
2. Passive cooling options e.g. passive building design measures, summer night ventilation without the need for auxiliary energy.
3. Passive cooling options using auxiliary energy, e.g. cooling towers, desiccant cooling, aquifers.
4. Solar-assisted, concentrating solar power, or shallow geothermal all driving active cooling systems.
5. Biomass integrated systems to produce cold (possibly as trigeneration – see below).
6. Active compression cooling and refrigeration powered by renewable electricity.

Active cooling systems involve a range of technologies such as the production of cold through absorption cooling driven by a renewable source. Solar-assisted cooling (SAC) is promising but these technologies tend to be relatively costly at this early stage of their commercialisation,

[3] They discharge heat from the building to the outside air to provide internal cooling, but are usually considered to be an energy efficiency measure by reducing the electricity demand of traditional building cooling systems. Therefore they are not covered in detail in this report on renewable energy.
[4] See for example IEA Solar Heating and Cooling for details at www.iea-shc.org.

although the cost is declining with experience in system design (IEA, 2007a). Solar-assisted cooling for air-conditioning and refrigeration systems is therefore gaining interest.

Open cooling cycles use desiccant and evaporative cooling systems that directly condition the air. 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.

Closed systems, including both adsorption and absorption chillers, can be used for central or decentralized conditioning. This thermally driven process is complex, being based on a thermo-chemical sorption process. A sorption chiller is a heat pump used mainly as a central air-conditioning system with decentralised fan coils or cooled ceilings. It is based on a chemical heat driven process rather than electrical so has a higher coefficient of performance. A liquid or gas refrigerant can either be attached to a solid, porous material (adsorption) such as silica gel or absorbed by another liquid or solid material (absorption) such as lithium bromide.

Both solar adsorption and solar absorption designs have reached the early commercial stage with several companies offering products from 15kW to several MW scale. Plants are operating for example at Munich airport (3.6MW), Cologne airport (2MW) and Hornsby library, New South Wales, Australia (60kW) (IEA, 2009b).

Ground source heat pumps can be used virtually anywhere in the world for space cooling (air-to-ground) 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 to reach the necessary temperature by a heat pump. Over the winter the ground nearby normally cools to below 10 °C as a result. This ground temperature enables water to be circulated through the system in summer for cooling and thus used in heat exchangers to lower the internal building temperature. Initially this is usually sufficient to provide the desired cooling but if increased cooling is required later in the season, the heat pump can be operated (in reverse). 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 system but these give lower operating efficiencies.

Trigeneration (or combined cooling, heating and power generation CCHP) can use a single renewable heat source including, synthesis gas, liquid biofuels or solar energy as well as natural gas. The heat from the power generation is utilised for heating in the winter or cooling in the summer so high efficiencies result.

As is the case with district heating, the uptake of energy efficiency, deployment of other cooling technologies and structure of the market will determine the viability of developing a district cooling scheme.

8.2.2.6 Benefits and costs of large scale penetration

The use of geothermal energy, solar energy or biomass in a district heating or cooling system provides heat at low or zero CO_2 emissions. The costs and benefits of a RE based district heating or cooling system very much depend on site specific conditions such as the availability of RE resources, the availability of appropriate infrastructure, or the heat demand density.

Because of high capacity factors of biomass and geothermal systems, high penetration levels are not a technical problem and in general result in favourable economic performance. There are many geothermal and biomass heating or CHP plants integrated into district heating systems that are successfully operating under commercial conditions. Many other cities and towns have opportunities for CHP development as well as for district heating and cooling (DHC). CHP and DHC often do not need financial incentives to compete in the market place, although government attention to address non-financial barriers such as planning constraints, could aid greater deployment (IEA, 2008d).

Several large scale solar thermal systems with collector areas of around 10,000 m² were recently built in Denmark (Epp, 2009). The integration of the solar collectors into existing district heating systems redeems within less than 10 years without any subsidies. At solar shares of up to 20%, the large number of customers connected to the district heating 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 case study below).

8.2.2.7 Case studies

8.2.2.7.1 Solar assisted district heating system in Crailsheim, Germany

In Crailsheim, Germany, a former military area has been transformed into a new residential area with 260 houses, a school and sports hall with more than 50% of the total heat demand to be covered by solar energy. A prerequisite for achieving such high solar shares is the use of a seasonal heat storage facility.

The new residential area consisting of the former military barracks, a school and a sports hall equipped with 700 m² of solar collectors and others installed on new single family buildings (in rows and semi-detached houses). The residential area is separated from a commercial area by a noise protection wall, on which the main area of the solar collectors has been installed. The first phase of the project, which was put into operation in summer 2008, focused on the realisation of 260 accommodation units with an expected total annual heat demand of 4,100 MWh. The total solar collector area is 7,300 m². A borehole thermal energy storage system with 75 boreholes at a depth of 55 m serves as seasonal storage. In a second phase, the residential area will be extended by 210 additional accommodation units. The total collector area will then be around 10,000 m², and the seasonal storage system will be expanded to 160 boreholes (Mangold and Schmitt, 2006).

The solar system is separated into a diurnal part and a seasonal part (Fig. 8.17). The diurnal part consists of the solar collectors on the modernised buildings, the school and the sports hall together with a 100 m³ buffer tank. Energy from this part of the system is mainly used to directly cover the instantaneous heat demand from the residential area. The solar collectors on the noise protection wall together with the borehole thermal storage system and a second 480 m³ buffer tank constitute the seasonal part of the system. The second tank is required to design the borehole storage system according to the required heat storage capacity (which is quite large in summer days), rather than to the heat discharge capacity. The integration of a 530 kW heat pump allows the discharge of the borehole storage system down to a temperature of 20°C. This leads 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 September and the lowest temperature at the end of the heating period will be 20°C. Maximum temperatures during charging will be above 90°C. The whole system is designed to achieve a 50% solar fraction of total heat supply. Solar heat costs are estimated to be around $0.152005/kWh (Mangold et al., 2007).

The annual heat production of the solar thermal system today is 3 million kWhth, which is equivalent to the consumption of 300,000 litres of fuel oil. By halving the fossil fuel consumption and by providing the remaining heat with a highly efficient fossil heating station linked to the district heating network, CO_2 emissions can be reduced by more than 1,000 tonnes per year (Wagner, 2009).

Figure 8.17: Solar assisted district heating system in Crailsheim, Germany with diurnal and seasonal heat storage systems. [TSU: Source?]

8.2.2.7.2 Biomass CHP district heating plant in Sweden

District heating in Sweden expanded rapidly between 1960 and 1985 but was entirely dependent on oil up until the second oil crisis. Thereafter the fuel mix has changed considerably and in 2007 biomass accounted for 44% of fuel supply in Swedish district heating.[5] The town of Enköping is a documented and illustrative case of this transition and it also demonstrates an innovative approach for how to integrate CHP, short rotation forestry and waste water treatment. The district heating system was constructed in the early 1970s and was using to oil fired heat-only boilers until fuel switching started in 1979. After going through a period of using a mix of oil, biofuels, coal, electric boilers and LPG the transition to near 100% biofuels was completed in 1998. The transition was driven by carbon dioxide taxes, other policy instruments and a local decision to completely avoid fossil fuels (McKormick & Kåberger, 2005). An important step in this process was the construction of a biofuel fired CHP plant in 1994-1995 with a capacity of 45 MW heat and 24 MW electricity.

What makes Enköping different from other district heating systems is the unique cooperation between the local energy company, the sewage plant and a local farmer that started in 2000. The energy company was interested in diversifying fuel supply fearing that there may not be enough forest residue fuels in the region to meet future demand. The municipal sewage plant was obligated to reduce nitrogen discharges by 50 percent. The use of willow (Salix) as a vegetation filter system was identified as a cost-effective approach to reduce nitrogen discharges and at the same time produce biofuel. A 80 ha willow vegetation filter was established in the year 2000 on farmland close to the sewage plant. The agreement involves contracts by which the farmer is paid for receiving wastewater and sewage sludge, and for delivering fuel to the CHP plant at market prices. There are several factors explaining the success of this model: parties were proactive and open to new solutions, advisors have worked as catalysts, regional and local authorities have been positive and interested, and risks have been divided between the three parties (Börjesson and Berndes,

[5] The remaining production was based on 9.9 TWh of municipal solid waste (18%), 5.8 TWh of industrial waste heat (10%), 2.9 TWh of coal (5%), 2.0 TWh of oil (4%), 2.3 TWh of natural gas (4%), 2.8 TWh of peat (5%) and 5.8 TWh of heat from heat pumps (10%) (IEA, 2009c).

2006). In 2008 the local area of willow plantations had increased to 860 ha and it is the ambition of the energy company to continue increasing the currently 15% salix fuel share in the system.

8.2.2.7.3 District heating in South Korea

Although most district heating and cooling schemes have been developed in Europe and North America, the Korea District Heating Corporation claims to be the world's largest district heating energy provider (www.kdhc.co.kr [TSU: URLs are to be cited only in footnotes or reference list.]) 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. 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 district heating business aims to save energy as well as to promote the public benefits of district heating and cooling and its convenience for customers. The corporation has constructed over 1100 km of twin forward and return pipes as part of the Seoul metropolitan heating network.

District heating is provided by the company to over 60% of the nation's total households with the aim to steadily expand the business and provide district cooling and heating services to 2 million households nationwide by 2015. Particular business emphasis is given to RE sources, including landfill gas, and the long term company plans are to develop community energy services as well as to enter the relatively untapped Middle East market through a joint business venture with Tabreed Company from the United Arab Emirates, the largest district heating and cooling company in the region.

8.2.2.7.4 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. The IEA Implementing Agreement "District Heating and Cooling" (that also includes CHP) provides details of several examples of cooling demonstration schemes. As a result of several successful demonstrations, the opportunity now exists for governments to encourage further deployment of cooling projects based on RE sources. A few examples are described below.

Deep water cooling allows a relatively high thermodynamic efficiency by utilizing water at a significantly lower heat rejection temperature than the ambient temperature. This temperature differential and higher efficiency results in less electricity being consumed as a lower volume of 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 is transferred directly to the lake water heat sink. Power is needed to run pumps and fans to circulate the lake water and the building air but this is generally much less than would be the demand for refrigeration chilling to produce the same cooling effect.

Successful projects include the Cornell University, Ithaca, USA, 51 MW cooling project 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. 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 USD 58M scheme, the lake 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, from both reducing the annual power demand by 20 GWh (around 80-90% of the previous electricity demand for cooling) and avoiding the 12-13t of CFCs used in the 6 chillers.[TSU: Source?] However 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.

Stockholm has a similar but smaller district cooling system based on sea water from the harbour and 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.

Solar district cooling systems based on the heat-activated refrigeration principle of absorption chillers are less well developed. 'Single-effect' chillers require heat delivered at 70 to 90 °C, meaning solar hot water can possibly be used as the main heat-transfer medium in a simple heat-delivery mechanism at the small scale. However at the larger district heating scale, 'double-effect' chillers require heat to be delivered at temperatures above boiling point, meaning pressurised water or steam has to be generated by concentrating solar collector systems.

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 cooling projects for individual buildings (www.sdc.my[TSU: URLs are to be cited only in footnotes or reference list.]). The solar cooling technology will be located in Cyberjaya and used initially for office and residential applications, though it is hoped that rapid uptake of the cooling service will also attract larger customers such as hospitals, schools, district councils and airports. Natural gas is planned for back-up, though in cases where suitable heat storage is included in the system design for use during night-time and cloudy days, this can be minimised. 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 of this technology to date. Policy support measures by interested governments could help bring down the manufacturing, project design and installation costs of this technology as a result of the traditional experience learning curve (IEA, 2008c).

8.2.3 Integration of renewable energies into gas grids

The main objective of a gas grid is to transport gas from producers to consumers. The system consists of gas productions plants, transmission and distribution pipelines, gas storage, and industrial or private gas consumers. The basic design of a gas system depends mainly on the type and source of energy, the end-user demand, and the locations of these.

Over the past 50 years large integrated natural gas networks have been developed in several parts of the world including USA, Europe, and Japan. The European natural gas grid is, arguably, one of the most integrated and developed gas grids in the world with major transmission lines coming in from the North, East, and South. This gas grid, which currently includes 27 countries (EU27), has a total of 1.8 M km of pipelines of which about 155,000 km are high-pressure transmission pipelines. It also has 127 gas storage facilities with a total working volume of 75,000 Mm^3, and supplies more than 110 million customers (Eurogas, 2008).

Over the past decade there has been an increased interest to "green" existing natural gas grids. In Europe the EU-directive 2003/55/EC opened up the gas grid to carry other gases such as hythane, hydrogen, and biogas (Persson et al., 2006; NATURALHY, 2009). In Germany the target for 2020 is to substitute 20% of CNG (compressed natural gas) 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 et al., 2009). Similar directives and initiatives have been made for the natural gas grid running through the United States along the West Coast of North America (USA and Canada). In this regard, a Bioenergy Action Plan (CEC, 2006), has been brought into action by the Governor of California in his Executive Order on Biomass.

Gaseous fuels from renewable sources are largely produced from biomass sources including municipal solid and industrial wastes, agricultural residues, animal by-products, energy crops and wood-fuels. They can be produced by thermo–chemical (syngas) or anaerobic digestion processes (biogas) routes (Sims et al., 2008). Currently about 40% of the total gas produced from biomass in the world comes from aerobic digestion of organic wastes contained in landfills (Sims, 2007).

Biomethane (from biogas or syngas) can be combusted to produce electricity and/or heat. It can also be fed into natural gas grids or distributed to filling stations for use in dedicated or dual gas-fuelled vehicles, although these applications first require the biogas to be cleaned and upgraded. Gasification of biomass can be highly efficient, especially for electricity production in combined cycles. The gas produced (a mixture of CH4, H2 and CO) can be used to produce a range of liquid fuels using various processes or it can be used in gas engines or gas turbines (internal combustion engines) to produce heat and electricity.

8.2.3.1 Characteristics of RE with respect to integration into gas grids

There are several ways to integrate RE gases into gas grids (Fig. 8.18).

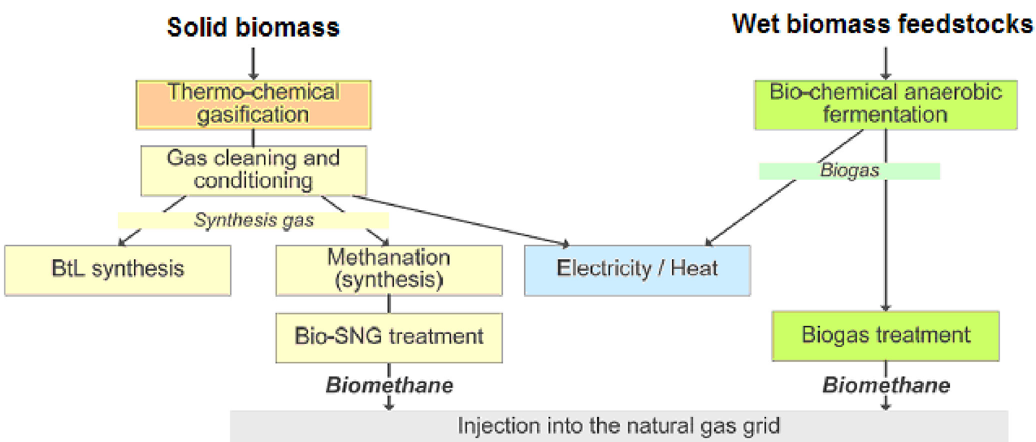


Figure 8.18: Injection into the natural gas grid of example gases produced from solid biomass or wet biomass feedstocks such as green crops or organic wastes (Müller-Langer et al., 2009).

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, and in some cases it has been transported via trucks to gas filling stations for gas vehicles (Hagen et al., 2001; Persson et al., 2006). However, the biogas business is growing rapidly and is currently being commercialized by large industrial players (Biogasmax, 2009). Several large gas companies around the world are now making plans on how to upgrade large quantities of biogas and feed them at the required quality into national/regional transmission gas pipelines (NationalGrid, 2009). If made feasible, it will offset some of the demand for natural gas in existing and future markets.

Coal or waste-derived syngas has been widely used for heating, cooking and power generation, especially in areas where natural gas is not available. Synthetic gases can also be produced via gasification or partial oxidation of biomass feedstock. They consist of a mixture of carbon monoxide, hydrogen, methane, higher hydrocarbon gases, and carbon dioxide. The heating value of syngas is less than that of methane. The existing natural gas grid would need modification to use syngas directly due to its different flow and combustion properties. Modifying the system would need to include replacing meters and burners.

Once the energy feedstock for the gas has been established, it is important to determine the end-use of the gas, for heating, in combined heat and power (CHP) systems, as raw material for the chemical industry, or as fuel for vehicles. The optimal choice will depend on the electricity system and energy mix in the region where the gas grid is being considered. National and regional electricity and gas transmission grids must complement each other, in the long-distance transport of energy. Similarly, distributed gas grids must compliment local heating and cooling networks.

Local gas urban distribution systems have mainly been dedicated to space and water heating purposes. However, over the last decade there has been significant progress in the development of fuel cell technology (such as proton exchange membrane designs) which opens new opportunities for small to medium sized distributed combined heat and power systems based on gas (DeValve and Olsommer, 2006; Zabalza et al., 2007).

Hydrogen is another gas that can be produced from RE, for example by water electrolysis or biogas reforming (Sherif et al., 2005; Balat, 2008). Future production and distribution of hydrogen will depend significantly on the interaction with existing electricity systems (Sherif et al., 2005; Yang, 2007).

In the short to medium term (prior to 2050) it is more likely that hydrogen will be produced in distributed systems via small-scale water electrolyzers or reformers (Riis et al., 2006). This would mainly require local hydrogen storage and distribution pipelines (Castello et al., 2005). In the long-term, large-scale production of hydrogen via water electrolysis using wind power or via large-scale biogas-to-hydrogen reforming plants is conceivable. Blending of hydrogen with natural gas (up to 20%) and transporting long-distances in existing or new natural gas grids could be an option when building a large-scale hydrogen economy (NATURALHY, 2009).

8.2.3.2 Features and structure of gas grids

A natural gas grid typically consists of three types of pipelines (Fig. 8.19):

- high pressure (40-70 bar) gas transmission pipelines;
- medium pressure (8-40 bar) gas distribution pipelines; and
- low pressure (< 8 bar) gas distribution pipelines.

High pressure transmission pipelines go between the production plant and the distribution network, passing over public land and third party properties. They are typically used for long-distance transport of gas from large, centralized production plants to large power plants, CHP plants, large industry users, or distribution networks. Transmission pipelines can be placed over-ground, underground, or on sub-sea floors, while distribution pipelines can be located over-ground, underground, or integrated into existing infrastructure to give common gas feeds.

Medium pressure distribution pipelines are more suitable for medium sized CHP systems or chemical production systems. Distribution pipelines, including mains feeders, station connections and valves, are usually contained on the property (generally owned by the customer) at the end-use point (EIGA, 2004). They are typically used to transport the gas to domestic or low consumption end-users. Similar low pressure gas distribution systems can be found in dedicated rural gas distribution systems.

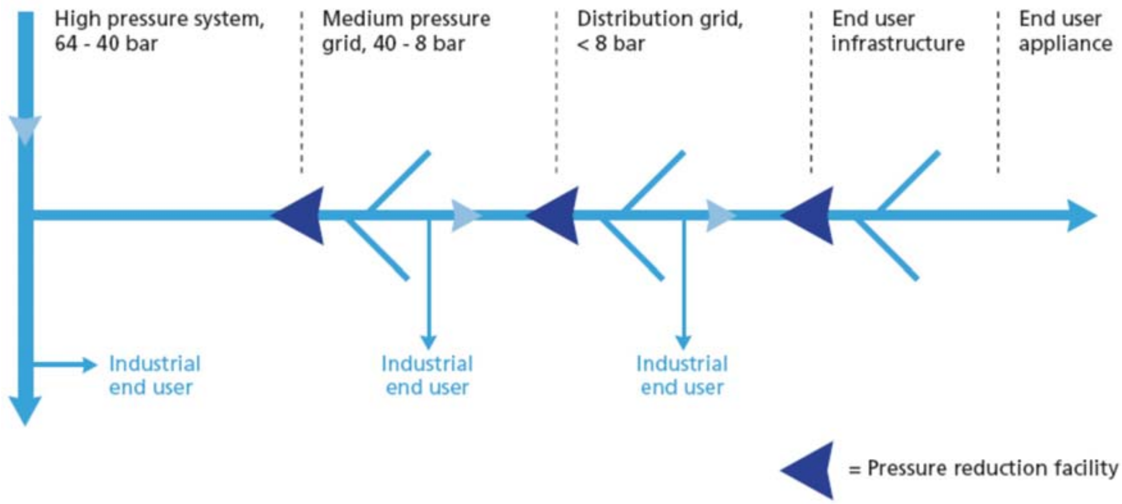


Figure 8.19: Typical natural gas grid with high, medium and low pressure pipe lines (NATURALHY, 2009).

The design of a gas transmission and distribution system depends on a variety of factors. The primary design criteria is to deliver adequate amounts of gas, when and where it is needed whilst meeting the user's required heating value, pressure, and purity. The gas flow rate depends on the scale and physical attributes of the gas (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. Either design choice could increase gas flow, the lowest cost solution depending on the situation. Larger diameter pipelines have a higher capital cost, but higher pressure requires a larger, and more costly compressor and more energy input. Often a compromise is best, where the pipeline diameter is kept relative small whilst "booster" compressors are located along the pipeline to keep the pressure (and flow rate) sufficiently high.

Long distance natural gas transmission pipelines that move large volumes of gas can operate at pressures up to 7-10 MPa and have diameters above 1 m. Such pipelines are commercially used in North America and Europe to deliver hydrogen to industrial users such as oil refineries. Hundreds of kilometres of hydrogen pipeline are currently in use. Using existing natural gas pipelines with hydrogen could work by blending hydrogen in with the natural gas, but pure hydrogen pipelines would require different steels to reduce leakage. Any conversion of a natural gas pipeline to pure hydrogen would have to be carefully examined for compatibility of materials.

Local gas distribution systems operate at lower pressures, and have smaller diameter pipelines. These widespread networks have smaller diameter pipelines (5-25 cm), and generally operate at lower pressures of 1-20 bar (0.1-2.0 MPa). One of the key issues is designing these pipeline systems to reach consumers with built-in redundancy so that gas could be supplied via more than one pathway. Natural gas distribution systems are often built around concentric rings, with feeder lines to individual users.

In order to balance supply and demand, gas storage also needs to be included at various levels in the system. The need for gas storage depends on how the gas is produced, the end use application, and how the gas can be integrated into the gas grid. In general, the size of gas storage is normally minimised to reduce costs and safety hazards. Most existing natural gas systems incorporate large-scale gas storage to account for seasonal demand. For example, in the United States, gas demand for residential heating peaks strongly in the winter. Underground gas reservoirs, as well as above ground gas storage, are part of the overall supply system.

The choice of material for the gas pipelines varies from system to system, depending on the basic 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 often used in distribution gas grids operating at lower temperatures (< ca. 100 C) and pressures (< ca. 10 bar). Metal based pipelines have the potential for internal and external corrosion problems (Castello et al., 2005).

8.2.3.3 Challenges caused by integration into gas grids

The payback time for integration of RE gases into gas grids is large due to high gas infrastructure investments. Payback time is also sensitive to the estimated long-term gas consumption and price. The price will be affected by future demand, taxation and carbon emission values which will be affected by the end-use for the gas. Large local and regional differences in existing infrastructure (and energy production and consumption) make planning on a national and regional level difficult.

Technical challenges relate to gas source, composition, and quality. The composition of biogas or syngas (and the calorific values) depends on the biomass source, gasification agent utilized in the process and reactor pressure. The heating value of syngas is about 10-15% of the heating value of natural gas. Landfill gas, produced by anaerobic fermentation, has concentrations of methane around 50%.

To produce syngas via the Fischer-Tropsch process, a distillation unit is required to separate the different fractions and an additional hydro-cracker may be necessary depending on operating conditions. Gas exiting the distillation column can be upgraded in order to recover the light hydrocarbons such as methane.

The removal of tar is another technical barrier for the advancement of biomass gasification, especially for power production. Pressurized IGCC (integrated gasification, combined-cycle) technologies can reduce tar concentrates but catalytic reforming followed by scrubbing, and hot gas clean up are still needed (Maniatis, 2001). Energy consumption of these processes is high, equivalent to 20% of the electricity output in some designs, making clean-up uneconomic. Recent R&D efforts are indicating areas of improvement (Nair, 2003; Wang, 2008; Arena et al., 2009).

Landfill gas typically has methane concentrations around 50% although advanced waste treatment technologies can produce biogas with 55-75% CH4. Methane can be concentrated in biogas up-grade systems to reach similar composition standards as natural gas then cleaned before being fed into the natural gas grids or used in vehicle engines. This process removes water, carbon dioxide and additional products from the gas stream. The cost of upgrading varies according to the scale of the facility. An equivalent 3-6% of the energy content of the gas is consumed in the form of electricity. Biogas must also be free from bacteria, pathogens and any other substances injurious to utility facilities, when considering its distribution in natural gas grids.

In order to increase the lower heating value of the biogas (before injection into the grid) most of the CO_2 must be removed (to reach below 5%). In some cases the biogas is blended with propane (LPG) in order to increase the heating value. Biogas upgrading plants have equipment to remove CO_2, hydrogen sulphide (H2S), trace gases such as halogenated hydrocarbons, siloxanes, oxygen, and nitrogen, and water vapour.

Gas clean-up is a critical step for biogas and syngas use. Only gases of a specified quality can be injected directly into existing natural gas grids (Table 8.4). Before gas is used, particulates and condensates must be removed. The main impurities are hydrogen sulphide, mercaptans, carbon dioxide, hydrocarbons, siloxanes, water vapour, nitrogen, oxygen and particulates.

Table 8.4: Composition and parameters of gas from different sources including landfill gas and biogas from anaerobic digestion (AD) (Persson 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	30–47	–	–
Nitrogen	vol-%	15	0,2	0,3	14
Nitrogen, variation	vol-%	5–40	–	–	-
Oxygen	vol-%	1	0	0	0
Oxygen, variation	vol-%	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	–

CO_2 removal can be achieved by absorption in water (water scrubbing) or organic solvents (such as polyethylene glycols or alkanol amines), pressure swing adsorption (PSA), separation membranes (gas-gas (dry) or gas-liquid (wet)), or cryogenic separation. There are different operational issues and disadvantages for each of these techniques:

- water scrubbing requires large amounts of water and plugging of the equipment due to organic growth can also be a problem;
- organic solvents require large amounts of energy for regenerating the solvents;
- PSA-processes requires dry gas;
- separation membranes requires handling of the methane in the permeate stream (which increases with high methane flow rates in the upgraded gas stream), and
- cryogenic separation requires removal of water vapour and H_2S prior to liquefaction of the CO_2.

The removal of H_2S from the biogas is also necessary to protect upstream equipment, as this is corrosive and must not affect metal pipelines, gas storage, and end use equipment. Micro-organisms can be used to reduce the level of sulphide 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 hydrogen sulphide and can be regenerated when saturated. Finally, siloxanes must also be removed as these organic silicon compounds can form deposits on pistons and cylinder heads that are extremely abrasive and hence cause damage to the internal components of the engine (Hagen et al., 2001; Persson et al., 2006).

In the case of hydrogen, it is important to purify and dry the gas before it is stored and distributed. Hydrogen for use in low temperature fuel cells normally has to be high purity (> 99.9995% H2 and <1 ppm CO). Industrial hydrogen with lower purity can be transported in dedicated hydrogen transmission and distribution pipelines, so long as there is no risk for build-up of water vapour or any other substances that can lead to internal corrosion. For hydrogen, regular checking for corrosion and material embrittlement of pipelines, sealings and storage equipment is important (EIGA, 2004).

There is no international gas standard for pipeline quality of biogas or hydrogen. However, Sweden and Germany have developed their own national standards (Tables 8.5 and 8.6).

Table 8.5: Swedish national standard for biomethane injection into natural gas grids (Persson et al., 2006).

PARAMETER	UNIT	DEMAND IN STANDARD
Lower Wobbe index	MJ/nm^3	43,9 – 47,3[1]
MON (motor octane number)	-	>130 (calculated according to ISO 15403)
Water dew point	°C	<t[2]-5
$CO_2+O_2+N_2$	vol-%	<5
O_2	vol-%	<1
Total sulphur	mg/nm^3	<23
NH_3	mg/nm^3	20

Table 8.6: German standard G260/G262 for injection of biogas into natural gas grids (Persson et al., 2006).

PARAMETER	UNIT	DEMAND IN STANDARD
Higher Wobbe index	MJ/nm^3	46,1 – 56,5[3] in H gas[4] grids 37,8 – 46,8[5] in L gas[6] grids
Relative density	-	0,55 – 0,75
Dust	-	Technically free
Water dew point	°C	<t[7]
CO_2	vol-%	<6
O_2	vol-%	<3 (in dry distribution grids)
S	mg/nm^3	<30

Once methane, hydrogen, syngas or a mixture have been upgraded, purified, dried, and brought up to the prescribed gas quality, it is ready to be injected into the gas distribution grid. Then the main operational challenge is to avoid leaks and regulate the pressure and flow rate so that it complies with the given pipeline specifications (which vary). Compressors, safety pressure relief systems and gas buffer storage must be in operation continuously in order to maintain the correct pressures and flow rates in the grid.

8.2.3.4 Options to facilitate the integration into gas grids

8.2.3.4.1 Technical options

Hydrogen can be injected but may require some upgrading of pipelines and other components used in existing natural gas grids (Huttenrauch and Muller-Syring, 2006). Pure hydrogen has a lower volumetric density compared to natural gas so pipelines will need higher pressures or larger diameters (around 3 times higher) in order to carry the same amount of energy per unit time as existing natural gas pipelines.

Dedicated distribution gas pipelines for biogas or hydrogen can operate at low pressures and volume flow rates, and with less stringent gas quality requirements. 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 quality of the gas in such gas distribution systems will depend significantly on the end-use.

Renewable-based gas systems are likely to require a significant gas storage capacity to account for variability and seasonality of supply. Since RE gases can be produced regionally and locally, gas storage is 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 of production and the end use. In small applications, the pipe can also be the store (Gardiner et al., 2008). Solutions with several complimentary end users of the gas can reduce the specific infrastructure cost (less pipeline and gas storage per customer) and the overall need for gas storage due to synergies.

Options for large-scale storage of biomethane, will be similar to those of natural gas, namely compressed gas storage (CNG) or liquefied gas storage (LNG). In distribution gas grids, small to medium-sized gas storage buffers tanks can be introduced into the system to balance local supply and demand. Methane can be collected and stored for a few days in inflatable gas bags made of rubber. In more up-scaled and industrialized biogas process plants, the 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). Distribution of biogas for vehicles can be achieved using trucks with LNG-storage.

Small-scale storage of hydrogen can be achieved in 50 l, 200 bar steel cylinders. Composite-based hydrogen gas cylinders that can withstand pressures up to 700 bar have been developed and are now being installed in demonstration 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 et al., 2005). However, for safety reasons, such storage will normally have to be situated far away from densely populated areas.

At the large-scale, hydrogen can be stored as a compressed gas or cryogenically in liquid form. However, this will come at a larger cost 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 is 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 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 must be evaluated on a case-by-case basis and safety needs attention.

8.2.3.4.2 Institutional options

System reliability, regulation, and standards for new gas carriers relate to RE gases. The reliability of gas grids, adequacy, and security of supply are influenced by a number of factors (McCarthy et al., 2006) such as:

- Is there enough gas supply to meet demand?
- Can the gas be delivered where and when it is needed?
- Is the gas system robust to disruptions due to natural or hostile acts?

Adequacy of supply can be influenced by the variability and seasonality of the RE resource. For example, biomass resources can be seasonal in their availability and quantities can vary from year to year. If hydrogen is made from variable RE sources the fluctuations of the primary energy supply must be considered. Designing a system to provide gas on demand may require storage of the primary feedstock (for example, baled straw or pelletized biomass) or storage of the produced energy carrier such as the high pressure storage of biomethane or hydrogen. Adequate capacity of the gas transmission and distribution systems can also be a concern.

The security of gas pipeline systems involves assuring a secure primary supply, and building robust networks that can withstand either natural or malicious physical events. In terms of security, biomethane or hydrogen networks are likely to be more secure than current transport-fuel networks because they can use many different primary sources rather than being wholly dependent on a single petroleum feedstock. Similarly, diverse local or regional RE resources for gas production offer more secure supply than imported natural gas. To enhance network security, gas pipeline networks often include some degree of redundancy (such as having multiple paths between supplier and user). Therefore 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 problems and corrective action.

Feed-in regulations can enable the introduction of biomethane into a natural gas grid in a similar way to RE feeding into an electricity grid. After clean-up, well-established safety regulations and standards for natural gas pipeline systems and end-use appliances should also be applied to biomethane.

Hydrogen is widely used in the chemical and petroleum refining industries and safety procedures and regulations 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 current lack of safety information on hydrogen components and systems used in a hydrogen fuel infrastructure, which poses a challenge to the commercialization of hydrogen energy technologies. Uniform international codes and standards are necessary to standardize technology and to gain the confidence of local, regional and national officials in the use of hydrogen and fuel cell technology, but these have not yet been developed.

Over the past few years, there have been concerted efforts in individual countries and internationally to develop consistent safety information on hydrogen and to harmonize existing codes and standards. For example, the United States Department of Energy maintains a variety of resources on hydrogen codes and standards, including a Hydrogen Safety Bibliographic Database and "Best Practices" website [TSU: Insert link as footnote or reference.]. Industry organizations such as the National Hydrogen Association and the US Fuel Cell Council provide information, and hold workshops on hydrogen safety. The International Energy Agency has a Hydrogen Implementing Agreement with a task focused on safety, codes and standards. The European Union through its HyWays project is working toward international standards. The International Partnership for a Hydrogen Economy addresses similar issues.

8.2.3.5 Benefits and costs of large scale penetration of RE into gas grids

Gas must be delivered at an acceptable cost to compete with other energy carriers for a particular application, such as heating or transport. The cost of a gas transmission pipeline exhibits strong economies of scale: to achieve low costs per unit of energy delivered, a high flow rate is desirable. The major cost of a pipeline is the pipe itself with installation costs, permits and rights of way and compressors also part of the overall investment.

Operational issues relating to gas grids are mainly influenced by gas pressure, quality, and safety and the operating cost of a gas grid is dependent on these parameters. In general, the handling costs associated with hydrogen storage will be higher than for other gases because of its volumetric energy density being about three times lower than methane.

A significant part of the extra investment cost for storing gas at high pressures is the extra cost for materials since thicker walls in pipelines and storage tanks are needed. From an operational point of view, increasing the gas pressure will result in increased running costs for the gas compressors, which also have to be serviced fairly frequently.

The cost of local distribution depends on the density of urban demand, with denser, more compact systems yielding a lower cost. When planning a new gas distribution network, it is common to plan for anticipated future expansion. If demand grows rapidly, increased pressure can provide additional gas flow. When additional new pipes must be installed, this is a costly option.

Since relatively large investments are required for building new gas grids, and their economic and environmental viability depends on the local RE and energy infrastructure (gas grids, electricity, heating/cooling networks), a clear policy on the end-use of the gas is required on a regional basis, particularly for RE-based gases, so that these energy carriers do not compete in the same markets.

Methane is already well-established for applications in heating, cooking, power generation, and transportation and cleaned biomethane is compatible with the existing natural gas system. Hence, there is a straightforward transition path for introducing RE into the existing supply chain using existing natural gas grids with the costs of transmission and distribution similar.

Biomethane should primarily be used in highly efficient industrial processes (with future possibilities for CCS (carbon dioxide capture and storage) and/or advanced CHP systems. Biomethane as a transport fuel will require additional systems and infrastructure. To avoid this, hydrogen should primarily be produced locally and used as a fuel for vehicles. In a larger hydrogen economy, the gas could be injected into the natural gas grid.

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. Biomethane is limited by available supplies but, in some regions such as the EU, could provide a large resource by 2020, thereby replacing significant amounts of imported gas (Fig. 8.20).

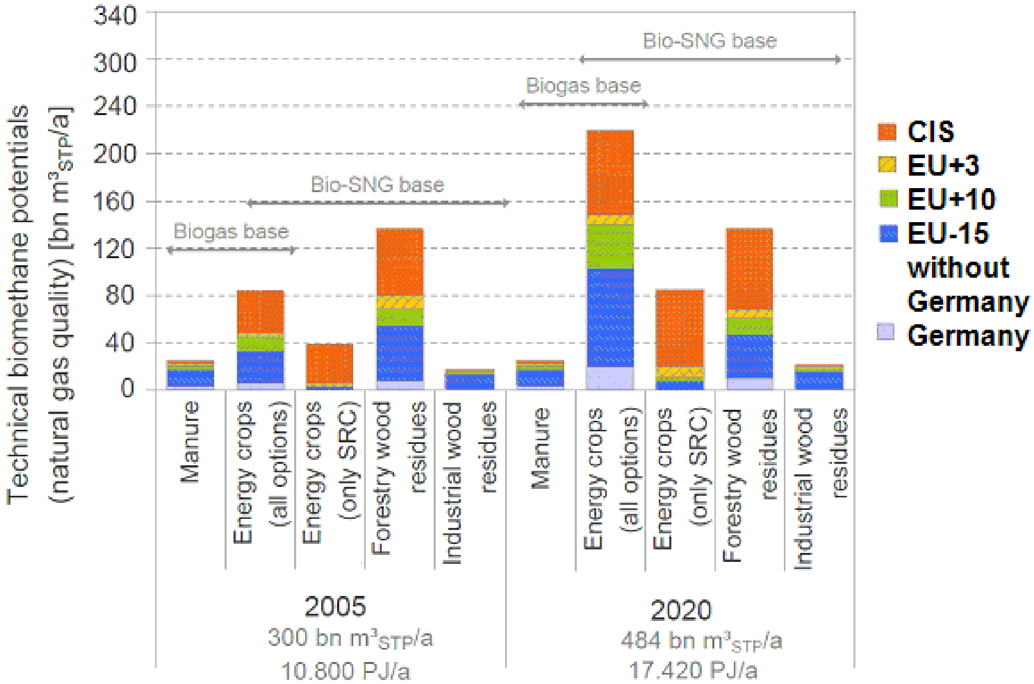


Figure 8.20: Technical potentials of biomethane at standard temperature and pressure (STP) in the EU-region in 2020 (Müller-Langer et al., 2009).

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. For remote biogas plants it may be better to use the methane on-site to avoid the need for transmission. Similar considerations apply to syngas produced from biomass and hydrogen. Blending syngas into the natural gas system could be feasible, but may require changes to gas distribution and end-use equipment which is tuned for natural gas. "Town gas" city networks that currently employ fossil fuel-derived syngas may be good markets for biomass derived syngas.

The potential RE resource base for hydrogen is greater than for biogas or biomass-derived syngas. The rate limiting factors are more likely to be the capital and time involved in building a new hydrogen infrastructure. If hydrogen is used as a transport fuel, it would require several hundred billion dollars spent over four decades to fully develop a suitable infrastructure for refueling vehicles (NRC, 2008). Incorporating variable RE sources could add to the cost because of the added need for storage.

8.2.4 Liquid fuels

8.2.4.1 Characteristics of RE with respect to integration

Renewable-based liquid fuels are basically produced from biomass sources. Currently most biofuels are produced from sugar, carbohydrate and vegetable oil food crops. Alcohol fuels can replace gasoline in spark ignition engines, and biodiesel can be used in compression ignition engines (see Chapter 2). Biogas can also be combusted directly in internal combustion engines similar to those suitable for running on compressed natural gas (cng). Solid biomass (ligno-cellulosic) sources can be converted to "second generation" liquid fuels by means of biological processes such as enzymatic hydrolysis or by thermo-chemical processes to produce synthesis gas (mainly CO + H2) followed by the established Fischer-Tropsch conversion to produce a range of synthetic liquid fuels suitable for aviation, marine and other applications

If biomass is going to play an important role in the future, the demand for large amounts of traditional solid biomass used for cooking and heating is likely to be replaced by more convenient liquid fuels such as dimethyl ether (DME) or ethanol gels (IEA, 2008b). Most of the projected demand for liquid biofuels is for transport, though industrial demand for liquid fuels could be as bio-lubricants and methanol (for use in petro-chemical industries).

The type of fuel storage and delivery system will vary depending on properties of the biofuel and compatibility with the existing petroleum fuel system. Biofuels can take advantage of existing infrastructure components already used by the petroleum-based fuels for storage, blending, distribution and dispensing. Most biofuels have fairly similar properties to gasoline and diesel and can be blended in any proportion with these petroleum fuels. Biofuels are compatible with the petroleum storage and delivery infrastructure (NAS, 2009). Transition barriers would be low as these fuels could be introduced without costly modifications to existing petroleum storage and delivery systems. Fuels could be transported from bio-refineries via truck, barge, ship or pipeline to terminals and from there trucked to retail outlets. Storage and distribution costs should be similar for petroleum-based fuels. Bio-refineries are generally smaller in capacity than oil refineries, and could be located in different geographic regions where the resource exists (for example, in the United States bio-refineries are in the Mid-west or South-east whereas oil refineries are concentrated on the coasts). At high levels of biofuel use, various fuel transport routes and delivery modes from refinery to terminal might be preferred.

Integration issues are challenging for bio-ethanol. Replacing a substantial proportion of gasoline with blends or neat fuel would require 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 (gasohol) cannot be easily stored, transported and delivered in the existing petroleum infrastructure because of the incompatibility of materials and water absorption by ethanol in the pipelines. Ethanol tanks need to be double-layered to avoid condensation occurring. 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.

8.2.4.2 Features and structure of liquid fuel supply systems

Ethanol is used today in several countries, as a transportation fuel additive or blend especially USA, France and Brazil or as a neat fuel (Brazil, Sweden). The structure of a biomass-to-liquid fuel system is well understood (Fig. 8.21).

Transportation of biomass feedstocks (sugar cane, corn grain, soybeans, straw etc.) to a biorefinery is by road over short distances or rail. Depending of the feedstock, transport costs vary considerably. For second generation biofuels, ligno-cellulosic materials can be transported at low energy densities to centralized biomass-processing plants. This bears a transport cost and can result in greenhouse-gas releases. In Brazil, ethanol is stored at the refineries where it is blended, but also at the production sites. Transport and storage costs play a critical role in the development of the cellulosic-ethanol industry (NAS, 2009). Due to the agricultural seasonality of many crops grown as feedstocks, storage of the biofuel produced is crucial to meet all-year-round demand.

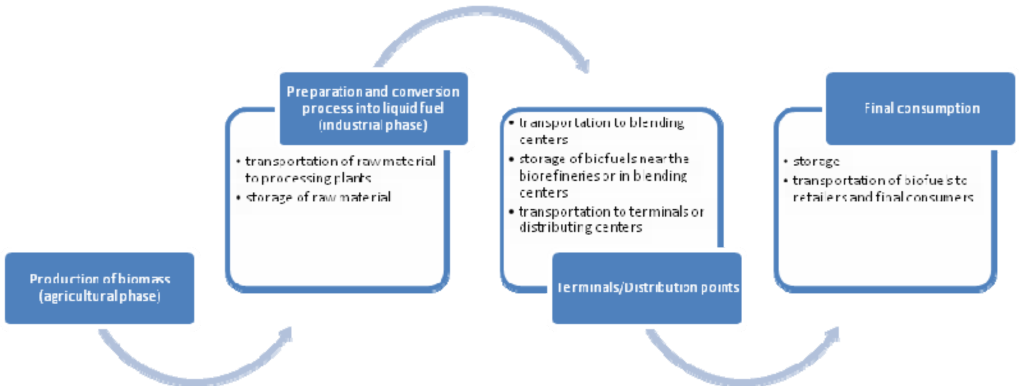


Figure 8.21: The typical biofuel process, blending and distribution system.

For short distances between plantations, bio-refineries, and blending centres, road transportation is usually the most cost effective transportation mode. In Brazil and USA ethanol has also been transported in pipelines also used to transport oil products. Pipelines can be cost effective when production is geographically concentrated otherwise road and rail transportation is preferable. Existing pipelines are not necessarily close to bio-refineries.

8.2.4.3 Challenges of integration

Decentralized biomass production, seasonality and agricultural locations not necessarily existing near oil refineries or distributing centres can impact on the logistics and storage of biofuels. Land use competition, fertilizer inputs and pesticide applications are concerns commonly raised.

Problems faced by sharing oil-product infrastructure (storage tanks, ducts, pipelines, trucks) with biofuels, especially ethanol, are water contamination and corrosion that can result in new materials needed to preserve the lifetime of equipment. Since oil pipelines are not air-tight, moisture can get in and increase the water content of the ethanol being transported. If the water content is above the technical specification, further distillation will be required. The affinity for water of ethanol and its solvent properties require use of a dedicated pipeline or significant cleanup of existing pipelines. Moisture does not represent a great problem with oil-products and can be easily drained off.

Covering ethanol storage vessels and where it is loaded can reduce condensation. “Sacrificial buffers” of neat ethanol can be sent down a pipeline ahead of the “primary” batches of an ethanol or gasohol shipment to absorb the moisture. The shot is then discarded or re-distilled. Ethanol can also dissolve and carry impurities that are present inside multi-product pipeline systems. These impurities are potentially harmful to internal combustion engines. Ethanol in high concentrations can also lead to accelerated stress corrosion cracking (SCC) in steel pipelines especially at weld joints or bends. These effects could be ameliorated by adding tank liners, selective post-weld heat treatment, and coating of internal critical zones (at pipeline weld points, for example) but these all increase costs. Ethanol may also degrade certain elastomers and polymers found in seals and valves in pipelines and terminals as well as some engines.

It would probably not be economic to retrofit existing multi-purpose pipelines. However, new pipelines could be constructed with ethanol-compatible polymers in valves, gaskets, and seals and be designed to minimize SCC (NAS, 2009). Phase separation during pipeline shipment can be avoided by first shipping hydrous ethanol which is then used directly by end-users or distilled, and then anhydrous ethanol which is later blended with gasoline.

8.2.4.4 Options to facilitate integration

8.2.4.4.1 Technical options

Biofuel technologies could evolve to produce biofuels that are more compatible with the existing petroleum infrastructure (Sims et al., 2008). Quality control procedures need to be implemented to ensure that biofuels meet all applicable product specifications (Hoekman & Kent, 2009). This will also facilitate the integration of biofuels into the liquid fuel supply system. Biodiesel is more prone to variation in its composition during storage due to the action of micro-organisms leading to rises in acidity and corrosion whereas ethanol is more stable.

As biofuels started to be traded internationally there was a need for international standards to be developed. Ethanol and biodiesel are in most cases blended into gasoline and diesel which in turn present regional differences depending on the types of predominant vehicle engines and local emission regulations. There are variations in current standards for regulating the quality of biodiesel on the market, though less variations for ethanol fuel since it is a single chemical compound whereas biodiesel varies with the feedstock. This translates to variations in the performance characteristics of each biofuel. A comparison was made of existing standards for biofuels (Anon. 2007) as used by the three main biofuel producing and consuming regions (US, Brazil and EU). The standards for biodiesel in Brazil and US reflect its main use as a blending component in conventional mineral diesel fuel, whilst the European biodiesel standard describes a product that can be used either as a stand-alone fuel or as a blending component. Bioethanol regulations differ with respect to the water content, but no technical specification constitutes an impediment to international trade.

8.2.4.4.2 Institutional aspects

Agencies in charge of regulating the oil-product markets could also include biofuels under their jurisdiction. Specifications and quality control at the production level as well as at the fuelling station or retail level could be put in place.

8.2.4.5 Benefits & costs of large scale penetration

The adaptation of existing transport, storage and dispensing equipment at fuelling stations is possible to handle biofuels and blends but would be expensive. To retrofit existing fuelling stations, underground storage-tank systems, pumps, and dispensers must be converted to be compatible with higher-ethanol blends. Issues relating to retrofitting of existing fuelling stations are similar to those associated with pipeline transport of ethanol and blends including phase separation, SCC, and contamination of incompatible materials found throughout conventional fuelling stations (NAS, 2009).

Ethanol terminals usually have one or more storage tanks ranging from 750,000 to 15 Ml capacity. New ethanol storage tanks cost around USD 0.15 /l [TSU: Needs to be presented in 2005 US$/l] capacity for small tanks to USD 0.05 /l[TSU: Needs to be presented in 2005 US$/l] for large tanks (Reynolds, 2000). It is sometimes possible to refurbish gasoline tanks for ethanol storage at lower costs. Collection terminals at ports and refineries often include equipment for blending ethanol (costing around $300,000[TSU: Needs to be presented in 2005 US$]), receiving shipments via rail, truck, boat or pipeline, and loading blended product onto road tankers. Upgrading an existing large gasoline terminal to handle ethanol blending can cost as much as USD 1 M[TSU: Needs to be presented in 2005 US$] (Reynolds, 2000).

In the US, the majority of ethanol is transported by rail as well as road tanker and barge (NCEP, 2007). At present no ethanol pipelines are in use. The choice of transportation mode used depends on the shipping distance, the volume of ethanol transported, and whether the product is accessible to water. Capacities and costs vary for ethanol storage and delivery equipment (Table 8.7). For reference, ethanol plants in the US produce 0.3-1.2 Ml /day; demand for 1 million cars using E10 would be about 0.4- 0.8 M l / day and terminals can hold 4-12 Ml.

Table 8.7: Equipment capacity for ethanol storage and long-distance transport (RFA, 2009).

	Capacity	**Cost (USD)** [TSU: Needs to be presented in 2005 US$]
Truck/trailer	25 m^3	USD 110,000 (USEPA, 2007) USD 125,000 (Reynolds, 2000)
Rail car	90 m^3	$90,000 (USEPA, 2007)
River barge	Several units @1,200 m^3/unit	USD 2M for 450,000l (USEPA, 2007)
Ocean barge/ship	3,000-30,000 m^3 (Reynolds, 2000)	
Pipeline (300 mm diameter)	12,000 m^3/day	USD 0.30-0.75 M/km
New terminal storage tank	3,000 m^3 6,000 m^3	USD 450,000 (Reynolds, 2000) USD 760,000 (Reynolds, 2000)
Retrofit gasoline storage tank	1,200 m^3	USD 20,000 (USEPA, 2007)
Blending equipment for terminal		USD 150,000-400,000 (Reynolds, 2000)
Total terminal refit	6,000 m^3 capacity	USD 1 M (Reynolds, 2000)
Ethanol production plant	230-950 m^3/day	
Ethanol terminal	600 m^3 (local)- 12,000 m^3 (regional)	

For short distances under 500 km carrying relatively small quantities of ethanol, road tanker transport is usually the most efficient and cost effective delivery mode (Reynolds, 2000). 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 method for medium and longer distance destinations incapable of receiving ethanol by ship (i.e. 500 to 3,000 km) (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 unloading and inspection, rail shipments require more effort at the terminal level. Unit trains for ethanol (containing up to 75 railcars) are not used at present but they have been proposed as an alternative to pipeline development.

Barges are used for long distance transport when ethanol production plants have access to rivers or sea. In the US, ethanol barges travel down the Mississippi river from Midwestern ethanol plants to ports at the Gulf where ethanol is stored in terminals and transferred to ships for transport to overseas or national coastal destination terminals for blending.

Ethanol and blends are not currently shipped via pipeline in the US, except in a few proprietary short distance industry pipelines (Yacoub et al., 2007). 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 logistic challenges remain. Moreover, current ethanol demand volumes are considered too low to justify the cost and operational challenges (Reynolds, 2000). An average US passenger car might use 4-8 l /day of ethanol assuming it ran on 100% ethanol. This implies that a geographically localized fleet of 2 million dedicated ethanol vehicles (or 20 million vehicles using E10) would be needed to justify building an ethanol pipeline delivering 12 Ml /day of ethanol.

Storage and transport are relatively small costs for ethanol on a USD /l[TSU: Needs to be presented in 2005 US$] basis. According to Reynolds (2000), when transporting larger ethanol shipments over greater distances, the economics for waterway (barge and ship) and rail prevail over truck transport. Estimates for ethanol shipping cost varies from USD 0.005 to 0.01 /l[TSU: Needs to be presented in 2005 US$] for ship and ocean barge; USD 0.02 to $0.08 /l[TSU: Needs to be presented in 2005 US$] for barge; $0.01 to $0.35 /l for rail, and $0.01 to $0.02 /l[TSU: Needs to be presented in 2005 US$] for trucks used only for short distance transport.

In Brazil, depending on the origin of the biofuel, the costs of transporting ethanol from the producing regions to export ports is around USD 0.038 – 0.07 /l[TSU: Needs to be presented in 2005 US$], which also includes storage costs at the terminal (Scandiffio, 2008). Ethanol pipelines are being planned to connect main rural producing centres to coastal export ports with an expected cost ranging from USD 0.021-0.031 /l[TSU: Needs to be presented in 2005 US$] (CGEE, 2007).

8.2.4.6 Case studies

8.2.4.6.1 Brazilian ethanol

In Brazil almost all new vehicles sold are flex-fuel and capable of using bioethanol blends ranging from E20 to E95. The distribution system, retailing, and production of flex-fuel engines works smoothly without being too expensive. All gasoline sold has a content of 20-23% of anhydrous ethanol (by volume) and is used in Otto engine vehciles. Since 2003 the fleet of hybrid motor vehicles that can run on any mixture of ethanol and gasoline (Fig 8.22). Over the last 30 years a country-wide storage and distribution system was implemented and ethanol is available in practically all fuelling stations throughout the country. Ethanol prices to the consumer have declined steadily in Brazil and are competitive with gasoline prices (Fig. 8.23).

Implementation of the ethanol programme followed the strategy as outlined below.

- Large incentives to producers 1979-85
  - Subsidies for new distilleries, retrofits, upgrades, etc.
  - Government purchased all production at a given price.
  - Production grows from 0.6 to 11.6 bn litres per year.
- Subsidies given to ethanol consumers; national fixed pricing; country-wide distribution.
- Blends with gasoline and introduction of 100% ethanol-fuelled cars.
- Incentives (tax cuts) for ethanol cars especially taxis and government fleets.

- Gasoline taxed heavily (1979-85).
- Private sugar industry became interested in increased productivity.
- In the 1990s
  - deregulation and
  - priority for sugar and sugar exports.
- Internal market grows and flex-fuel vehicles introduced in 2003.

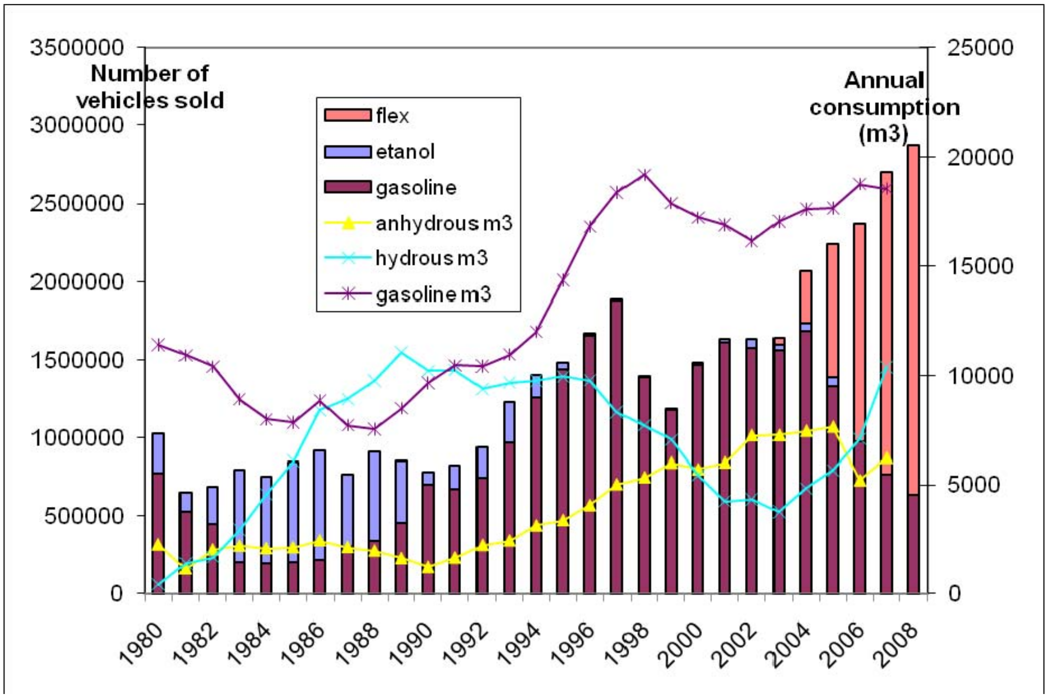


Figure 8.22: Light vehicle annual sales in Brazil and annual consumption of hydrous and anhydrous ethanol from 1980 to 2007 (ANFAVEA, 2009; MME, 2008).

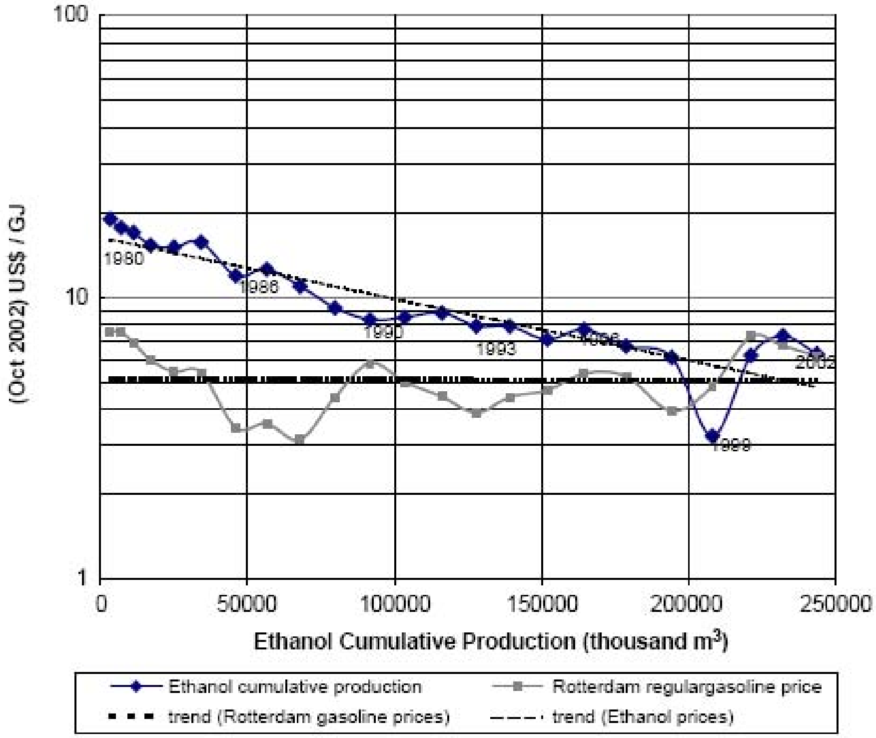


Figure 8.23: Global ethanol and gasoline prices (1980-2002) (Goldemberg et al., 2004a).

8.2.4.6.2 Biofuels for cooking in Malawi

The use of ethanol, DME and synthetic fuels (from Fischer Tropsh) for cooking are potential biofuel applications with wide global relevance. Combustion of biofuels for cooking will yield emissions of pollutants that are lower than emissions from cooking with solid fuels (Hutton et al., 2006; WHO, 2006; Goldemberg et al., 2004b). The example of sugar cane ethanol is well documented (Zuurbier and van de Vooren, 2008) with cost benefits of ethanol as a domestic fuel. A project is currently being carried in Madagascar and some experience has been gained in this field in Malawi.

The household sector in Malawi consumes 7.5 Mt of woody biomass which exceeds sustainable supplies by 3.7 Mt. The major cooking fuel is charcoal, followed by firewood, then electricity. Electricity is used for cooking in 11.5% of urban households and kerosene by 1.2%, mostly located in central and southern regions. Biomass fuels are the main source of cooking energy giving one of the highest health impact due to particulate emissions in the region. The World Health Organization (WHO, 2007) has evaluated the national burden of disease (that expresses the mortality and morbity of a given population) attributable to the risk from burning solid fuels in Malawi to be 5.2%.

Cost comparisons were carried out with other fuels based on current market prices, tax free prices and useful energy. When the most efficient ethanol stove is used (Fig. 8.24), ethanol is cheaper than LPG but it remains more expensive than charcoal or firewood which are indirectly subsidized. If taxes were to be lowered for ethanol while they are retained for kerosene, cooking with ethanol could become cheaper.

Figure 8.24: Clean Cook ethanol stove (source: Project Gaia, www.projectgaia.com)

An economic analysis conducted by WHO (Hutton et al., 2006) calculated that the returns from investing in household energy in 11 sub-regions (Table 8.8) would be positive if around 50% of the population in this African sub-region would switch from solid biomass to ethanol.

Table 8.8: Returns from investing in household energy assuming 50% of the African sub- region population cooking with solid biomass in 2005 switched to cooking with modern biofuels by 2015. [TSU: Needs to be presented in 2005 US$]

Cost items	Urban	Rural	Total
Annual value of health system cost savings (USD M)	10	16	26
Annual sickness time avoided (million work days)	26	43	69
Annual value of sickness time avoided (USD M)	55	91	146
Annual number of deaths averted (thousands)	39	57	96
Annual value of deaths averted (USD M)	552	810	1362
Annual value of patient cost savings (USD M)	0.8	1.3	2.1
Annual value of total health care cost savings (USD M)	11	18	29

(Hutton et al., 2006)

8.2.5 Autonomous systems

8.2.5.1 Characteristics

In order to be sustainable, an energy system needs to keep demand-supply balance in various time frames depending on the nature of the energy, as electricity, liquid fuel or gaseous fuel. When an electricity system is small, the difficulty of the demand-supply balance 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 as follows.

- *Autonomous power supply systems.* Different RE generators can meet a part of an autonomous power system demand to enhance the sustainability of the system in, for example, an off-grid island. Currently, it is usual that fossil fuel generators are also included for security, reliability and flexibility of system operation.
- *Autonomous 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 off-grid electrification. A stand-alone hybrid power supply can improve its performance with further integration of energy storage technologies to overcome RE variability.
- *Autonomous remote area fuel supply.* There is a possibility to produce gaseous or liquid fuels from biomass or hydrogen from electrolysis of RE electricity.
- *Autonomous buildings.* Urban houses and commercial buildings are less dependent on network energy supply through energy efficiency enhancement and utilization of RE technology. Rural buildings are more suitable to be autonomous due to the increased RE resource in the vicinity.
- *Specific utilization.* In areas where the provision of commercial energy is not economically available, RE is often 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

Autonomous power supply systems. An autonomous RE power system begins with the limited deployment of a single type of renewable power generation technology such as wind power that then develops into a comparatively large system. The capacity of the RE generation will increase with additional generation units of the same type, or, to enhance operational flexibility, by adding other types of RE generation technologies. 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.

Autonomous power supply in developing economies. The balance between cost and quality of the power supply is critical when deploying autonomous power supplies in developing economies. The simplest type of remote area power supply is a direct current power supply from stand-alone PV panels to meet lighting, radio and television demands of one or more households. For the increased cost of adding a battery, power becomes available during the night. Where a wind resource is available, a hybrid wind/solar system may have benefits.

Technically, energy storage technologies can enhance the performance of small-scale power supplies. However, it is usually an expensive technology so capital and operational costs should be carefully evaluated along with the desired reliability.

Autonomous remote area fuel supply. Fuel supply from biomass is either at the large-scale from agriculture, plantation forests, or food and fibre processing industries and used for vehicle fuel, electricity generation or heat for industry, or at the small-scale when social activities provide self-supply of fuel for domestic lighting, cooking, and heating in a household or small community.

8.2.5.2.1 Technical options

For an autonomous RE system, energy storage and energy utilization technologies are essential.

Energy storage technology. These are more important in autonomous energy systems than in electricity network integration due to the variability of several RE technologies and strict demand-supply balancing of small-scale systems. Among the energy storage technologies suitable for power systems (see section 8.2) the following are applicable to autonomous energy systems:

- pumped hydro storage (PHS) - small scale and including sea water pumped storage;
- compressed air energy storage (CAES);
- flywheel energy storage;
- batteries (lead acid, lithium ion, Redox flow etc.);
- ultra capacitor;
- hydrogen (from electrolysis).

Many 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 PHS + wind integration in Canary Islands (Bueno et al., 2004) and PV + wind + hydrogen storage in Greece (Ipsakis et al., 2008). Liquid fuels produced from biomass energy are comparatively easy to store in a tank or container as are gaseous fuels under pressure.

Energy utilization technology. Autonomous RE systems have the possibility to enhance value or performance when integrated with special energy utilization technologies such as a solar still; humidification-dehumidification; membrane distillation; reverse osmosis or electro-dialysis for desalination (Mathioulakis et al., 2007); water pumping consisting of PV arrays and an AC or DC motor (Delgado et al., 2007); solar-powered adsorption refrigerator (Lemmini et al., 2008); and multi-seeds oil press (Mpagalile et al., 2005).

Autonomous building. Zero-emission energy buildings generate as much energy as they consume through energy efficiency technologies and on-site power generation. The Net-Zero Energy Commercial Building Initiative of the USDOE aims to achieve marketable net-zero energy commercial buildings by 2025 (US DOE, 2008d). Low-rise buildings have good potential to become autonomous buildings through the combination of air-tight structure, high heat insulation, energy efficient air conditioning, lighting, ventilation and water heating, and high utilization of RE technologies (see section 8.2.5.7). New technologies such as building-integrated photovoltaics (BIPV) (Bloem et al., 2008), distributed energy systems (IEA, 2009b) and off-grid operation (Dalton et al., 2008) are available.

8.2.5.3 Benefits and costs of RE integration design

In autonomous energy systems the electricity generated should be competitive with traditional energy supplies but is usually more expensive than that from a network. Integration of different kinds of RE may improve the economy and reliability of the supply (Skretas et al., 2007). The viability of autonomous energy systems should be evaluated including the possible sustainability constraints of fossil fuel supply in the future, and current technology innovation and cost reduction (Nema et al., 2009).

For remote off-grid areas, it is widely recognized that electrification can contribute to rural development through increased productivity per person; enhancement of social and business services such as school, markets, drinking water and irrigation; decreases in poverty; and improvements in education, gender, health and environmental issues (Goldemberg, 2000; Johansson, 2005; Takada et al., 2006; Takada et al., 2007). Other than for electric power, the use of biomass-based autonomous remote-area energy supplies, where biomass resources or organic wastes are substantial, is inevitable to supply basic services of cooking, lighting and small-scale power generation.

In an autonomous building where more technologies can be integrated to provide various services, there is more room to enhance the performance of the system. In China, extensive solar energy utilization in the building industry brings great environmental and economic benefits using solar water heater systems (Li et al., 2007). Some Japanese house suppliers, such as Misawa Home Co. Ltd. sell net-zero energy houses which are 100% electrified but compensate for their power consumption by the power generated from PV on the roof. The urban autonomous building can increase its benefit with special functions such as having a green value, and non-interruptable power service (Shimizu Construction Co., Ltd.).

As in off-grid circumstances, autonomous energy to supply telecommunication facilities is economically feasible in both developed and developing countries. Solar water pumping is at the commercial stage in many developed countries, but is not often employed in developing countries where it is needed such as the Algerian Sahara (Bouzidi et al., 2009).

8.2.5.3.1 Constraints on the rate and extent of deployment

Technological constraints and planning tools. The role of RE technologies changes from a niche to a major role in autonomous energy systems. Hence the need for system integration will increase. For each type of autonomous system, appropriate planning methodologies should be established (Giatrakos et al., 2009). In the utilization of RE technologies, the variable feature and the variety of possible technologies makes planning more difficult. To instigate planning methodology, reliable databases should be established through the best use of research, demonstration, and commercial experiences that reflect various combinations of technologies, specific site conditions, and life styles (Amigun et al., 2008; Himri et al.,2008). In the case of biomass, sustainability criteria should be included (Igarashi, 2009).

Institutional and social constraints. Autonomous RE systems feature variations of technical specifications. Major constraints can arise from the difficulty of appropriate planning, designing, construction and maintenance which lead to capital and operational cost increases and disclaimers after a failure. In order to avoid these factors, establishing standardization and certification of the products, integrating planning tools, developing a database and capacity building are important (Kaldellis et al, 2009) together with local capacity building and market establishment for low capital and operation cost (Meah et al., 2008).

Implementation and operation. Generally, RE technology is capital-cost-intensive as compared with fossil fuel conversion technology that is operation-cost-intensive. Accordingly, even if an integrated system is economically feasible, there is a need for an appropriate financial scheme for the dissemination of autonomous RE systems to remove the barrier of large capital costs. Local operation and maintenance resources can be secured through appropriate capacity building programmes.

8.2.5.4 Case studies

8.2.5.4.1 Aegean Islands (Greece)

Generators of 848 MW and 800 MW produced 2750 GWh and 2200 GWh electricity in Crete and in the other Aegean Archipelago islands in 2005. The islands, excluding Crete, can be categorized by the size of their generation capacity: very small(<1 MW); small (>1 - <9MW); medium (>9 - <20MW); medium/large (>20 -<50MW) and large (>50MW). Generation capacity consists of steam turbines, combined-cycle units, diesel units, gas-turbine units and a limited amount of wind power.

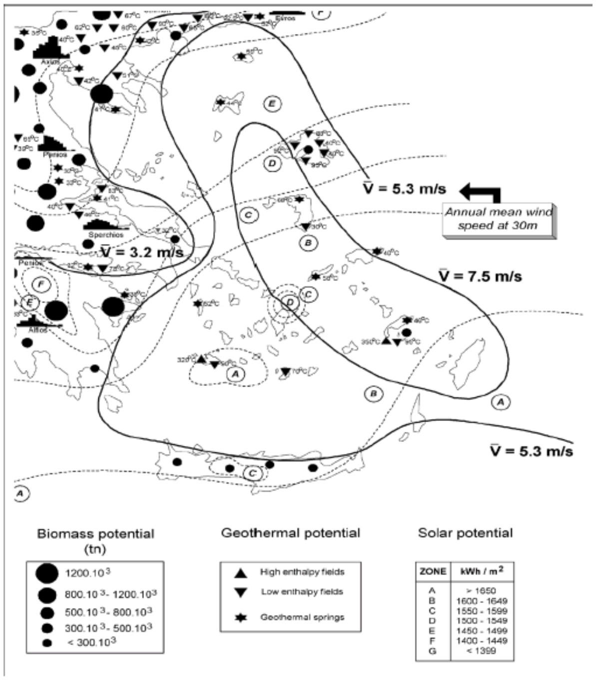


Figure 8.25: RE potential in the Aegean Archipelago region (Kaldellis et al., 2009).

In the area, despite abundant wind, solar and geothermal resources (Fig.8.25), and other RE resources available, the power demand increase has been met mainly by fossil fuel generation and only limited amounts of wind power. The limitation is due to the costs of RE and also to deterioration of the power supply quality due to the poor load-following capability of the autonomous power system without there being sufficient controllable generation resources.

In a small capacity, autonomous power system, the load and additional supply fluctuations from the variable RE generation can cause serious difficulties of the demand-supply balance control of the system. Due to these difficulties, the penetration of RE in the area is less than 15% energy production and 30% generating capacity. In order to overcome the obstacles for RE integration, there are alternatives being practiced. Improvements in the characteristics of generation units such as wind turbines and solar PV panels can decrease their generation when necessary to improve the demand-supply balance. Diversification of RE sources through the deployment of different kind of generation can reduce the total fluctuation of RE generation and the total cost including energy storage.

In the short term, energy storage systems can affect the short cycle, demand/supply balance control. In the future, after the costs of energy storage technologies have been reduced, they can take over the function to smooth the daily demand-supply balance. Energy storage technologies will be selected in accordance with the energy demand, charge-discharge capacity needed, and natural conditions of the site. A techno-economic comparison of energy storage systems was provided for very small, medium and large island autonomous power systems (Kaldellis et al., 2009)

Power system inter-connection by submarine cables is a promising technical option. Deployment depends on an economic evaluation of the option. The connection between islands and the main power system can change the situation totally (Hatziargyriou, 2007).

8.2.5.4.2 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. There are around 70 desalination plants using fossil fuel electricity and plans to construct more.

After several demonstration plants, the current most successful solar desalination system consists of a PV array, battery bank, and seawater reverse osmosis (PFSWRO). The system can produce 19 m^3/day of freshwater with a total dissolved solids content of less than 250 ppm and consuming as little as 2.6 kWh/m^3 of water (Contreras, 2007).

Small-scale desalination using PV is an attractive water supply option for small remote communities. The two major issues of the PFSWRO are an energy recovery device for small processes and integration of battery banks to enable the smooth operation for 24 hours. There is room to identify the balance between smooth operation and cost reduction through the optimized integration of battery banks. In the future, further integration of the desalination plant and rural electrification will be beneficial for water and energy supplies to remote rural communities, by adopting the best available process technology of desalination.

8.2.5.4.3 The Renewable Energy House, Brussels, Belgium.

The concept of refurbishing this 140 year-old office building and meeting facilities of approximately 2,800 m² aimed to reduce the annual energy consumption for heating, ventilation and air conditioning by 50% compared to a reference building, and to cover energy demand for heating and cooling by 100% RE sources. Key elements of the renewable heating and cooling system are two biomass wood pellet boilers (85 kW + 15 kW); 60 m² solar thermal collectors (30m² evacuated tube collectors, 30 m² flat plate collectors); four geothermal energy loops (115 m deep) exploited by a 24 kW ground source heat pump in winter and used as a 'cooling tower' by the thermally driven cooling machine in summer; and a thermally driven absorption cooling machine (35 kW cooling capacity at 7-12°C).

In winter, the heating system mainly relies on the biomass pellet boilers and the geothermal system. The solar system and the biomass boilers heat the same storage tank, while in winter the geothermal system operates on a separate circuit. The solar contribution in winter is low but when available, contributes to the reduction of pellet consumption. The core of the cooling system for summer operation is the thermally-driven absorption cooling machine, which is powered from relatively low temperature solar heat (85°C) and a small amount of electrical power for the control and pumping circuits (Fig. 8.26). Since solar radiation and cooling demands coincide, the solar thermal system provides most of the heat required for cooling. The solar system is backed up on cloudy days by the biomass boiler. The geothermal borehole loops absorb the excess low-grade excess heat from the cooling machine, thus serving as a seasonal heat storage system which is used during winter operation (EREC, 2008).

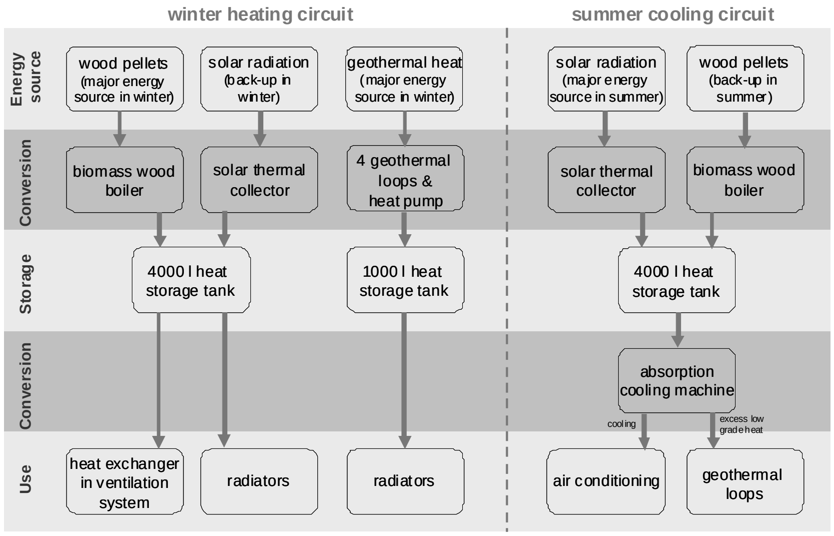


Figure 8.26: Renewable heating and cooling system in an autonomus office building (EREC, 2008).

8.2.5.4.4 Wind/hydrogen demonstration system at Utsira, Norway

An autonomous wind/hydrogen energy demonstration system located on the island of Utsira, Norway was officially launched by Norsk Hydro (now StatoilHydro) and Enercon in July 2004. The main components of the installed system are a wind turbine (rated 600 kW, but cut-off set at 300 kW), water electrolyzer for hydrogen (10 Nm^3/h), hydrogen gas storage (2400 Nm^3 at 200 bar), hydrogen engine (55 kW), and a PEM fuel cell (10 kW) (Nakken et al., 2006). The system gives 2-3 days of full energy autonomy for 10 households on the island, and is the first of its kind in the world.

Operational experience and data has been collected from the plant for the past 4-5 years. 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 LHV). The efficiency of the hydrogen engine generator system was about 25% at nominal operating conditions. Hence, the overall efficiency of the hydrogen storage system (AC-electricity to hydrogen to AC-electricity) was only about 10%. If the hydrogen engine had been replaced by a new 50 kW PEM fuel cell (the 10 kW fuel cell at Utsira did not operate properly), the overall hydrogen storage efficiency would be likely to increase to about 16-18%. If the electrolyzer had been replaced by a more efficient unit (e.g. a PEM electrolyzer or a more advanced alkaline electrolyzer), the overall efficiency would have increased to about 20%. Overall, the low hydrogen storage efficiency illustrates the challenge with up-scaled hydrogen energy storage systems.

Nevertheless, the system at Utsira has demonstrated that it is possible to supply remote area communities with wind power using hydrogen as the energy storage medium. The project has also demonstrated that further technical improvements and cost reductions need to be made before wind/hydrogen-systems can compete with existing commercial solutions, for example wind/diesel hybrid power systems. Several areas for improvements have been identified. In general, the overall wind energy utilization must be increased (at Utsira only 20% of the wind energy is 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 should also be used to meet local heating demands, both at the plant and in the households. In addition, the hydrogen could be utilized (and possibly the oxygen) in other local applications, e.g. as a fuel for local light-weight vehicles and boats.

More compact hydrogen storage systems and more robust and less costly fuel cell systems 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 will enable a smooth integration of renewables to occur with the conventional energy systems. Multi-benefits for the energy end-users should be the ultimate aim.

In the IPCC 4th Assessment Report -Mitigation (IPCC, 2007) the economic potentials for each of the sectors were analysed in detail: transport (chapter 5); residential and commercial buildings (chapter 6); industry (chapter 7); and agriculture (chapter 8) linked with forestry (chapter 9) (Fig. 8.27). 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). Around half of the economic potential from energy supply in 2030, assuming carbon prices up to USD 100 /tCO_2-eq[TSU: Needs to be presented in 2005 US$/t$CO_2$-eq], was as a result of the share of renewable electricity in the generation mix reaching between 26% and 34% of the total from the present 18%. In the transport sector, fuel savings in all vehicle types accounted for most of the mitigation potential in 2030, with biofuels projected to increase from a 3% share of total transport fuel use in the baseline to 5-10%. For a carbon price range between USD 20 and 100 /tCO_2-eq[TSU: Needs to be presented in 2005 US$], a mitigation potential of 0.6 – 1.0 GtCO_2-eq would result, subject to future oil prices and the success of technologies to utilise cellulosic biomass (IEA, 2008a). In the building sector, most of the potential came from savings in heating fuel and electricity due to improved efficiency, with 0.1 – 0.3 GtCO_2-eq coming from solar installations. RE provided limited potential in the industry sector, other than from increased biomass use in the food processing and pulp and paper industries, concentrating solar thermal systems to provide process heat, and solar drying. The agriculture, forestry and waste sectors supplied the biomass used across all sectors including their own, but used little other RE themselves.

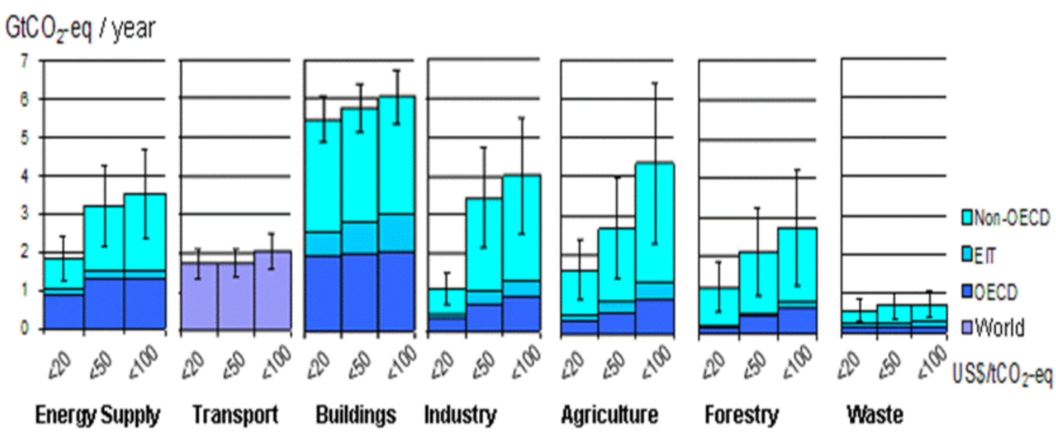


Figure 8.27: Estimated economic, mitigation potential ranges for energy supply and end-use sectors, above the assumed baseline for different regions as a function of the carbon price in 2030 and based on end-use allocations of emissions including from electricity generation.

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 of the transport, buildings, industry and primary production sectors, 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 is vastly different in mega-cities with commercial high-rise buildings and apartments than in small towns of mainly individual dwellings; in wealthy suburbs than in poor urban areas; in established districts than in new sub-divisions; and in farming and fishing communities in OECD countries than in small village settlements in developing countries that have limited access to energy services.

8.3.1 Transport

8.3.1.1 Sector status and strategies

Significant fractions of global primary energy use (19%), GHG emissions (27%)[6], and air pollutant emissions (5-70%, depending on the pollutant and region) come from the direct combustion of fossil fuels for transportation (IEA, 2009a). Although improved energy efficiency in buildings or low-carbon electricity generation might offer lower cost ways of reducing carbon emissions in the near term (McKinsey, 2008; IEA, 2008b; Lutsey, 2008), improving the efficiency of, and decarbonising, the transport sector will be critically important to achieving long-term, deep cuts in carbon emissions required for climate stabilization (IEA, 2009e).

Energy supply security is also a serious concern for the transport sector. Demand for mobility is growing rapidly with the number of vehicles projected to triple by 2050 (IEA, 2008e). About 97% of transport fuels currently come from petroleum, a large fraction of which is imported. To meet future goals for energy supply security and GHG reduction, oil use will need to be radically reduced over a period of several decades. Light duty vehicles (LDVs) account for over half of transport energy use worldwide, with heavy duty vehicles (HDVs) 24%, aviation 11%, shipping 10%, and rail 3% (IEA, 2009e).

There are three approaches to reducing transport-related energy use and emissions.

- Reduction of travel demand or vehicle miles travelled. This might be 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 our cities with denser population so that people do not have to travel as far to work, shop and socialize (Johnston, 2007; Pew Climate Center, 2007).

- Shifting to more efficient modes of transport, such as from LDVs to mass transit (bus or rail), or from trucks to rail or ships. 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, the lowest GHG intensity mode on a tonne-km basis, is shipping, followed by rail, and then, by at least an order of magnitude greater, LDVs and air (IEA, 2009e). Further reductions could be achieved by adopting more energy efficient vehicles including reducing vehicle weight, streamlining, and improved deigns of engines, transmissions and drive trains, including hybridization. These can often pay for themselves relatively quickly. The introduction of battery and fuel cell electric vehicles could potentially pay for themselves over the vehicle lifetime, given sufficient vehicle cost reductions in the longer term depending on prevailing carbon and liquid fossil fuel prices. Consumer acceptance of

[6] 27% in 2005 on a well-to-wheel basis, (IEA, 2008e)

high efficiency drive trains and lighter cars will depend on a host of factors including fuel price, advancements in materials and safety. In the heavy duty freight movement sub-sector and in aviation, there is also promise of significant efficiency improvements.

- Replacing petroleum-based fuels with low or zero carbon alternative 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. Alternative fuels have had limited success thus far in most countries – the total number of alternative-fuelled vehicles is currently less than 1% of the global fleet. Exceptions include Brazil, where around 50% of transport fuel (by energy content) is ethanol derived from sugar cane, Sweden, where imported ethanol is being encouraged, India, Pakistan and Argentina, where compressed natural gas (CNG) is widely used, and the United States where ethanol derived from corn is currently blended with gasoline up to 10% by volume in some regions, and accounts for 3% of US transport energy use (USDOE, 2009). However, the context for alternative fuels is rapidly changing and a host of policy initiatives in Europe, North America and Asia are driving toward lower carbon fuels and zero-emission vehicles.

Recent scenario studies (IEA, 2008e; NRC, 2008; Yang et al., 2009) strongly suggest that a combination of approaches (reduction in vehicle miles travelled (VMT), higher efficiency and low carbon fuels) will be needed to accomplish 50-80% reductions in GHG emissions by 2050 (compared to current rates) while meeting growing demand and diversifying primary supply. In IEA (2008e) scenarios, vehicles become about twice as efficient by 2050, and in the 50% GHG reduction by 2050 "Blue Map" scenario (Fig. 8.28), conventional gasoline automobiles are largely replaced by battery electric vehicles (EVs) or hydrogen fuel cell vehicles (HFCVs) while biofuels are used extensively in the heavy duty, air and marine sections. GHG reductions come from a mix of improved efficiency (which accounts for at least half of the reductions) and alternative fuels. In these scenarios, biofuels, electricity and hydrogen make up 25-50% of the total transport fuel use in 2050.

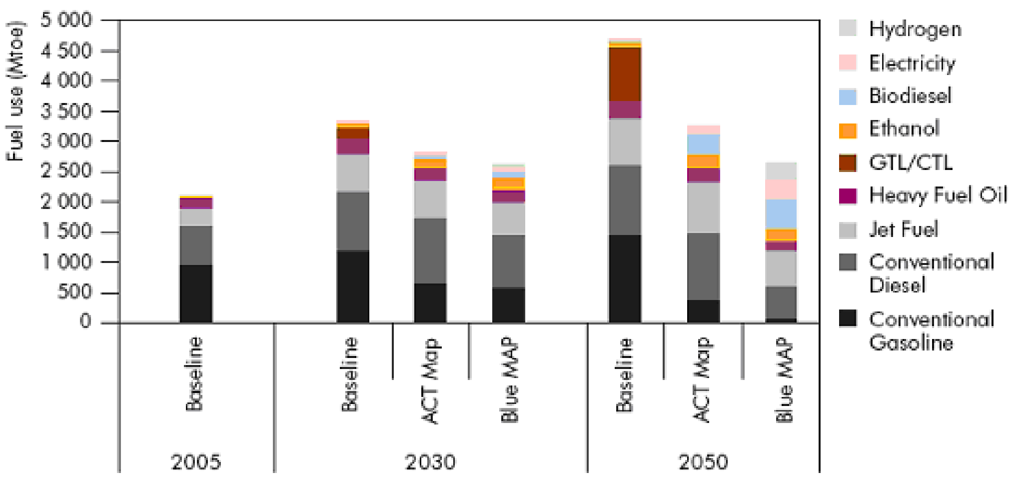
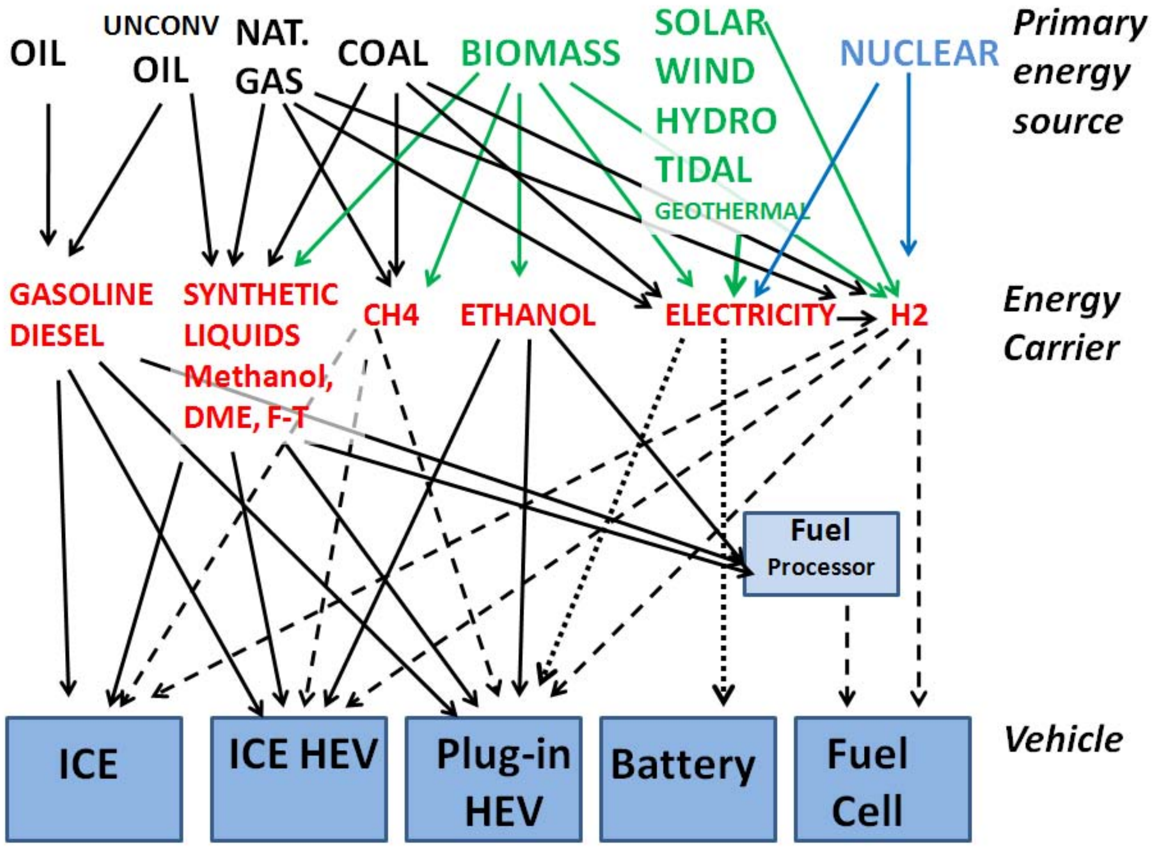


Figure 8.28: Projected mix of global transport fuels in 2005, 2030 and 2050 according to IEA scenarios (Source: IEA, 2008e).

The potential exists to make a transition to the transport sector using large quantities of RE. In this section, renewable fuel and vehicle pathways are reviewed within the larger context of future vehicles and fuels, and transition issues and future trends discussed.

8.3.1.2 Renewable fuels and light-duty vehicle pathways

A variety of more efficient vehicles, and alternative fuels, including liquified petroleum gas (LPG), CNG, ethanol, methanol, electricity and hydrogen have been proposed to address climate change and energy security concerns. Possible fuel/vehicle pathways begin with the primary energy source, conversion to an energy carrier (or fuel), and use in a vehicle "engine" (Fig. 8.29).



F-T= Fischer-Tropsch process. HEV=hybrid electric vehicle.

Figure 8.29: Possible fuel/vehicle pathways, from primary energy sources (top), through energy carrying fuels (red) to vehicle options (bottom) showing renewable resources (green).

Primary energy use and GHG emissions vary with different fuel/vehicle options. Well-to-wheels (WTW) analyses (Wang et al., 2008; CONCAWE, 2007; Bandivekar et al., 2009; Maclean, 2004) account for all the emissions 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 (see Chapter 2). Air quality and energy security are other important considerations for future transport pathways and sustainability issues such as land-use, water and materials requirements may impose constraints. New vehicle technologies could require large amounts of scarce or hard to access mineral resources: current automotive fuel cells require platinum and advanced, lightweight batteries require lithium. Composite sustainability indices for fuels have been developed (Zah et al., 2008) that include a variety of attributes in addition to GHG emissions.

8.3.1.2.1 Status and prospects - vehicle technology

A variety of alternative vehicle drive trains could use renewable-based fuels. These include advanced internal combustion engine (ICE) vehicles using spark-ignition or compression-ignition engines, EVs, HEVs, plug-in hybrids (PHEVs) and HFCVs. Several recent studies have assessed the performance, technical status and cost of different vehicle types (Heywood, 2000; Kromer and Heywood, 2007; Bandivedakar et al., 2008; CONCAWE, 2007; Plotkin and Singh, 2009; IEA, 2009e). A series of simulations of current and future (up to 2035) vehicle technologies estimated vehicle fuel economy and cost (Table 8.9).

Table 8.9: Attributes of light duty vehicles out to 2035 (Bandivadekar et al., 2008; Kromer and Heywood, 2007).

Vehicle type	**Status**	**Projected average fuel consumption in 2035** (litres gasoline equivalent / 100 km)	**Added retail price (from mass production) compared with 2035 gasoline ICE models** (USD 2007)	**Fuel options**	**Range** (km)	**Refuelling time**	**Infrastructure availability/ compatibility**
Spark ignition – ICE gasoline	Commercial	8.9 (2008) 5.5 (2035)	USD 2000 more than current model	Gasoline	500+	2-4 minutes	Baseline
	Commercial	Similar to gasoline (CONCAWE, 2009)	100-200 (EFC, 2009)	Ethanol (E85)	500+	2-4 minutes	Regional ethanol availability; blending possible with gasoline; separate storage and dispenser required.
	Commercial, in limited production	Similar to gasoline (CONCAWE, 2009)	1000-2000	Methane (CNG) or propane (LPG)	400	5 minutes	Available in some urban areas; bio-methane could be blended with CNG.
Spark ignition- ICE hybrid	Commercial	3.1	2500	Gasoline or liquid biofuels	700+	2-4 minutes	Same as baseline
Compression ignition- ICE diesel	Commercial	4.7	1700	Diesel biodiesel, or synthetic diesel	500+	2-4 minutes	Biodiesel widely available, though less than gasoline.
Spark ignition- ICE plug-in hybrid	Demonstration (commercial planned for 2010-2011).	2.2	5900	Gasoline (and/or liquid biofuels) and electricity. Battery cost, performance, safety issues.	500+ 50 on electric only	2-4 minutes for gasoline; 2-6 hours for battery charging	Common for gasoline; home charging possible; very limited public charging available to date.
Battery electric (EV)	Demonstration (limited commercial use as local fleet vehicles + 2-wheelers)	1.7	14,400	Electricity from a variety of RE sources. Battery cost, performance, safety issues.	200-300	2-6 hours for domestic charging; 10-15 minutes for public fast charge	Home charging possible; very limited public charging available to date.
Fuel cell –	Demonstration	2.3	5300	High purity hydrogen from	500+	3-5 minutes	Limited hydrogen fuelling networks in

hydrogen	(commercial around 2015-2020)			a variety of sources (from natural gas, biomass, electricity). Lifetime and cost; H_2 infrastructure; storage; safety issues.			Europe, Iceland and N. America with 100 stations worldwide. H_2 storage requirements and volumes will be a challenge at the service station forecourt.

Two-wheel motor-bikes and scooters are large and fast-growing vehicle segments in the developing world. They have significant potential for fuel efficiency improvement and GHG reduction through greater electrification. Electrification of bikes and scooters in China is already taking place on a large scale with 20 million annual sales in 2007 (ICCT, 2009).

Many ICE vehicles already use liquid biofuels whereas only a small fraction of ICE vehicles have been adapted to run on gaseous biofuels or renewable hydrogen. Hybrid electric drive trains have been introduced for gasoline vehicles and could be easily adapted in the near term to use biofuels. Most of the existing fleet of gasoline and diesel ICE vehicles can only operate on relatively low concentration blends of biofuels up to 10% by volume of ethanol or 5% biodiesel, (although Brazil gasoline is blended with up to 25% ethanol) to avoid adverse effects on the vehicle operation.

Plug-in hybrid vehicles are still under development, spurred by recent policy initiatives worldwide, and several companies have announced plans to commercialize them within the next few years. Costs and lifetime of present battery technology are the main barriers to both plug-in hybrids and battery electric cars. Hydrogen fuel cell vehicles have been demonstrated, but are not likely to be commercialized until at least 2015-2020 due to barriers of fuel cell durability, cost, and on-board hydrogen storage. The timing for commercializing each technology is discussed further under transition issues (8.3.1.4).

8.3.1.2.2 Status and prospects -liquid biofuels

Biomass can be converted to liquid fuels using many different routes (see section 8.2.4 and Chapter 2). “First generation” processes are commercially available today and advanced processes aiming to convert non-food cellulosic materials and algae are under development (Fig. 8.30).

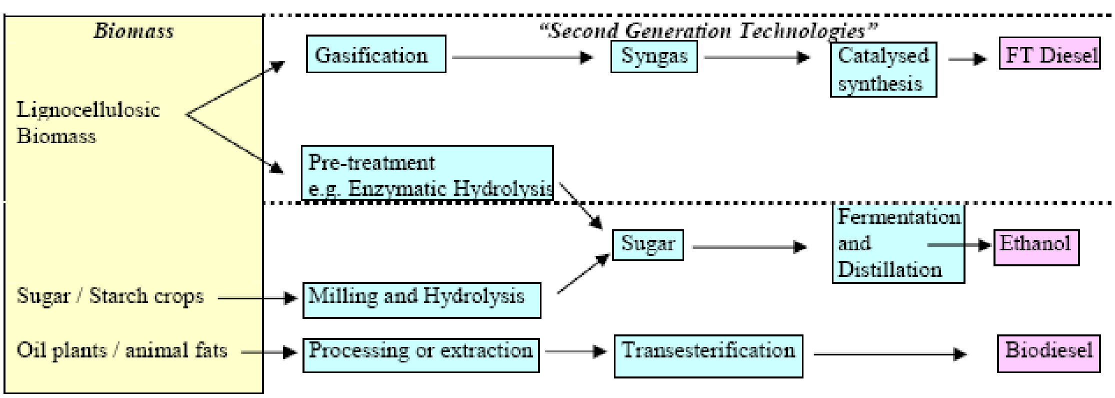


Figure 8.30: Examples of liquid biofuel production pathways (Doornbosch and Steenblik, 2007).

Conversion of biomass to biofuels entails energy losses. The IEA (2008e) estimated up to 29 EJ of advanced liquid biofuels could be produced each year by 2050, accounting for about 25% of the total transport fuel supply. Conversely, CONCAWE (2007), estimated a lower penetration displacing less than 15% of road fuels. Other routes such as electricity or hydrogen production can displace more petroleum (CONCAWE, 2007).

Incremental costs of many biofuels are higher than gasoline and diesel, Depending on the biofuel pathway, 2nd generation biofuels would add USD 0.15 to 0.45 /l[TSU: Needs to be presented in 2005 US$] gasoline equivalent assuming the crude oil price to be USD 60/bbl[TSU: Needs to be presented in 2005 US$] (IEA, 2009e) and USD -0.10 to +0.25 cents if oil was at USD120/bbl[TSU: Needs to be presented in 2005 US$].

8.3.1.2.3 Status and prospects – hydrogen/fuel cells

Hydrogen is a versatile energy carrier that can be produced by high temperature chemical processing of hydrocarbons (such as fossil fuels or biomass) or via electrolysis using electricity to "split" water into hydrogen and oxygen (Fig. 8.31). Today, industrial grade hydrogen (< 99.99% pure) is produced in large quantities primarily from fossil fuels for oil refining and chemical applications (National Hydrogen Association, 2009). Hydrogen can be produced regionally in industrial plants or locally at vehicle refuelling stations or buildings. Well-to-wheels GHG emissions vary for different fuel/vehicle pathways but both RE and hydrogen pathways offer reductions (Table 8.10).

In the United States a mix of low carbon resources including natural gas, coal (with carbon sequestration), biomass and wind power could supply ample hydrogen for vehicles (NRC, 2008). The primary resources required to provide sufficient fuel for 100 million passenger vehicles from various gasoline and hydrogen pathways have been assessed (Fig. 8.32). For example, enough hydrogen could be produced from wind-powered electrolysis to fuel 100 million fuel cell cars in the United States, using about 13% of the technically available wind resource. However, the combined inefficiencies of making the hydrogen via electrolysis then converting it back into electricity on a vehicle via a fuel cell lose more than half of the original RE inputs. Electricity is used more efficiently in a battery-electric or plug-in hybrid vehicle.

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 extremely pure (> 99.999%) and must generally be compressed to 35 to 70 MPa before dispensing. Hydrogen at the pump might cost USD 3 - 4 /kg[7][TSU: Needs to be presented in 2005 US$] excluding taxes with higher costs near-term (NRC, 2008). Given the potential higher economy of fuel cell vehicles, the fuel cost per kilometre could become competitive with gasoline vehicles in the future.

Hydrogen distribution to consumers will require development of a new storage and delivery infrastructure (see section 8.3.1.4).

[7] 1 kilogram of hydrogen has a similar energy content to 1 US gallon or 3.78 litres of gasoline

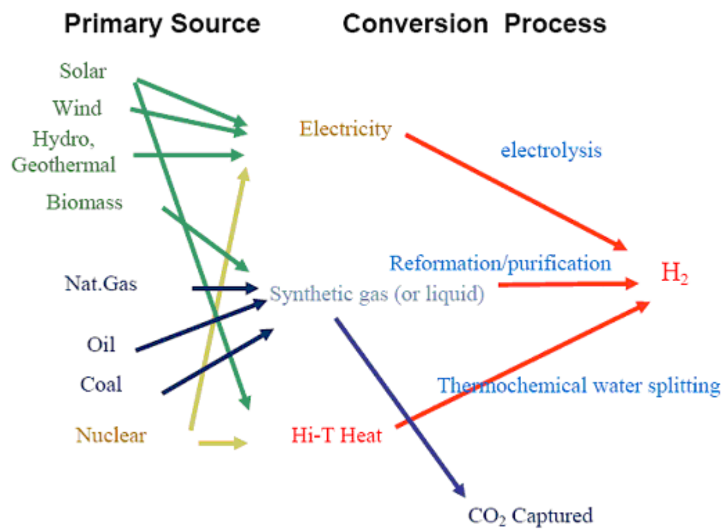


Figure 8.31: Some possible hydrogen production pathways.

Table 8.10: Well-to-wheel greenhouse gas emissions for light duty vehicles in 2010 using fossil fuels and biomass as feedstocks (CONCAWE, 2007).

	GHG emissions (gCO_2/km)	**GHG emissions relative to current gasoline ICE vehicles**
Fossil-derived fuels		
Conventional - gasoline SI-ICE vehicle	160- 170	-
Hybrid - gasoline SI / electric vehicle	125-150	-12 to -22%
Conventional - diesel CI-ICE vehicle	145-155	-9%
Hybrid - diesel CI / electric vehicle	110-140	-18% to -31%
Coal-to-liquids via F-T /CI-ICE vehicle	325 to 380	+103 to 124%
Coal-to-H_2 /fuel cell vehicle	250 to 350	+56 to +106%
CNG SI-ICE vehicle	120-140	-18% to -25%
Gas-to-liquids via F-T / CI-ICE vehicle	160 - 175	0 to 3%
Gas-to-H_2 /fuel cell vehicle	70-90	-47 to -56%
H_2 from gasified biomass /fuel cell vehicle	10-15	-91% to -94%
H_2 from RE electrolysis /fuel cell vehicle	0	-100%
Biofuels		
Ethanol - sugar cane / SI-ICE vehicle	20 - 39	-83 to -88%
Ethanol –wood / SI-ICE vehicle	35 – 60	-65% to -78%
Ethanol – straw / SI-ICE vehicle	15-65	-62% to -91%
Bio-diesel /CI-ICE vehicle	25-125	-27% to -84%
Biogas - dry animal manure /SI-ICE vehicle	0 - 5	-97% to -100%
Biogas - liquid manure /SI-ICE vehicle	-175 - -125	-174% to -206%
Biogas – municipal solid waste /SI-ICE veh.	25-35	-79% to -84%
DME - waste wood / CI-ICE vehicle	0 - 10	-94% to -100%
DME - farmed wood /CI-ICE vehicle	10-20	-99% to -94%
F-T diesel - waste wood /CI_ICEV	0 - 10	-94% to -100%
F-T diesel - farmed wood CI_ICEV	10-20	-99% to -94%

SI= spark ignition. CI=compression ignition. F-T = Fischer-Tropsch process.

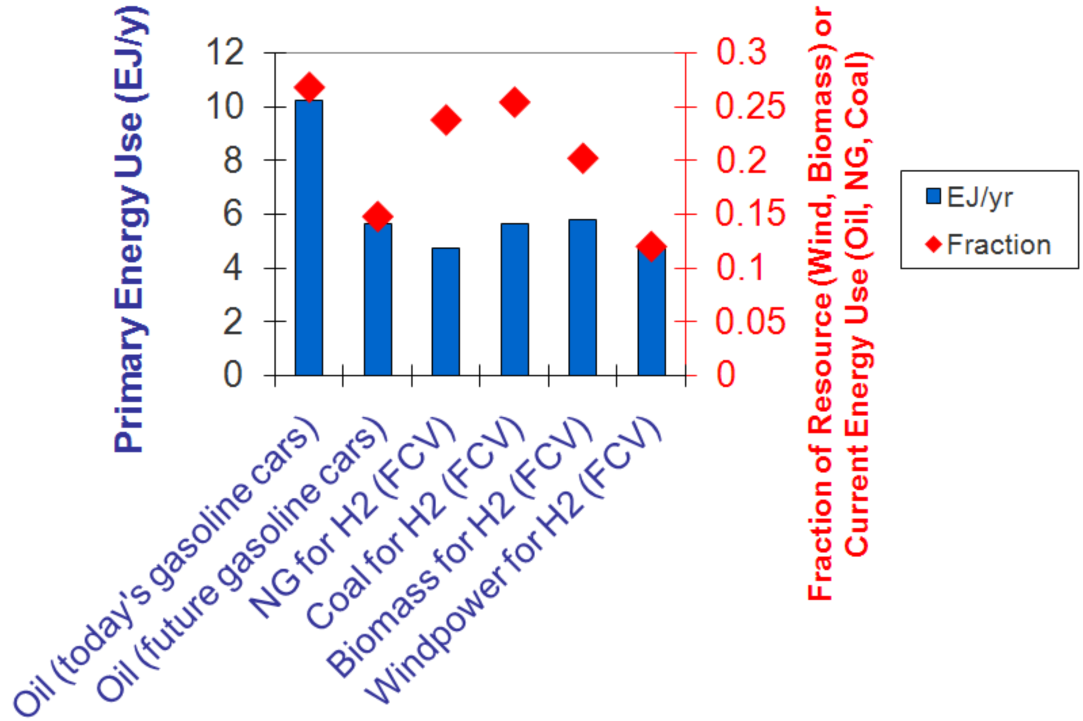


Figure 8.32: Primary energy resources required to fuel 100 million gasoline or hydrogen-fuelled vehicles, also shown as the fraction of the current US annual fossil fuel use or the projected RE resource demand (Ogden and Yang, 2009).

8.3.1.2.4 Status and prospects – electric and hybrid vehicles

While electricity generation from primary energy sources is typically only 30%-55% efficient, electric vehicle (EV) drive chains are relatively efficient and battery charging is an efficient way to store primary renewable electricity. Combined EV drive train and battery charge/discharge efficiencies (plug-to-wheels) are in the order of 60%-75%.

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 54% dependent on coal, WTW emissions from EVs would not be much of an improvement over efficient gasoline vehicles (Fig. 8.33.). Various studies have developed scenarios for decarbonising the grid over the next few decades that would give reduced WTW emissions for EVs and PHEVs (EPRI/NRDC, 2007; IEA 2008e). With large fractions of renewable electricity, WTW emissions for EVs could be very small. An integration issue is the timing of vehicle recharging when variable renewable electricity is available. An electricity cost/infrastructure issue is timing of vehicle recharging during off-peak periods (typically, middle of the night).

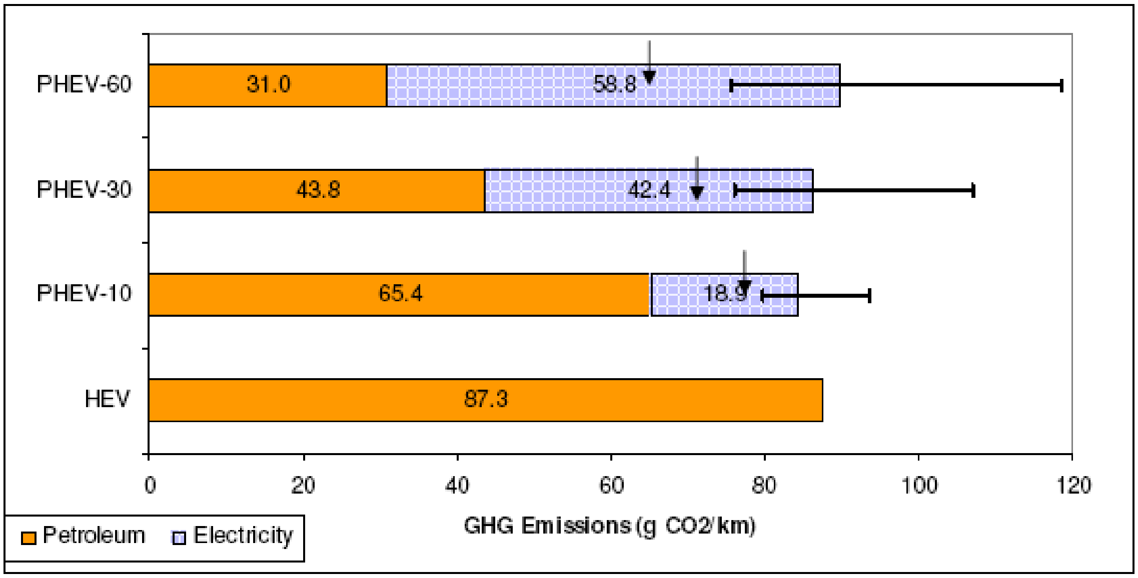


Figure 8.33: Well-to-wheels GHG emissions for gasoline-fuelled hybrids (HEV) and plug-in hybrids (PHEV) showing the various all-electric range.

Notes: PHEV-10 corresponds to an all-electric range of about 30 km and PHEV-60, around 100 km. Horizontal bars indicate the emission range when using electricity from natural gas to coal-fired generation.
Vertical arrows indicate emissions from a partially decarbonized grid similar to that in California today (Kromer and Heywood, 2007).

8.3.1.3 Comparison of alternative fuel/vehicle pathways

Fuel economy and incremental costs of alternative-fuelled vehicles have been compared (Figs. 8.34 and 8.35). Since each study employed different criteria for vehicle design and assumptions about technology status, the results shown have been normalised to those for an advanced, gasoline ICE vehicle (as was defined in each study). (Not all vehicle/fuel pathways were covered in all studies.) The relative efficiency of different vehicle types varied among the studies, especially for less mature technologies, although the overall findings are consistent. Several trends are apparent.

- There is significant scope to improve fuel economy relative to an advanced gasoline vehicle by adopting new drive trains.
- Hybrid vehicles and adoption of electric drives give increasing efficiency.
- Hybrids can improve fuel economy by 15-70%.
- Fuel cell vehicles are 2 to 2.5 times as efficient as gasoline ICE vehicles.
- Battery electric vehicles are 2.7 to 3.5 times as efficient.
- On a total WTW fuel cycle basis, these relative efficiency improvements for HFCVs and EVs are generally less when electricity generation and hydrogen production losses are included.
- There is more uncertainty in the fuel economy and cost projections for EVs and HFCVs which are still far from commercialization.
- In general, the higher the fuel economy the higher the vehicle price.

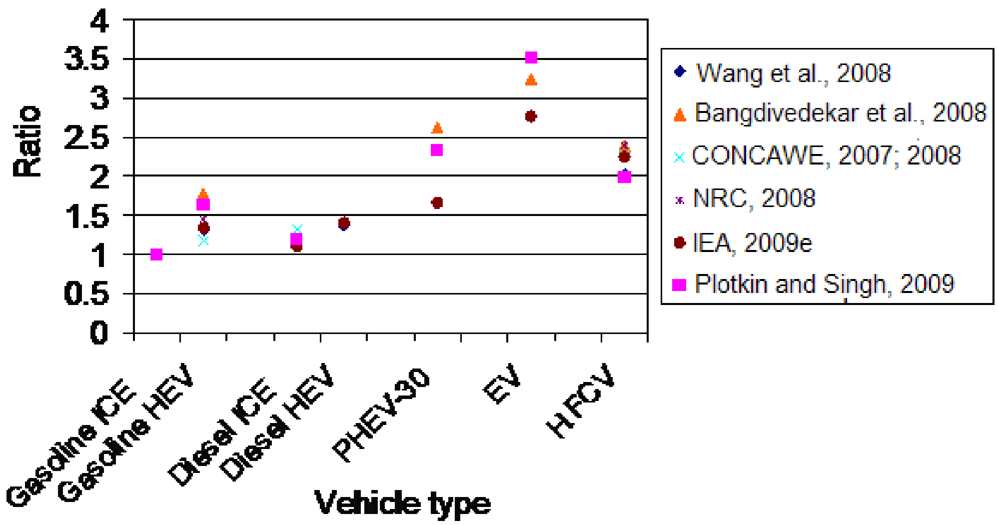


Figure 8.34: Relative fuel economy of future alternative fuelled light duty vehicles compared to advanced spark ignition, gasoline-fuelled, ICE vehicle based on various studies. (Well-to-tank inefficiencies such as electric power generation and hydrogen production not included).

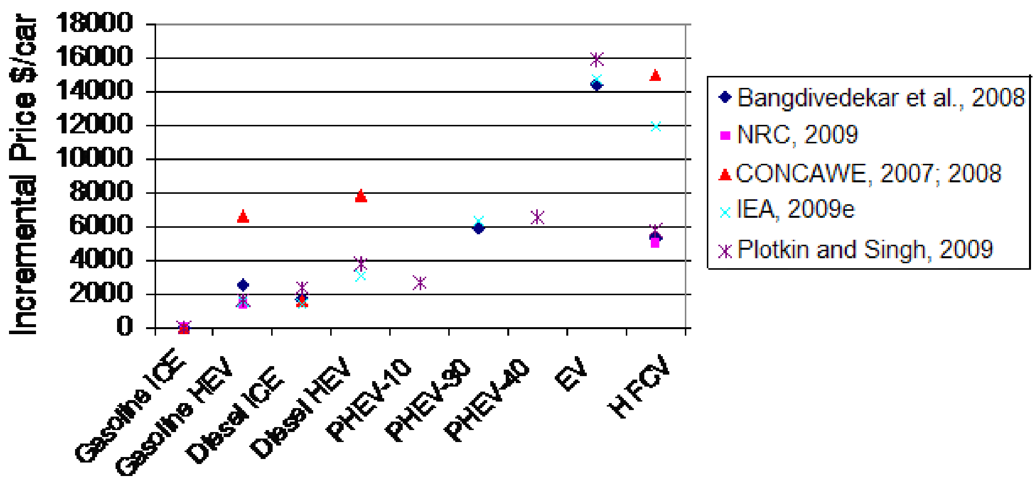


Figure 8.35: Incremental retail price for alternative light duty vehicles compared to an advanced gasoline SI-ICEV.

Notes: Bangdivedekar et al, 2008 vehicles were projections for 2035 technology.
NRC, 2009 is for a mature technology with learned-out costs post 2025.
CONCAWE 2007 and 2008 is for 2010+ technology.
IEA, 2009e and Splotkin and Singh, 2009 were 2030 technology projections.

8.3.1.4 Transition issues

To meet future goals for transportation energy security and GHG emissions reduction, the transport sector will need to be fundamentally transformed. Historically, major changes in transport systems such as building canals and railroads, paving highways, and adoption of gasoline cars, have taken many decades to complete. Transitions in the transport sector take a long time for several reasons.

- Passenger vehicles have a relatively long lifetime (15 years average in the US). Even if a new technology rapidly moves to 100% of new vehicle sales, it would take a minimum of 15 years for the vehicle stock to "turn over". In practice, adoption of new vehicle technologies occurs much more 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. HEVs still represent only about 1% of new car sales and less than 0.5% of the worldwide fleet.This slow turnover rate is also true for relatively modest technology changes such as the adoption of automatic transmissions or fuel injection. The timeframe for new technologies relying on electric batteries, fuel cells, or advanced biofuels could be even longer since they all need further RD&D investment before they can be commercialized.

- Changing a fuel supply infrastructure, especially if switching on a massive scale from liquids to gaseous fuels or electrons, will require both time and a significant amount of capital. This will take many decades to complete (IEA. 2009e; Splotkin and Singh, 2009). Developing new supply chains for renewables and replacing existing fossil fuel and electricity plants will take time. Such paradigm shifts will require close co-ordination among fuel suppliers, vehicle manufacturers and policy makers.
- Each fuel/vehicle pathway faces its own transition challenges which can vary with region. Transition challenges in terms of technology readiness (of fuel and vehicles) include infrastructure compatibility, consumer acceptance (for example, limited range or long recharging times for batteries), primary resources available for fuel production, GHG emissions, cost, and other environmental and sustainability issues (such as air pollutant emissions, and water, land and materials use).

8.3.1.4.1 Transition issues for biofuels

Second generation biofuels should give much lower WTW GHG emissions than petroleum derived fuels, but these technologies are still perhaps 10 years from market introduction (IEA, 2008a). An advantage of liquid biofuels is their relative compatibility with the existing liquid fuel infrastructure. Biofuels can be blended with petroleum-derived fuels, though typically cannot be shipped in existing fuel pipelines (section 8.2.4) and have limits on the concentrations that can be blended. Although ethanol would likely need its own distribution and storage systems, this would be less of a radical change than supply chain changes needed to provide either electricity, hydrogen, or even CNG where such a network is not yet in place. Biomethane could be purified and used in the existing natural gas system.

Biofuels are generally compatible with ICE vehicle technologies. They can be blended with petroleum products and most ICE vehicles can be run on blends or even on pure biofuels. Millions of vehicles with flex-fuel engines that can run on 100% gasoline up to 100% ethanol, have been sold around the world. Biodiesel blends can also be used with current compression ignition engine technologies, but limits depend on the triglyceride feedstocks used and ambient temperatures.

Since liquid biofuels blended in limited amounts are much like gasoline or diesel in terms of vehicle performance and refueling time, they can be relatively "transparent" to the consumer. Fuel cost may therefore be the main factor determining consumer acceptance. In Brazil for example, flex-fuel vehicle users can select the 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 resource availability is a serious issue for biofuels. Recent studies (IEA, 2009e; Splotkin and Singh, 2009) have assessed the national or global potential for biofuels to displace petroleum products. They found that environmental and land-use concerns would limit biofuel 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, HEVs, PHEVs, or HFCVs), if successfully developed and cost effective, might come to dominate the light duty sector.

8.3.1.4.2 Transition issues for hydrogen

Hydrogen produced from fossil fuels is used in oil refining to upgrade heavier crude slates and to hydro-treat petroleum products to remove nitrogen and sulphur impurities. In addition, hydrogen contributes to the energy content of petroleum-derived fuels. Hydrogen-rich synthesis gases (produced by thermal gasification of coal or heavy oil) have been used for electric generation. Hydrogen production currently consumes around 2% (USDOE, 2009) of global primary energy, and is growing rapidly. If all this hydrogen were further purified and then used in fuel cell cars, it could supply about 150 million, about 20% of the world fleet. While most hydrogen is produced and used in oil-refineries or chemical plants, some 5-10% is delivered to distant users by truck or pipeline. In the United States, this “merchant hydrogen” delivery system carries enough energy each year to fuel several million cars (but would first need purification). In the near term, excess hydrogen capacity from refineries and industrial hydrogen plants could fuel up to 100,000 cars in California alone (Ritchey, 2007).

Hydrogen has the potential to tap vast new energy resources to provide transport with zero or near-zero emissions. If hydrogen made from natural gas, the most common method today, is used in an efficient fuel cell car, GHG emissions would be about half those emitted from the tailpipes of today’s conventional gasoline cars and somewhat less than those from a gasoline HEVs. To fully realize the benefits of a hydrogen economy, a transition to cost-effective, zero emission, fuel supply pathways is needed.

Hydrogen from renewable sources has near-term cost barriers rather than technical feasibility or resource availability issues. In the longer term, biomass and wind hydrogen could compete with gasoline (NRC, 2008). In the very long-term, advanced renewable pathways employing direct conversion in photo-electro-chemical or photo-biological systems could become practical for production of hydrogen or other fuels.[8]

RE and other low carbon technologies will likely be used first to make electricity, a development that could help enable zero-carbon hydrogen that might be co-produced with electricity in energy complexes. Hydrogen should be seen in the context of a broader transition to low-carbon sources across the energy system, though it is likely that low-carbon hydrogen from renewables would cost more than hydrogen from natural gas. Public policy will be needed to assure that low carbon sources are used for hydrogen.

Although hydrogen can be burned in an ICE vehicle, more efficient HFCVs are seen as holding greater promise. Most of the world’s major automakers have developed prototype fuel cell cars, and several hundred of these vehicles are being demonstrated in North America, Europe and Asia. 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 HFCVs will fall with further improvements from R&D, economies-of-scale from mass production, and learning by doing (NAS, 2008).

[8] Hydrogen from nuclear energy has other challenges including cost (for electrolytic hydrogen), technical feasibility (for thermo-chemical water splitting systems powered by nuclear heat) and public acceptance. Nuclear hydrogen would have the same waste and proliferation issues as nuclear power.
Large-scale production of hydrogen from fossil fuels with CCS can offer near-zero emissions at poetentitally modest C prices, assuming suitable C disposal sites are nearby. Establishing the viability and acceptance of CCS is crucial for long-term use of hydrogen from fossil resources, especially coal.

HFCVs could match current gasoline vehicles in terms of vehicle performance and refueling time, and could be "transparent" to the consumer, in most respects. The maximum range of present-day fuel cell cars of about 500 km is acceptable so fuel availability and high cost of both vehicle and fuel remain the factors determining consumer acceptance.

Unlike electricity, natural gas, gasoline and biofuels, hydrogen is not widely distributed to consumers today. Bringing hydrogen to large numbers of vehicles would require building a new refuelling infrastructure that will be a decades-long process. The first steps to provide hydrogen to test fleets and demonstrate refuelling technologies in mini-networks are in place in Iceland and being planned through projects like the California Hydrogen Highways Network, the HyWays and Norway's projects in Europe. System level learning from these programmes is valuable and necessary, including development of safety codes and standards. When in the future hydrogen vehicles are mass-marketed, hydrogen will have to make a major leap to a commercial fuel available at perhaps 5% of refuelling stations (or an equivalent number of sites) and must be offered at a competitive price. The cost of hydrogen dispensing stations is likely to be higher than current gasoline or diesel stations due to the equipment, energy and safety measures needed to generate (or transport if the hydrogen is made off-site), compress, handle, and store the high purity hydrogen (350-700 bar) needed for fuel cell vehicle refuelling. Whether stored as a liquid or compressed, the energy density of hydrogen is 5-12 times less than oil-products. On-site storage equipment will therefore make up a significant portion of total station costs.

Recent studies (NRC 2008; Greene et al., 2007; Gronich, 2007; Lin et al., 2006; Gielen, 2005) indicate the costs to "buy-down" fuel cell vehicles to market clearing levels (through technological learning and mass production) and to build the associated infrastructure might cost tens of billions of dollars, spent over the course of one to two decades. The majority of the cost would be associated with early hydrogen vehicles, with a lesser amount needed for early infrastructure. It is almost certain that government policy will be needed to bring these technologies to cost-competitive levels.

Ancillary benefits could be important for hydrogen. Since hydrogen vehicles have zero tailpipe emissions, WTW air pollutant emissions can be lower than comparable advanced ICE vehicles including hybrids (Ogden et al., 2004; CONCAWE 2007; Jacobson and Collela 2007; Wang and Ogden, 2008). Zero-emission vehicle regulations are a motivation for hydrogen vehicles. Sustainability issues include the added demand for platinum for fuel cell manufacture.

8.3.1.4.3 Transition issues for electricity

For renewable electricity to serve large transport markets, several innovations must occur such as development of 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 renewable sources. Conversely, for distributed energy systems, the EVs become an integral part of the system and provide "vehicle to grid" storage (IEA, 2009b).

Home recharging would require new equipment. a recent study estimated that in-home electric vehicle charging systems capable of an overnight recharge might cost $800-2100 per charger (USDOE, 2008c). However, the distribution grid could need upgrading to handle the added load. To manage the significant new demand, "smart grid" technologies could be the solution.

EVs currently have limited use as neighbourhood and fleet vehicles including from small go-cart vehicles to pick-ups and buses. There are also a limited numbers of passenger EVs still operating from the original models sold by GM, Toyota, Honda and others in the 1990s and early 2000s.

Commercialization of EVs and PHEVs is planned over the next few years (CARB, 2007). 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. Battery lifetimes for advanced lithium battery technologies are perhaps 3 years, when 10 years is required for automotive applications.

Consumer acceptance is a key issue as well. One of the attractions of electricity is that vehicles could be recharged at home, avoiding trips to the gasoline station. However, for typical residential power levels, charging a battery would take several hours, unlike the quick fill possible with liquid or gaseous fuels. Even at fast charge outlets that might bring batteries to near full charge in 10-15 minutes, recharging would take more time than refilling a gasoline car. Moreover, an EVis likely to have a shorter range than a gasoline car, 200-300 km versus 500 km. While this range is adequate for 80% of car trips, these factors may make long distance travel less attractive with an EV. This could be overcome by owners of small commuter EVs using rental or community-owned vehicles for longer journeys (IEA, 2009b).

The added vehicle cost for PHEVs, while still significant, is less than for an EV and there are no range limitations. One strategy is to introduce PHEVs initially while developing and scaling up battery technologies. This would lead to more cost-competitive EVs. However, regular ICE hybrids will always be cheaper to manufacture than PHEVs due to the smaller battery. Advances in battery technologies would make them more competitive. Incentives such as low electricity prices relative to gasoline, carbon charges 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 substitute for another.

8.3.1.5 Comparisons and future trends

Transition issues vary for biofuels, hydrogen and electric vehicles (Table 8.11). No one option is seen to a clear "winner", and all will take several decades to implement at the large scale.

Table 8.11: Transition issues for biofuels, hydrogen and electricity

	Biofuels	**Hydrogen**	**Electricity**
Technology Status			Limited current use of EVs.
Vehicles	Millions of flex-fuel vehicles using ethanol	Demo HFCVs. Commercial: 2015-20	Demonstration PHEVs. Commericial EVs: 2015-2020 Commercial PHEVs:2010-15.
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. Not competitive as transport fuel. Renewable H_2 often more costly.	Commercial power. Renewable electricity can be more costly, but can compete with retail power prices if generated in buildings.
Cost (vs. gasoline vehicles)			>USD 5900 (2035) (PHEVs)
Vehicle price (USD)	Similar	>USD 5300 (2035)	>USD 14,400 (2035) (EVs).
Fuel cost (USD /km)	Competes with gasoline at USD 0.15-0.45/l	Competes with gasoline at USD 0.50-0.75/l (mature H_2 infrastructure). Renewable H_2 at least 2-3x more expensive.	Competes with gasoline at if using renewable electricity at USD 0.10-0.18/kWh.
Compatibility with existing	Partly compatible with	New H_2 infrastructure	Widespread electric

infrastructure	existing petroleum distribution system.	needed. Infrastructure deployment must be coordinated with vehicle market growth.	infrastructure in place. Need to add in-home and public chargers, renewable generation sources, upgrade transmission and distribution.
Consumer acceptance	Fuel cost; alcohol vehicles have shorter range than gasoline. Potential cost impact on food crops and land use.	Vehicle and fuel cost. Availability in early markets.	Vehicle initial cost. Electricity cost of charging on-peak. Limited range unless PHEV. Modest to long recharge time, but home recharging possible.
Primary resources (potential in 2050)	Sugar, starch crops. Cellulosic crops; forest, agricultural and MSW. Algae and other biological oils.	Fossil fuels. Nuclear. All renewables- hence potential renewable resource base is large.	Fossil fuels. Nuclear. All renewables – hence potential renewable resource base is large.
GHG emissions	Depends on feedstock, pathway and land use issues. Low for fuels from wastes, residues. Near-term can be high for corn ethanol. 2nd generation biofuels lower.	Depends on H_2 production mix. Compared to future hybrid gasoline ICE vehicle. WTW GHG emissions for HFCV using H_2 from gas are slightly more to slightly less depending on assumptions. WTW GHG emissions can approach zero for renewable pathways.	Depends on grid mix On current US grid mix EVs, and PHEVs have WTW GHG emissions similar to gasoline hybrid. With larger fraction of renewable electricity, WTW emissions are lower.
Petroleum consumption	Low	Very low	Very low
Environmental and sustainability issues			
Air pollution	Similar to gasoline.	Zero emission vehicle.	Zero emission vehicle.
Water use	More than gasoline depending on feedstock and irrigation.	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.	Lithium in batteries.

Note: Costs quoted do not always include payback on the 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, 2009e). 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 by:

- further increasing vehicle efficiency, perhaps up to 30-40% by 2030 (IEA, 2009e). 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, speed reduction, and use of more efficient auxiliary power units (APUs) decoupled from the powertrain;

- streamlining operational logistics to freight handling and routing efficiency by GPS routing technology, optimized automatic gear shifting, avoiding empty return trips etc.; and
- partially switching to lower carbon fuels.

Today, about 85% of freight-truck fuel is diesel, with the remainder being gasoline. Integrating biofuels into the fuel mix would be the most straight forward renewable option. The IEA (2008e) 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 fuel cells or ICEs), or electricity (including EVs and trolley buses) would likely be limited to urban or short-haul HDVs. LNG might however be an option for freight transport. Another potential use of low carbon H2 or electricity might be to power APUs that could consist of on-board fuel cells or batteries, although neither of these options is yet cost effective.

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 kilometres travelled (VKT), little or no 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 fueling infrastructure, technology maintenance and, if needed, driver training. According to the IEA's baseline scenario (IEA, 2008e), HDV energy use by 2050, even with improved energy efficiency in the order of 20%, is projected to increase by 50% as the quantity of freight worldwide 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, 2009e). 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 up to 30-50% in future aircraft (IEA, 2009e). These include improved aerodynamics, airframe weight reduction, higher engine efficiency, and improvements in operation and air traffic control management to give higher load factors and better routing, and more efficient ground operations at airports (including more gate electrification and towing by low carbon fueled vehicles) (TRB, 2009). Although reductions in energy intensity (energy use per passenger 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 (TRB, 2009; IEA, 2009e), will further 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, and minimize drag in the process. In addition, due to safety, the fuels need to meet much more stringent requirements than for other transport modes, particularly thermal stability to assure fuel integrity at high temperatures, low temperature properties 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 renewables, various aircraft have already flown demonstration 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 (2008e) scenarios range from a few percent to up to 30% biofuel use in aviation by 2050.

Liquid hydrogen is another long-term option, but faces significant hurdles due to its low volume density, fundamental changes need in aircraft design due to the need for cryogenic storage, and distribution infrastructure hurdles at airports. The most likely alternative, albeit not necessarily lower carbon aviation fuels, 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, 2009e). 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. Unlike in other transport sectors, except perhaps rail, the negative radiative forcing of HFO combustion by-products, mainly sulphates that create aerosols, may actually mitigate the GHG impact from shipping. 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, 2009a; TRB, 2009) such as improvements in:

- vessel design (e.g., larger, lighter, more hydro-dynamic vessels, reduced ballast operation, 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).

These measures could potentially reduce energy intensity by as much as 50-70% for certain ship types (IEA, 2009e).

The key application of renewables in marine transport would be through the use of biofuels. Existing ships could run on a range of fuels, including blends of lower quality, lower cost, biocrudes. Engines would probably need to be modified, similar to HDV road vehicles, to operate on high fraction (80-100%) biofuel mixtures. Other renewables 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 motors plugged in while at port to a renewable grid source. Other limited low carbon options include LNG-powered tankers which are already in limited use today, expanded use of nuclear-powered vessels, and possibly all-electric ships (using future bulk energy storage systems or nuclear propulsion as for submarines) (TRB, 2009; IEA, 2009e).

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 occuring in non-OECD countries (IEA, 2009e). Rail moves more freight but uses an order of magnitude less energy than trucking due to its much higher efficiency (IEA, 2009e). Rail transport is primarily powered by diesel fuel being almost 90% in 2005 (IEA, 2009e), with the balance of the rail network mostly electrified. 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 negative radiative forcing effect of sulphates), but this trend has other negative environmental consequences and will likely decrease with stricter clean fuel regulations.

Options for improving rail energy efficiency include upgrading locomotives to more efficient diesel engines and APUs as well as hybrids, reducing the empty weight of the rolling stock, increasing the maximum train size through longer trains, higher load factors, and double-stacked containers, and operational improvements such as driver training, optimized logistics, reduced idling (IEA, 2009e; TRB, 2009). Efficiency increases of up to 20-25% are possible.

The two primary pathways for RE penetration in rail transport are through increased use of biodiesel and renewable "green" diesel (from around 2-20% in IEA (2009e) 2050 scenarios) 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), but also further reduce GHG emissions as electricity generation switches to renewables 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 fuel cells on locomotives appear to be fewer than for passenger HFCVs. Compared with light duty vehicles, a rail system system provides more room for H2 storage, provides 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 transportation is the projected explosive growth of numbers of vehicles worldwide. This is expected to triple by 2050 from 700 million vehicles today to 2 billion. (IEA, 2008e). Meeting this demand while achieving a low carbon, secure energy supply will require strong policy initiatives, rapid technological change, and monetary incentives or the willingness of customers to pay additional costs. There is scope for renewable 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 light duty sector, increased use of electric drive train technologies has already begun, beginning with hybrids, plug-in hybrids and leading to electric battery and hydrogen fuel cell cars (IEA, 2008e). Historically, the electric sector and the transport sector have been completely separate, but through electric-drive vehicles, they are likely to interact in new ways through charging battery vehicles or "vehicle to grid" electricity supply (McCarthy et al., 2008).

Ancillary environmental concerns and energy security are important motivations for new transport systems. Sustainability issues such as land-use, water use and materials requirements may impose constraints on the use of alternative fuels or vehicle designs. Understanding these issues will be necessary is a low carbon future transport system is to be achieved.

Meeting future goals for GHG emissions and energy security will mean displacing today's ICE vehicles, planes, trains and ships with higher efficiency, lower emission models (including electric-drive trains) 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 the need for further RD&D investment is needed for key technologies including batteries, fuel cells, hydrogen storage, and renewable and other zero-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 vehicle km travelled or km flown), more efficient vehicles, and a variety of low-carbon fuels. This approach will recognize that customers will ultimately make the vehicle purchase decisions, and that different technology/fuel options will fit their varying situations. Recent studies (IEA 2008e; IEA, 2009e) see a major role for renewable transportation fuels in meeting societal goals for transportation, assuming that strict carbon limits are put in place.

8.3.2 Buildings and households

- The basic energy services that people need may be summarised as below:
- cooking – 95% of staple foods must be cooked (DFID, 2002);
- heating – of space in colder climates, or water e.g. for washing or purification;
- cooling – of space in hotter areas and that is growing in demand;
- lighting – household, commercial building and street lighting;
- refrigeration – of food and perishable items including medicines;
- communications and entertainment – including TVs, radio, phone, internet and computers;
- mobility – transport of people and products;
- social services – including water pumping and purification; health (vaccine refrigeration, sterilization, lighting of operations, transport to clinics); education (time saving, lighting for night study);
- productive uses – producing other goods and services for consumption as well as sale for income generation such as agriculture, agro-processing, industry/enterprises etc.

These energy services are met by using a number of energy carriers including electricity and heat in appliances (such as cook stoves, light bulbs, motors, boilers, mills) as well as fuels.

- Solid fuels are extracted and either used directly from nature in the form of biomass, coal or uranium, or can be transformed into other more convenient energy carriers such as charcoal, pellets, briquettes and coke.
- Liquid fuels (section 8.2.4) are usually refined from fossil fuels, oil-containing plants, sugar and carbohydrate crops or other forms of biomass.
- Gaseous fuels (section 8.2.3) such as natural gas or biogas produced from decomposition of natural matter can be combusted directly to produce heat and power.

Energy carriers are converted into energy services in a variety of ways. Although it is possible to use different types of energy for the same use, it is also possible to utilize specific characteristics of the vectors which make them more or less suitable for meeting the specific requirements of the energy service provided (Table 8.12).

Table 8.12: Energy carriers and their suitability for providing basic energy needs.

	Solid (wood, charcoal)	Liquid	Gas	Mechanical power	Electricity
Cooking	XXX	XX	XXX		XX
Heating	XXX	XXX	XXX		XX
Cooling					XXX
Lighting	X	XX	XX		XXX
Refrigeration	X	XX	XX		XXX
Communication/ entertainment					XXX
Mobility	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.

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. Residential and commercial 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, water heating, and powering other gas and electrical appliances. 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 readily available.

The present use of fossil fuels to provide heating and cooling can be replaced economically in many regions by RE systems using modern biomass and enclosed stoves, geothermal ground source heat pumps, or solar thermal and solar sorption systems (IEA, 2007a). The total global demand for renewable heating (excluding traditional biomass at around 45 EJ/year) 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 have been described (IEA, 2007a). 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 (www.ipcc.ch) [TSU: Should rather be cited as a formal reference in the reference list].

8.3.2.1 Urban settlements in developed countries

8.3.2.1.1 Characteristics of urban energy supply/demand (including efficiency)

In OECD and other major economies, most buildings in urban environments are connected to electricity, water, and sewage distribution schemes. Others have natural gas supplied for heating and cooking that is more convenient for residents than using coal, biomass or oil-products to provide these services.

RE has low energy density by comparison with fossil fuels and conversion technologies can be comparatively expensive. Its integration in buildings is expanding in order to give residents quality of life at the same time as realizing low carbon and secure energy supplies (IEA, 2009b). RE deployment is often combined with the enhancement of energy efficiency in a building through technologies, management and energy conservation via behavioural change.

8.3.2.1.2 Challenges caused by integration into urban supply system

Efforts to improve energy efficiency and utilize carbon-free energy sources are largely dependent on the motivation of building owners, inhabitants and customers. Institutional and financial measures such as energy auditing, labelling, subsidies, regulations, incentives and charge systems can lead to increased deployment.

The features and conditions of energy demand in an existing or new building differ with location and from one building design to another. Therefore the technologies and pathways discussed in this section are, of necessity, generic. In reality, effective and efficient methods and products are being developed to apply to buildings under a variety of situations.

The transition from a fossil-fuel based, centralized urban space into a more distributed and RE system will need to revise drastically how urban space has been occupied. The location of public spaces and services in the urban environment has been planned around the design and construction of houses, apartments, commercial buildings and public facilities. The required changes in land and resource use to better accommodate RE technologies in parallel with the use of the existing energy supply is one of the major structural changes that will shape the integration of renewables into the energy system.

The greater deployment of RE such as solar systems and small wind turbines in an urban environment may require more use of roof and wall surface areas in city buildings (IEA, 2009a). This will impact on the orientation and height of buildings to gain better access to solar light and wind. Local seasonal storage of excess heat using ground source heat pumps and access to surface ground water may need to be considered. The local application of combined heat and power from biomass, solatr thermal or geothermal systems is an important spatial option for some cities requiring adaptation of the electricity grid and/or heat/cold distribution grid.

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 (see section 8.2.1). New technologies will need to be accompanied by new and progressive energy regulations and incentives to obtain more rapid dissemination of them (IEA, 2008c).

The opportunity is available for buildings to become energy suppliers rather than energy consumers if distributed RE generation systems could be used internally to produce sufficient heat and power to meet local demands (IEA, 2009b). Appliances in buildings could also contribute to the demand-supply balance of the system through demand response and energy storage technologies (including through the use of electric cars).

Many commercial or residential buildings are leased to the users, leading to the owner/tenant conundrum. Investing in energy efficiency or RE 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 solar water heaters, ground source heat pumps, new cook stoves etc. can be a constraint, possibly to be overcome by government grants, utility leasing arrangements, or micro-financing. Several examples exist of successful government policies and entrepreneurial initiatives that can be replicated elsewhere.

The present market of around USD 1.7 bn /yr[TSU: Needs to be presented in 2005 US$] for building integrated PV systems could be hindered over the next few years by lack of standardisation, low production volumes and competition from PV panels applied to buildings as retrofits (Lux, 2009). Retrofits can now encompass a broader class of building-mounted PV and include some traditional roof-integrated PV systems.

8.3.2.1.3 Options to facilitate integration into urban supply systems

New building designs for both domestic and commercial use in both hot and cold regions have demonstrated that imported energy for cooling/heating can be minimised by careful design, adequate insulation and thermal sinks. Building codes are steadily being improved to encourage the uptake of such technologies, with the hope that by around 2050 most new buildings will need little if any heating or cooling based on imported energy systems.

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 communication, cleaning, cooking and entertainment activities, then the more likely that RE can be employed to meet those demands.

RE supply

Solar photovoltaic generation technologies and solar thermal water heating and space heating are the most promising and active RE supply technologies for buildings because of the universal availability of the solar resource and the maturity of technology. PV technologies are also good for street lighting in combination with high efficiency lamps, because, with a deployment of a small battery, it does not need connection to a power distribution which leads to the reduction of capital and operational costs. The fundamentals of solar thermal technologies are well understood, but even though the technologies are mature, there are several possible improvements to the supply chain including new materials, products and adaptive designing.

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 but the technologies have not yet moved into the mainstream. Integration of PV panels into buildings during construction can replace the look and function of traditional building materials for roofs, window overhangs, and walls. They can be sold as single units and integrated into buildings to improve 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.

Combined heat and power (CHP) generation technology can run on solid, liquid or gaseous fuels, not only from fossil fuel sources but also from RE sources at medium and small scales (Liu et al., 2009). The heat can be used for water heating and/or space heating for residential or commercial buildings or sold to nearby industries. CHP has a possibility to use electrolysis H2 (see section 8.2.3) or other solid or gaseous fuels produced from biomass feedstocks. CHP combustion/steam generation engines, gas turbines, micro-gas turbines and other conversion technologies are available at large (50MWe) and small (5 kWe) scales and research including fuel cells and small/micro scale CHPs is on-going (Leilei et al., 2009).

Efficiency and passive renewable energy integration

Air heating and conditioning is one of the largest energy uses in buildings, both in high latitudes for heating and low latitudes for cooling. An air-tight, well insulated building can provide a high efficiency for air heating and cooling. Various kinds of building materials and construction methods are available including plasterboard, upgraded windows, and ventilated rain screen system of external insulation. In the future, technologies such as vacuum insulation panels, multi-foil insulation, insulation paint, vacuum glazing, and triple glazed windows could be used to enable a house to need very limited or zero space heating except on the coldest days.At the other extreme, in order to avoid over-heating, curtain and automatic shading systems are currently available, and new technologies such as electro-chromic glazing thermo-chromic system will be applicable in the future.

Substantial progress of high performance heat pump air conditioners/heaters utilising atmospheric or ground heat has been made. For air-tight buildings of single-residential, multi-residential, or commercial usage, high energy demands for continual ventilation can be reduced through appropriate selection and hybridization of photovoltaic generation, solar chimneys, wind cowls etc. (Antvorskov, 2007).

Water heating is also a major energy demand in buildings for which RE can be applied through the deployment of solar water heating, biomass, heat pumps or CHP systems (IEA, 2007a). Cooking is also a major energy use for residential buildings. Like water heating, there is room for greater efficiency in heat generation, cooking style and new appliance designs such as microwave ovens. For lighting, electricity is the usual energy source to give quality and low energy consumption. Lighting technologies continue to be developed, from incandescent lamps, to fluorescent lamps, compact fluorescent lamps, and recently to light-emitting diodes (LED). The theoretical conversion efficiency of electricity to light is much higher than that of current technologies which also produce much heat. Therefore innovative technologies continue to be sought by active R&D. More efficient technologies are also under development for various appliances used in residential and commercial buildings (Fig. 8.36) including liquid crystal display (LCD) screens, high thermal insulation refrigerator and energy reduction when in stand-by power mode. Smart appliances that use low energy and operate automatically at off-peak times for use with future intelligent electricity networks (IEA, 2009b), are reaching the market.

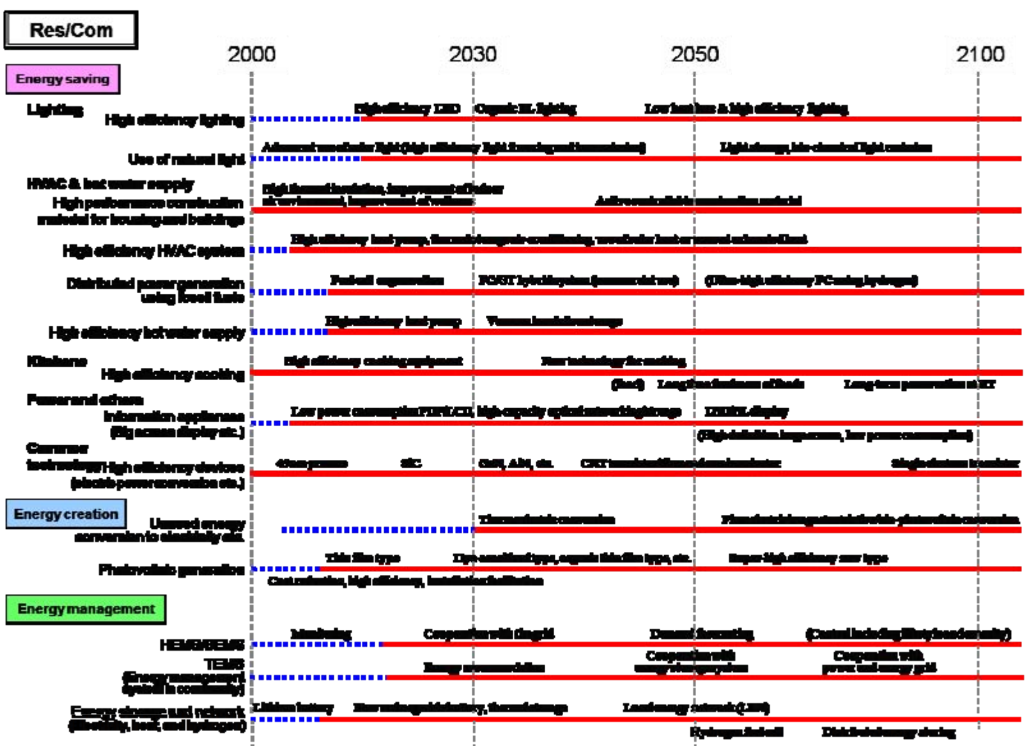


Figure 8.36: Technology development in future energy saving technologies for residential and commercial buildings (METI, 2005).

Energy management technology

Energy management awareness consists of measurement and monitoring of energy use and the interior environment (Wei, 2009), followed by decisions to control energy demand. The energy manager of a building should be responsible for multiple objectives including comfort, cost, energy efficiency, environmental impacts and the integration of RE. In commercial buildings, various building energy management systems, including advanced controls, have been developed to balance the multiple objectives (Dounis et al., 2009). Some monitoring has been deployed in multi-family buildings and many R&D projects are being conducted to produce “Home Energy Management” standard technologies for monitoring, control and actuators (interfacing to 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 technology for appliances, distributed generation and energy storage (NETL, 2008).The set of these technologies has become known as a “smart” or “intelligent” grid.

Assessing, planning and designing technology

The 4th IPCC Assessment Report concluded that buildings represented the largest and most cost-effective sector for GHG mitigation efforts. Greater integration of RE into the built environment is directly dependent on how urban planning, architectural design, engineering and technology will be able to be better integrated. Realizing RE and energy efficiency integration of buildings can be achieved using a combination of technologies. Accordingly, tools and methods to assess and support strategic decisions for planning new building construction and retrofits are useful (Doukas et al., 2008). For the subsequent stages of planning and design, other kinds of methods are necessary to project a strategy to reality for which there are several proposed tools including computer simulations (Larsen, 2008; Dimoudi et al., 2009).

Policies and regulations

Regardless of the type of renewables, policies including building codes and minimum air emission standards can encourage rapid deployment of technologies in new and existing buildings. These are needed to help overcome barriers including education and training of engineers, architects and installers. City planning regulations may need modification to encourage rather than hinder deployment (IEA, 2009b). For example, regulations to protect the solar envelope for PV and solar thermal installations and prevent shading from newly planted trees and new buildings need to be developed along with easing the process to obtain a resource or building consent within pre-determined guidelines.

8.3.2.1.4 Case studies

A study “Energy efficiency in buildings – transforming the market” (WBCSD, 2009) includes case studies of single-family homes in France, multi-family homes in China, and an office in Japan. The study depicts the pathway for each market as follows.

Single-family homes in France. The energy consumption of single-family homes is dominated by space heating being around two thirds of the total (Fig. 8.37). These buildings offer great potential for energy efficiency by reducing space heating needs through insulation, air tightness and more efficient equipment, and by improvements in domestic hot water and lighting. Solar PV and solar thermal are the major RE sources.

Figure 8.37: Shifts in building stock energy classes and impacts of energy saving measures in single family homes in France (WBCSD, 2009).

Multi-family housing in China[TSU: Case study on China in a section on 'Urban settlements in developed countries? – Better in 8.3.2.2 case study]. Most housing in urban areas is multi-family apartment buildings where over 90% of the population in most cities live. The major energy reduction potential is in space heating consumption, water heating and lighting (Fig 8.38). Solar thermal is the major RE source utilized. Sub-metering, apartment-level controls within the building, and charging of individual apartments are emphasized.

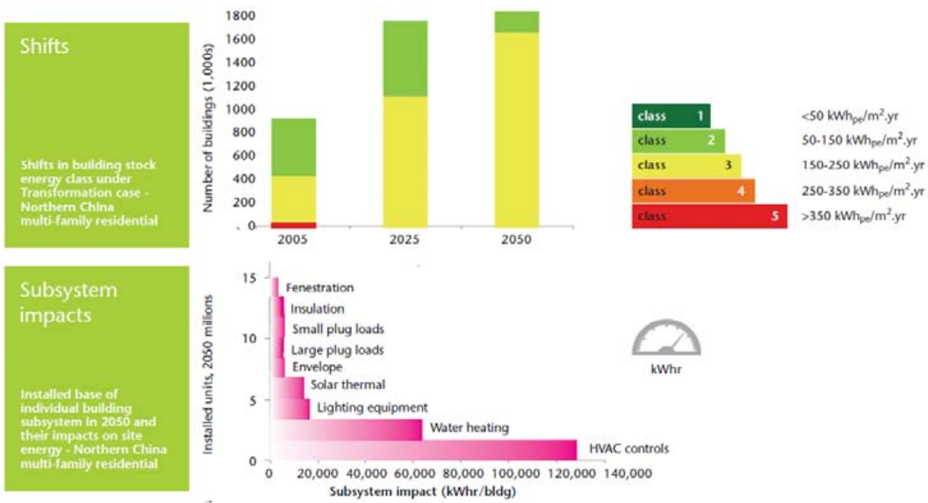


Figure 8.38: Shifts in building stock energy classes and impacts of energy saving measures in multi-family houses in China (WBCSD, 2009).

Office buildings in Japan. Heating and cooling equipment have the highest potential to curb energy demand in office buildings followed by lighting (Fig. 8.39). PV is the major RE source used, especially for low-rise buildings.

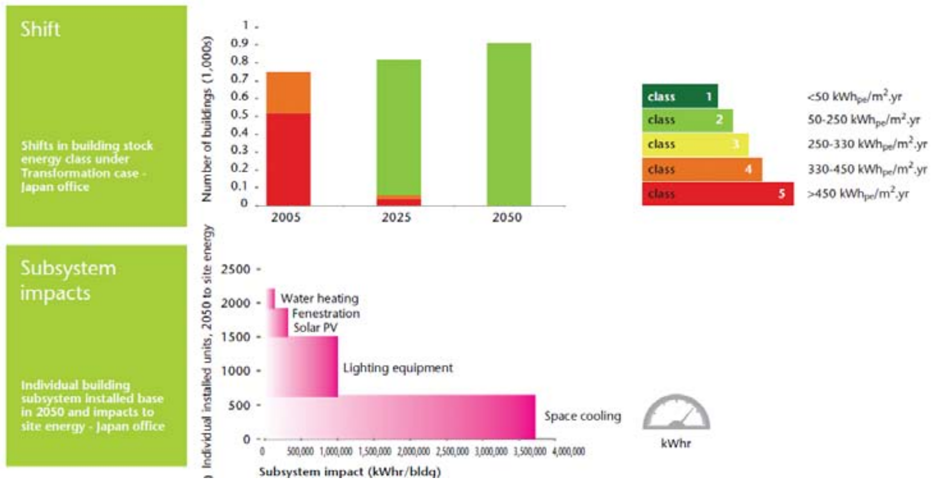


Figure 8.39: Shifts in building stock energy classes and impacts of energy saving measures in office buildings in Japan (WBCSD, 2009).

Urban residential and commercial buildings are expected to contribute to improve the demand-supply balance of energy networks which is subject to the additional fluctuation of “variable” RE generation outputs. Distributed energy management technology for buildings is now under development incorporating latest IT technologies to effectively control domestic peak demands and use energy storage equipment and distributed generation systems in or around buildings. When controls are made in harmonization with central energy management using an incentive or control signal, the improvement can be maximized. More variable RE can then be accommodated flexibly and economically in the energy system. Buildings that have been passive energy consumers could become energy producers and managers become co-operators of an energy network (USDOE, 2008c).

Assuming a 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 (see section 8.1.5 and 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 et al., 2009).

8.3.2.2 Urban settlements in developing countries

8.3.2.2.1 Characteristics

As far as urban poor in developing countries are concerned, particularly in the Sub-Saharan continent, the urban energy consumption pattern depends on the non-rational use of biomass, particularly from forest resources 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 women who still rely on wood energy for their basic cooking and heating needs.

Many urban areas are experiencing a rapid transition from wood to charcoal which is impacting negatively on deforestation, given the low energy conversion efficiency of traditional kilns used in the carbonization process.

8.3.2.2.2 Challenges and options

The major challenge is to reverse this consumption pattern by providing access to modern energy services while increasing the share of renewables. In some urban areas, grid electricity is available although limited to basic needs. It is therefore unlikely that decentralized renewables will secure significant penetration in the next two decades. During the 1980s, solar water heaters were considered as a good RE option in some urban areas of developing countries including China that now has over 50% of the global installed capacity. A market niche for solar water heaters remains, particularly in the service sector such as hotels and lodges as well as middle and high income households. Regulations and incentives could be necessary in many regions to reach a critical mass and gain a large dissemination of solar water heaters.

The introduction of liquid or gaseous RE fuels replacing solid biomass for cooking could play a critical role in improving the health of billions of people. The scale of biofuel production needed to meet cooking energy needs is far smaller than that for meeting transport fuel needs (see sections 8.2.4 and 8.3.1).

A further challenge is to ensure that woody biomass as used extensively by urban and rural populations in developing countries is supplied from sustainably produced forests. Many forests close to urban areas have already been depleted or have disappeared. For instance, in Senegal 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 inefficient transport vehicles.

Fuel switching is an option and in some regions LPG has displaced charcoal. However, this is a costly option and only a few countries have achieved a significant penetration. LPG is not affordable for the majority of poor people and if subsidised, is also 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 good potential (see Chapter 2).

Biomass will remain a valuable fuel in many urban centres in poor developing countries. To ensure the sustainability of forest 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. 8.40). This approach could be accompanied by fiscal policies (for instance differential taxation) to provide financial incentives for woody biomass supplied only from sustainable sources.

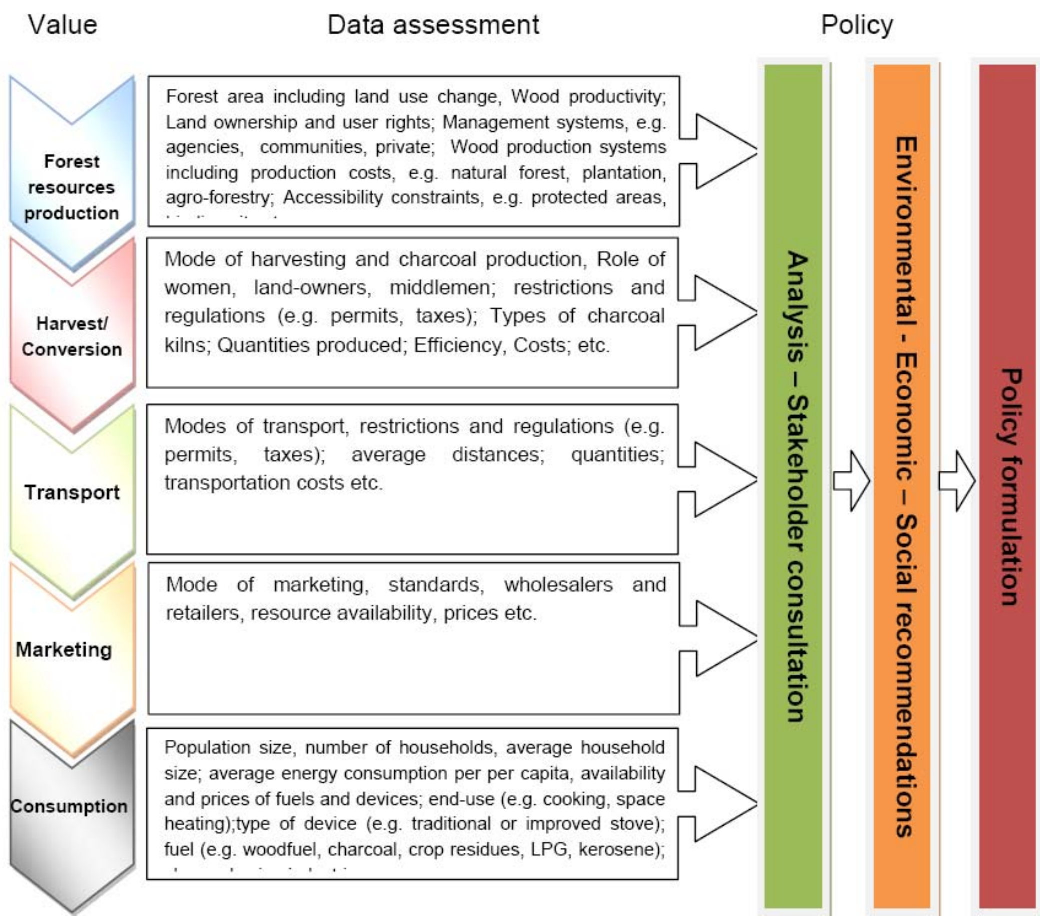


Figure 8.40: A holistic approach using chain analysis of biomass supplied for energy purposes. (Khennas et al., 2009).

8.3.2.2.3 Case Study - 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 for example, all major cities have a large fraction of their population settled in peri-urban areas and about one third of all municipalities have population living in peri-urban areas (IBGE, 2008). These areas frequently lack proper infrastructure and basic services and most of the urban-poor households are concentrate there. Woodfuel continues to dominate household energy use but there is an increased use of multiple fuels including mixing woodfuel with charcoal, kerosene and some LPG.

Housing patterns are, for the most part, quite precarious and constructions are fragile and often very temporary. These areas frequently lack basic urban infrastructure such as waterworks, sanitation and adequate electricity distribution. This can provide an opportunity to create new RE technologies. Energy planning in these areas will need to take place against a background of complexity and change. Depending on the type of settlement, a combination of small-scale technologies available for rural communities and urban dwellings could be employed. 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.

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, the greater penetration of RE technologies in the peri-urban areas will need to be accompanied by comprehensive energy policies and tariffs 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 for example have invested about USD 80 M annually in low-income energy efficiency programmes, about half of their compulsory investments in end-use programms under current regulations. A number of particular and complex issues still need to be tackled including the inefficacy of enforcing legal regulations, the need to develop more creative and technical solutions to treat theft and fraud in services, and the economic situation of such populations living in an urban setting.

In Brazil 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 and maintained individual connections (including re-wiring of domestic installations). Modern and state-of-the-art technologies are being used in peri-urban areas, including remote metering, real-time demand monitoring of households, more efficient transformers, new cabling systems and materials (ICA, 2009a). These regions are leap-frogging to new technologies.

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 utilities with reduced arrears and non-payments (ICA, 2009b).

8.3.2.3 Rural settlements in developed countries

8.3.2.3.1 Characteristics of rural energy supply/demand

The energy consumption pattern in rural developed countries does not differ a great deal from urban areas. Modern forms of energy such as electricity, natural gas, LPG and coal are the main sources, however there is scope for more RE, particularly sustainably produced biomass for space heating.

8.3.2.3.2 Challenges of integration of RE into rural supply systems

Renewable local energy resources are not only tapped to meet the local demand but also the surplus contributes to meeting the national demand. Financial, institutional and lack of awareness are among key barriers to reaching this objective. Although financing might be available for some schemes, up front investment is still 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.

8.3.2.3.3 Options to facilitate the integration of RE

In rural regions 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. Advanced bioenergy technologies for CHP systems can have a significant impact on the energy supply. In Sweden and the USA, as a result of increased biomass demand, the rate of afforestation has increased (Mabee and Saddler, 2007). The following case study illustrates opportunities for the deployment of renewables in rural developed countries.

8.3.2.3.4 Case study

[TSU: Missing case study title (for consistency with other case studies) – e.g. RE installations in rural England]

Cornwall is a rural peninsula in the south-west region of England, which is leading the way on partnerships for the delivery of energy initiatives. Because of its peripheral location, the region has limited access to natural gas pipelines but has sufficient RE resources in the form of solar, wind, marine, small hydro and biomass, to meet the county's demand. In 2004, the Cornwall Sustainable Energy Partnership (CSEP) published the UK's first sub-regional sustainable energy strategy and action plan (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). CSEP's Energy in Buildings Group is the lead delivery partnership for this local area agreement (LAA).

Two years after the CSEP began, the installed capacity of RE measures in domestic and community buildings tripled, and there has been a 6-fold increase in the number of RE measures installed in domestic and community buildings in Cornwall. As part of the LAA delivery plan, CSEP has been providing free technical and funding advice to developers, architects, housing associations, community groups etc. It has facilitated micro-generation installations in a number of social and private sector housing developments. The strategy commits the partnership to doubling Cornwall's current renewable electricity generating capacity to achieve a sub-regional target of at least 93 MW by 2010.

8.3.2.4 Rural settlements in developing countries

8.3.2.4.1 Characteristics of rural energy supply/demand

Rural households rely on traditional biomass (mainly crop residues, fuelwood and charcoal) for their basic energy needs for cooking ands heating. In 2005, there were 570 millions stoves used in rural areas of which 220 million were improved stove designs (REN21, 2006). Unlike urban areas, the biomass can be collected locally, generally by women from nearby woodlands and savannah lands. Although the time devoted to this task has been increasing in some regions as local resources become diminished in a non-sustainable fashion, the illusion of a free commodity coupled with severe poverty make it difficult to substitute firewood with modern energy or even to improve energy efficiency for cooking. Providing local plantations to harvest more sustainably is one solution but not always easy to accomplish due to land ownership and other social issues.

Lighting demands can be met by kerosene lamps, torches and candles, all of which are expensive options. Only a tiny fraction of rural households having access to modern energy services is a major constraint to eradicating poverty, and meeting the Millennium Development Goals by improving health, education, social and economic development. In sub-Saharan Africa for example, and many other developing countries, traditional biomass accounts for more than 75 % of cooking fuels. Resulting environmental impact and strategies vary depending on the regions and whether it is a rural, urban or peri-urban context.

8.3.2.4.2 Challenges of integration into rural supply system

Around 2.4 billion energy poor people rely on traditional biomass fuels for cooking and heating, including 89 per cent of the population of sub-Saharan Africa, and another 1.6 billion people who do not have access to electricity mainly in rural areas (Vijay et al, 2005). The key challenge for rural communities is to move up the energy ladder (Fig. 8.41).

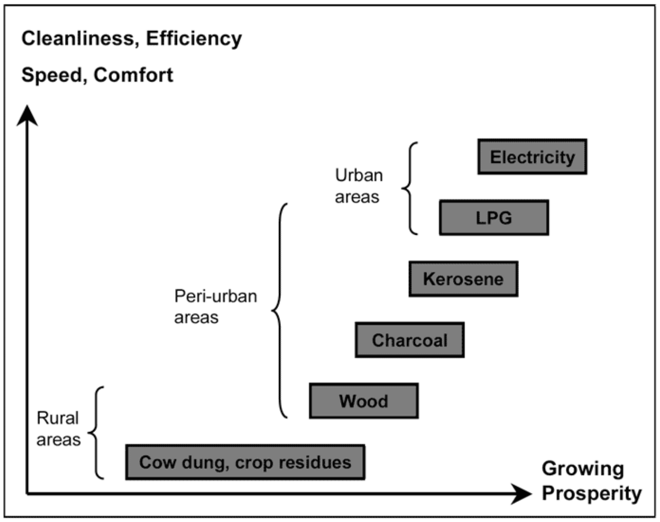


Figure 8.41: The "energy ladder" indicates how growing prosperity results from improved energy quality and availability. (Mahamane et al., 2009).

Some of the energy poor in peri-urban urbans may achieve sufficient funding for purchasing electricity from the grid in the next 20 years in some regions as extension of the distribution network reaches more peri-urban people currently without access to modern energy services. However, energy consumption might remain limited to basic needs such as lighting, ventilation and communication (including radio, television and mobile phone recharging). The energy poor in rural areas may better utilize local RE technologies as the least cost option available if innovative finance mechanisms can be put in place.

8.3.2.4.3 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.

8.3.2.4.4 Case study: RE in the Democratic Republic of Congo

The Congo Basin is the second largest tropical rainforest area in the world after the Amazon. The level of deforestation in absolute values is particularly high, particularly so in the Democratic Republic of Congo (DR Congo) which is the largest country and the most populated of the Congo Basin (Table 8.13). Paradoxically despite the large hydro potential in the region, the rural electrification rate is extremely low at less than 1% (Fig. 8.42). 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 hydro schemes have been identified for which preliminary data have been gathered (Knennas et al., 2009). The implementation of such a programme will dramatically increase the supply of RE for rural people in meeting energy needs for education, health and income generating activities. It may also contribute to limiting deforestation around villages.

Table 8.13: Deforestation and degradation rate of the forests in the Congo Basin.

	Forest area (1000 ha)	Deforestation (%/year)	Degradation (%/year)
Cameroon	19 639	0.19	0.02
Equatorial Guinea	1 900	0.42	0.52
Gabon	22 069	0.12	0.09
Central African Republic	6 250	0.07	0.02
Republic of the Congo	22 263	0.03	0.01
DR Congo	108 359	0.26[9]	0.15
Total Congo Basin	**180 480**	**0.19**	**0.10**

(Etat des Forêts, 2006).

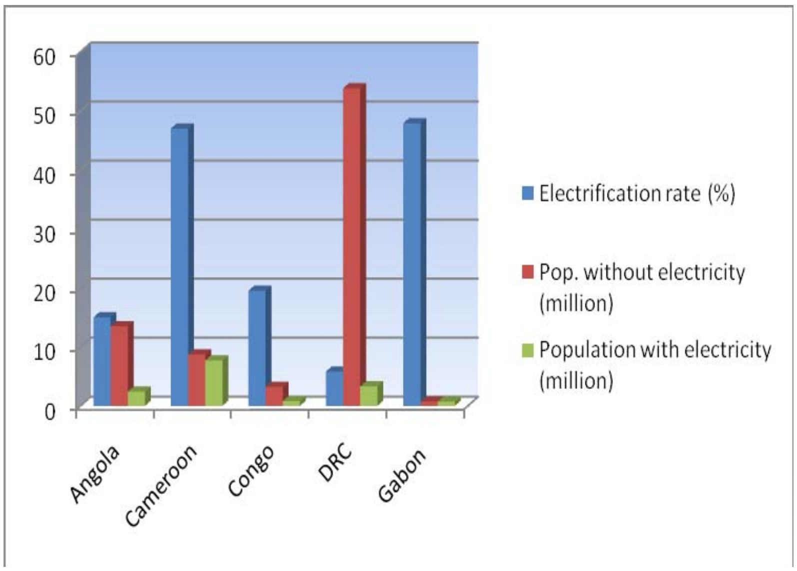


Figure 8.42: Electricity access in selected countries of the Congo Basin in 2005 (adapted from IEA, 2006).

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 et al., 2007). The production of these industrial goods has grown strongly in the past 30-40 years and is projected to continue growing.

[9] FAO, 2003 estimates that in DRC about 532,000 hectares (or 0.4%) of forest are cleared annually.

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 (IPCC, 2007). Other industry GHG gases include nitrous oxide (N20), HFC-23, perfluorocarbons (PFCs) and sulphur hexafluoride (SF6). Direct and indirect CO_2 emissions in 2006 were 7.2 and 3.4 gigatonnes (Gt) respectively, together being equivalent to almost 40% of world energy and process CO_2 emissions (IEA, 2009a).

Carbon dioxide emissions from industry can be reduced in several ways:

- energy efficiency measures reduce internal energy use and will in some cases release energy sources generated on-site available for export (as waste heat, electricity and fuels);
- materials recycling eliminates the energy-intensive primary conversion steps for many materials;
- energy input and feedstock substitution can reduce the use of fossil fuels;
- carbon dioxide capture and storage (CCS) of both fossil and renewable biomass origin can reduce emissions to the atmosphere.

All these measures are relevant for the integration of RE into present and future energy systems. In addition industry could provide demand-response facilities that could achieve greater prominence in future electricity supply systems.

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 et al., 2007). Thus, industry is not only a potential user of RE but also a potential supplier as a co-product.

There are no severe technical restrictions to the increased direct and indirect use of RE in industry in the future. Indirect emissions, mainly from electricity consumption, can be reduced by decarbonisation of the power sector. The share of electricity in industrial energy use is expected to increase (IEA, 2009a). Hydrogen is also a potential future energy and feedstock input to industry (section 8.2.3). The direct use of fossil fuels can be replaced by energy carriers such as electricity from renewable sources and solar thermal heat, as well as gaseous, liquid and solid fuels from biomass, albeit subject to resource limitations. CCS can be important in future low-carbon energy systems and is also relevant to consider in the context of integrating RE in industry.

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, 2009a). 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 to 6 GJ/t. However, the amount of scrap steel is limited and the increasing demand for primary steel is mainly met from iron ore. Electricity, used in the electric-arc furnace, can facilitate emission reductions through decarbonisation of electricity supply whereas replacing coal for coke-making with renewable biomass fuels may be more challenging, although charcoal is used for steel-making in some countries.

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 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. A few other steel mill blast furnaces have used sorted plastic waste to complement coke.

Options for increasing the use of RE in the iron and steel industry in the near term include substituting coal and coke with charcoal, subject to resource constraints, and switching to renewable electricity in electric-arc furnaces. 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 it is likely that CCS linked with coke combustion will 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 only 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.

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, 2008e). The main feedstocks are oil, natural gas and coal, for providing the building blocks of products as well as for energy. 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. 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:

- 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;
- feedstock can be converted using industrial biotechnology processes such as fermentation or enzymatic conversions; and

- 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 for export. 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 Box). [TSU: **Box 8.1:** Principles of power balancing in the system? Or is there to be another box inserted here?] 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, such as 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 replace fossil fuels in boilers, kilns and furnaces and there are alternatives for replacing petrochemicals 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 the main 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. 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). However, 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. 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 in various ways. 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 respond to RE policy by exporting fuels, heat and electricity. Sectoral approaches are considered in international climate policy in order to reduce carbon leakage risks and facilitate technology transfer.

8.3.3.2.1 Case study: 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 H2) can be used with high efficiency in combined cycles for CHP or for the production of biofuels via the Fischer-Tropsch process (section 8.2.4). A pilot plant for producing DME (di-methyl ether) is expected to begin production in Piteå, Sweden, in July 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.

8.3.3.2.2 Case study: 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 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, 2009).

8.3.3.3 Other non-energy intensive industry

In addition to increased use of biomass derived fuels and residues for heat and CHP production there are four main opportunities for integrating RE in non-energy intensive industries:

- indirect use of RE through increased use of electricity including electro-thermal processes;
- indirect use through co-location with biomass-based industries that generate waste heat at suitable temperatures;
- direct use of solar thermal energy for process heat and steam demands; and
- direct use of geothermal for process heat and steam demands.

Other RE sources may also find industrial applications.

Non-energy intensive industries, although numerous, account for a smaller share of total energy use than energy-itensive 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 (Schnitzer et al., 2007; IEA, 2007a). Solar thermal collector capacity in operation world wide in 2007 was almost 150 GW but less than 1% is in industrial applications (IEA-SHC, 2009).

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, some chemical reactions and space heating. 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. 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 or nuclear 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 production, the mills can be self-sufficient in 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. Advanced CHP technologies can make electricity available for export.

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. could 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, typically between different entities within the same company group (Wolf and Petersson, 2007). The potential for increased indirect use of RE in sucxh 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 various geographical and climatatic 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 have the largest impact both 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 transport and building sectors than on industry and consequently potentials are relatively un-charted.

8.3.3.3.1 Case study: 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 USD 0.20-0.30/ 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.

8.3.3.3.2 Case Study: 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. 43). (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 et al., 2008).

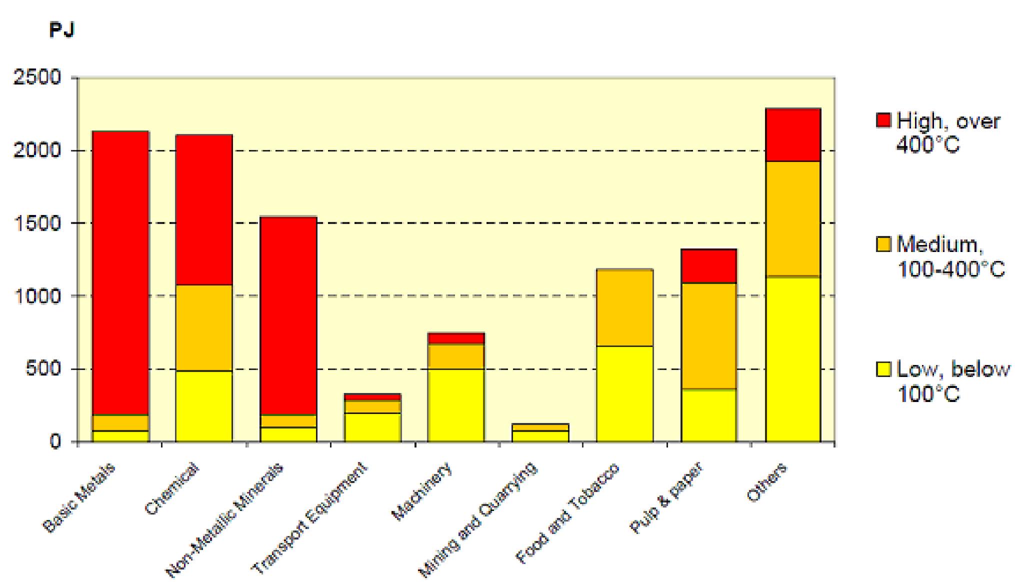


Figure 8.43: Industrial heat demands by temperature quality and by manufacturing sector for 32 European countries. (Werner, 2006).

Solar thermal energy technologies can be used to supply industrial heat including parabolic trough collectors (PTC) that can produce steam directly in the collector. A pilot plant installed at the production facilities of ALANOD[10] in Ennepetal, Germany in February 2007, the P3 project, aims to demonstrate direct steam generation in small parabolic trough collectors for industrial applications (Hennecke et al., 2008). The principal options for the integration of solar steam (Fig. 8.44) 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.

[10] One of the products of this aluminium anodizing plant is MiroSun™, an aluminium based mirror also used as reflector material in the SOLITEM PTC 1800 parabolic trough collector.

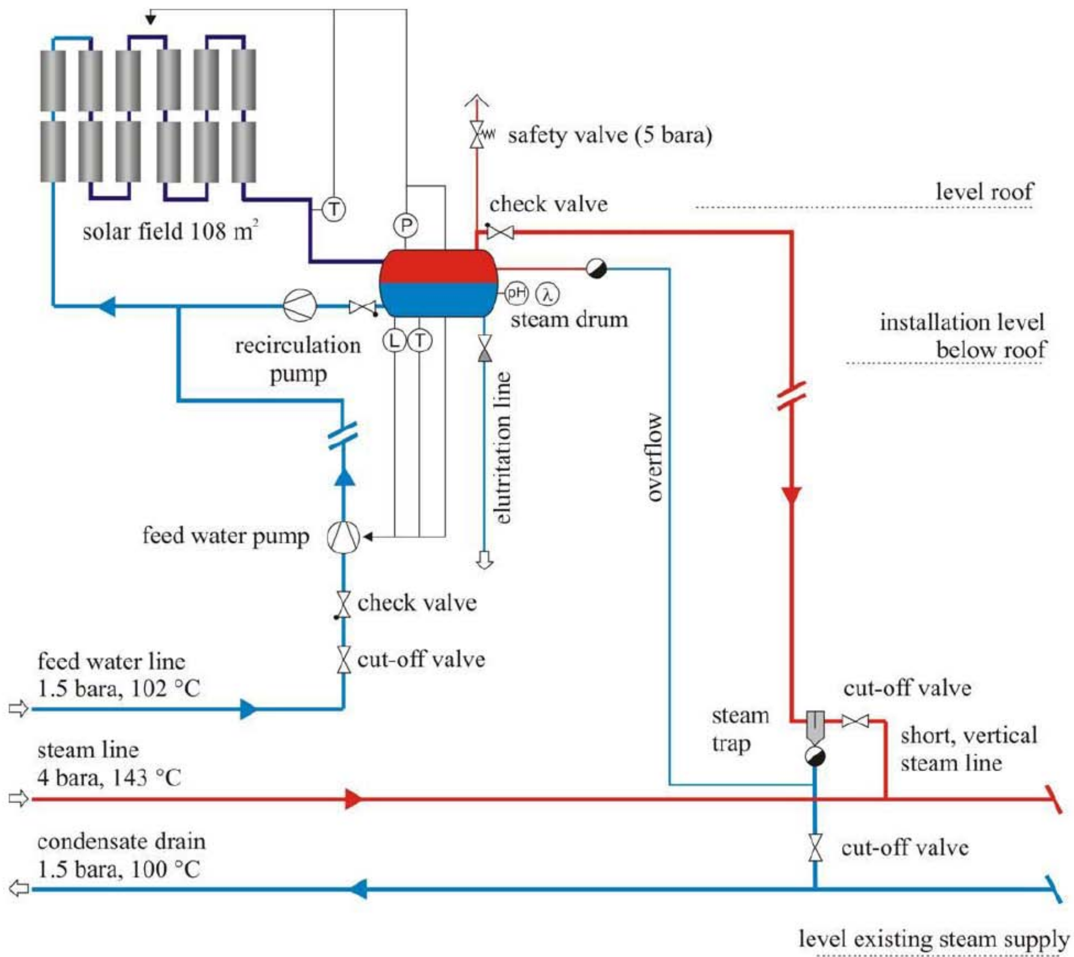


Figure 8.44: Layout of a direct solar steam integration system to be integrated at the ALANOD factory, Ennepetal, Germany (Hennecke et al., 2008).

8.3.3.3.3 Case Study: Ocean energy desalination

Desalination to produce fresh water is a growing industrial process. The two main process options are thermal (distillation) and membrane. RE-driven desalination systems are conceivable including stand-alone systems using variable RE sources since the product, potable water, can be stored cheaply (Koroneos et al., 2007). The National Institute of Ocean Technology, India, has developed a low temperature thermal desalination (LTTD) process and demonstrated it in the Lakshadweep islands. Low temperature evaporation of surface water at reduced pressure generates vapour which is condensed using deep sea-water at 12°C from 400 m water depth. After successful demonstration three more plants are now being built. The impact on the life and health of the islanders is remarkable as stomach disorders and various ailments related to dietary salt excess have been reduced. A barge-mounted offshore LTTD plant has also been demonstrated. Next development steps include the integration of an ocean thermal energy conversion module to power the LTTD plant to eliminate the need for purchased diesel or electricity (IEA-OES, 2008).

8.3.4 Agriculture, forestry and fishing

There has been a long and complex relationship between primary production, energy inputs and land use. Subsistence farming and fishing, as still practised in many regions of the world in order to feed billions of people living in rural areas, rely largely on human energy (as manual labour) and animal power. Biomass from crop residues and fuelwood, often scavenged from long distances, remains an essential energy source for cooking and heating applications (section 8.3.1.2). Conversely, industrialised agriculture, forest and fishing industries depend on significant energy inputs over and above the natural energy resource obtained from the sun. Intensive production of livestock, fish, crops and trees is widely practised in many countries to provide food and fibre products for consumption by city-dwellers. Energy inputs are mainly fossil fuels that are either combusted:

- directly for heating, drying and to power boats, tractors and machinery, or
- indirectly to manufacture fertilisers and agri-chemicals, construct buildings and fences, as well as to generate electricity for water pumping, lighting, cooling and operating fixed equipment.

For some food products such as potatoes, the 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, there are variations depending on the boundaries used and assumptions made and a positive energy ratio for potatoes has also been reported in Iran (Mohamaddi et al., 2008).

Typically in OECD countries, energy demand for the agriculture sector is around 5% of total consumer energy. Energy efficiency measures are being implemented in various farm and forest activities including tractor operation, milking shed power demands, cool store refrigeration, greenhouse heating etc. Future opportunities exist to reduce fertiliser and agri-chemical inputs by using precision farming application methods based on GPS techniques (USDA, 2009), improved manufacturing techniques and organic farming systems.

Primary industries can also provide a number of biomass energy carriers such as crop residues, animal manures, forest residues, meat wastes, fish wastes and energy crops. These can be used for a range of applications including liquid biofuels.[11] Landowners also have access to RE resources including wind, solar radiation, potential energy in rivers and streams and geothermal heat. Their availability varies with different farm enterprises depending on land use, terrain and location (Table 8.14). Wherever land is farmed, wind turbines could also be constructed on suitable sites and solar systems installed on farm buildings or directly on the ground to provide power, heat for drying crops, or irrigation water pumping. Ground source heat pumps could also be installed to meet low-grade heat demands.

Currently land use and land use change accounts for around 30% of total greenhouse gas emissions. A small amount arising from fossil fuel energy inputs but most coming 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 (Wilton 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 Meinzen-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,

[11] 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 and fibre processing operations are covered in the Industry section 8.3.3.

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 (Kugulman and Levenstein, 2009) or provide benefits when the advantages are equally shared, such as Brazilian sugar ethanol companies investing in Ghana (Renewable Energy World, 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.

8.3.4.1 Status and strategies

Large regional differences occur in primary production around the world due to climate, seasons, weather patterns, terrain, soil types, precipitation, cultural practices, land use history and ownership, and farm management using intensive or extensive methods (subsistence farming, versus low input (organic) farming, versus high input, industrialised farming). The classification of land ared and use by country or region can be found at the UN Food and Agriculture Organisation's web site faostat.fao.org. [TSU: URLs are to be cited only in footnotes or reference list.]

The integration of land use with the development of RE projects for electricity generation is well established. There are many examples of wind farms constructed on pasture and crop lands in areas with good mean annual wind speeds that have resulted from identification of the economic benefits from multi-purpose land use to the landowner. Only 2 to 3% of the total land area needs to be taken out of agricultural production for access roads, turbine foundations and control centre buildings. Installations can range from privately-owned, micro-scale (1 – 100 kW) plants that solely meet local individual or village demand, up to corporate–owned, large-scale (100s MW) where the power generated can be exported off the property to provide a return on the investment. Similar opportunities exist for small and large hydropower projects (although social disbenefits for local residents can also exist – see Chapter 9). Proximity to the load or to a nearby transmission grid, in order to avoid construction of costly power lines over long distances, can affect the economic viability of a project.

Hydropower projects are limited by local waterway characteristics. Having a high head is usually more efficient than a high flow. However low head turbines have been developed for run-of-waterway applications (using low weirs rather than high dams with water storage potential) including operation in low gradient water distribution channels to power the irrigation pumps (EECA, 2008).

Table 8.14: Primary production from industrial scale enterprises showing energy demand, energy use intensity (GJ/ha of land or buildings), RE resources available and potential for energy export across the farm boundary.

Type of enterprise	Direct energy inputs	Energy use intensity	Potential renewable energy resource	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 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 systems if roof space available.	Limited as used on-site.
Poultry	Electricity for lighting, heating, cleaning.	High if housed indoors, but low if free-ranging.	Combustion of litter for CHP. Solar systems.	High. Several multi-MW power plants already operating in UK, US.
Arable (e.g. cereals, maize, rapeseed, soyabean, cotton, rice, sugarcane, cassava, 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 where streams suitable.	High where energy crops are purpose-grown.
Vegetables large scale (onions, potatoes, carrots, etc.)	Diesel. Electricity for grading, conveying irrigation, cooling.	High for machinery. Medium if rainfed. 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	Diesel for machinery. Electricity for washing, grading.	Medium. Low for post-harvest.	Some residues and rejects for biogas.	Low.

Type of enterprise	Direct energy inputs	Energy use intensity	Potential renewable energy resource	Energy export potential
(mixture)		Medium if cool-stores.		
Nursery cropping	Diesel for machinery Heat for protected houses.	Low. Medium.	Some residues and rejects for combustion.	Low.
Greenhouse production	Electricity for ventilation, lighting and heating (or gas, oil or biomass).	High where heated. Medium if unheated.	Some residues and rejects for combustion.	Low.
Orchard (pip fruit, olives, bananas, pineapple)	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 plantation crops (pine, spruce, eucalyptus, palm oil, etc)	Diesel for planting, pruning and harvesting.	Low.	Forest residues. Short rotation forest crops. Oil palm bunches.	High – large volumes of biomass for CHP or possibly 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 Medium if facilities off-shore. Medium.	Residues 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.	Residues for biogas and oil.	Low.

Solar thermal systems have been commonly used for water heating, especially in dairy milking sheds, as well as for the drying of fruit and vegetables. Post-harvest chilling of fresh products using solar sorption technologies (Fan et al., 2007) remains in the development stage, but the technology holds good promise for air-conditioning, refrigeration, ice making and congelation of food products especially for hot regions.

Geothermal heat from natural hot water or steam near the Earth's surface has been used for various thermal applications in limited locations where the resource exists including for heating greenhouses and fish and prawn farming (Lund, 2002). Ground source heat pumps could have widespread use with applications for fruit and vegetable desiccation, heating animal livestock houses and drying timber, although the technology would not compete with simpler outdoor solar drying in sunny regions.

Biomass resources are commonly used to meet local agricultural and rural community energy demands. Although many examples exist, developing a 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. Guidelines to assist project developers and city planners have therefore been produced (IEA, 2007b).

Anaerobic digestion of animal manures, food and fibre processing wastes, or green crops to produce biogas is a well understood technology (Chapter 2). Fish processing residues can also be utilised, but tend to be dried and ground for animal feed. Chicken litter, with a major component of sawdust or shavings, is often better used for direct combustion. 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). Gas storage is costly, so matching supply with demand is a challenge for the system designer. Larger community scale plants have been successfully developed in Denmark, India, Indonesia and elsewhere. The odourless, digested solid residues can be used for soil conditioning and nutrient replenishment.

Dry crop residues such as rice husks, coconut shells 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) is around 50% moisture content (wet basis). So to avoid a major disposal problem it has traditionally been combusted inefficiently to provide just sufficient heat and power to supply the refinery, though with high levels of air pollutants. Partly resulting from the privatisation of the electricity industry in many countries, a number of sugar plant owners have now invested in very efficient CHP plants that generate around 5 to 10 times more 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).

Bagasse, husks, nut shells, etc. are produced at the processing plant, and therefore, in effect, are delivered free-on-site. 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 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. Although used mainly for heat and power production at present, with the possible advent of 2nd generation liquid biofuels from ligno-cellulosic feedstocks (IEA, 2008a), competition for this limited biomass resource could result in some regions. As a result, purpose-grown energy cropping has been proposed as a source of ligno-cellulose.

8.3.4.2 Pathways for renewable energy adoption

Much land under cultivation could simultaneously be used for RE production. Market drivers for RE power generation on rural land and waterways include electrification of rural areas, energy security and the avoidance of transmission line capacity upgrading where loads are increasing.

Many sites in Europe and elsewhere that used to house water mills could be utilised today for run-of-river micro-hydro power generation schemes. Fish farms may be able to utilise local waves or ocean currents for power generation opportunities in the future. In many cases much of the RE potential would be best utilised on the property to displace imported energy needed to run the enterprise (Table 8.14).

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. 8.45) 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, 2006).

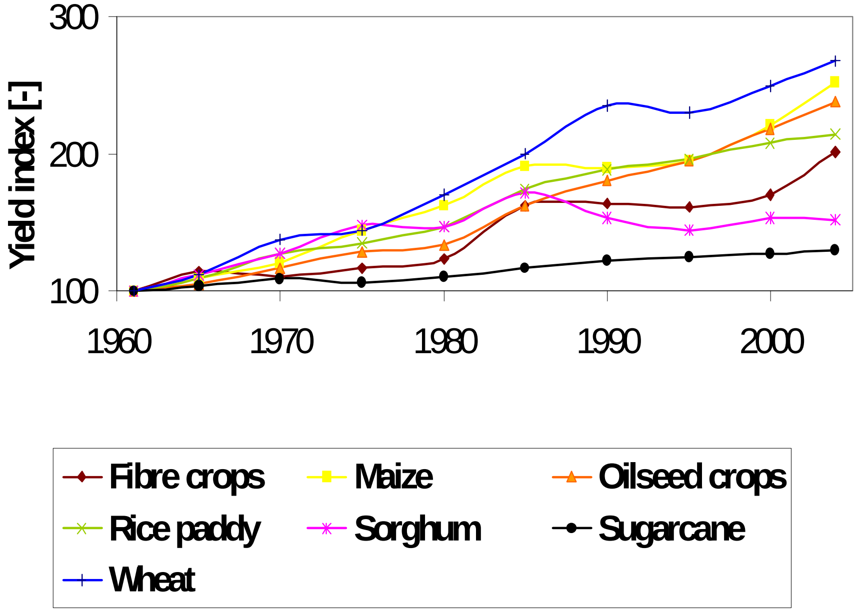


Figure 8.45: Increased productivity per hectare for a range of crops over the past few decades compared with base year 1962 (FAO, 2009).

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 becoming common, such as wind turbines constructed on grazing land, on-farm biogas plants, and crops grown to provide liquid biofuels and co-food products. The technologies are largely mature. However, based on the huge amount of RE resources available on farms and plantation lands, 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

RE is likely to be used to a greater degree by the global agricultural sector in the future to supply energy demands for primary production and post-harvest operations at both the large and small scales using a wide range of conversion technologies. The integration of RE with food and fibre production on the same land can provide a co-revenue stream for land owners. This will encourage steps towards sustainable development to be made in developing countries since the affordable supply of useful energy services is a critical component.

Distributed energy systems based on RE technologies are beginning to gain further traction in cities (IEA, 2009b) and also have large potential in rural areas. This concept, being developed for uptake in OECD countries, could 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". 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. 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 (Lehmann, 2007).

8.3.4.5 Case study. Distributed generation in a rural community

There are promising opportunities for rural communities to benefit by capturing and using local RE systems and exporting excess power to the grid. Distributed energy can provide climate change mitigation benefits, lead to sustainable development in developing countries, as well as give increased security of supply. A small demonstration project at Totara Valley, New Zealand aims to:

- demonstrate a decision making methodology for rural communities whereby the local energy resources can 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 supply companies and circumvent the commercial conundrum of having to supply the more remote customers for limited commercial gain; 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 et al., 2002) and enabled a series of electricity profiles to be produced showing both seasonal and daily variations (Figure 8.46) and identifying opportunities for energy efficiency improvements, solar water heaters and heat pumps. The wind speed and direction (together with the solar radiation resources) were monitored to develop a method of showing seasonal and daily variations.

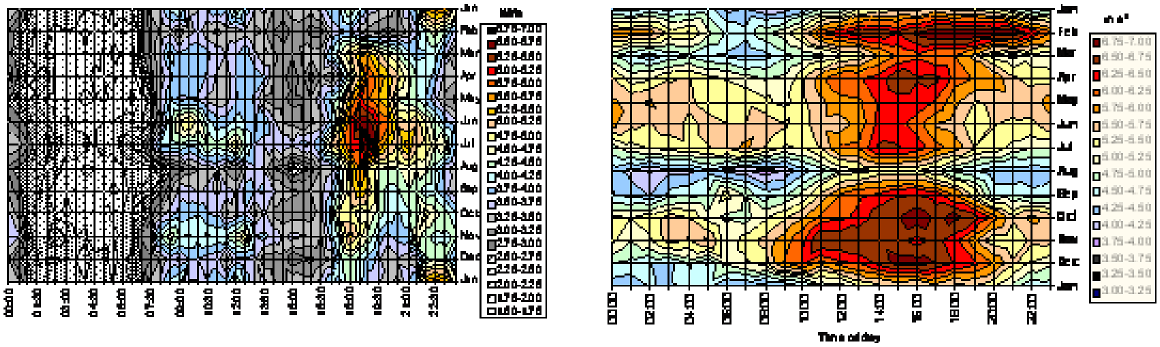


Figure 8.46: Average seasonal and daily electricity demand for the Totara Valley community households in kWh consumption per 30 minute period with annual and daily wind data showing a reasonable match with the demand. [TSU: Source?]

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 USD 13,000 TSU: Needs to be presented in 2005 US$] it is used to power an electrolyser (Sudol, 2009). The hydrogen produced is piped down to a fuel cell with losses of only around 1%. The pipe is used as an energy storage system for when the wind does not blow. A 1kW Pelton micro-hydro turbine was installed. Since wind and solar are variable and intermittent, 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. Several options exist to provide good quality and reliable power supply systems to a rural community.

- Each building could have its own independent generation system often combining wind and solar with 3 or 4 day battery storage and a small gasoline generator as back-up.
- The community could be independent with several sources of small-scale generation, possibly located on more than one property and with a mini-grid to connect all the generation plants and to supply all the buildings. This could require battery storage or diesel generation back-up for when the demand exceeded the supply. At Totara Valley a biodiesel-generator is controlled remotely by the line company when extra capacity is needed. Water heaters and cool stores on the farms provide load demand control as well.
- If already connected to a grid, the community could continue to use mains power in the usual way, but with the risk of ever increasing fixed supply charges to cover maintenance costs and eventual replacement of the lines and poles should they go down in a storm.
- The grid could be used as a “battery” for when demand exceeds supply from the power generated on site. This could be attractive to a distribution company when a line is reaching its maximum transmitting capacity. An expensive upgrade could be avoided by installing this embedded generation.

A line company could therefore have a strong business interest in becoming a joint venture partner in such a scheme, possibly to purchase and lease the power generation equipment to the community members. A related study from the line company perspective (Jayamaha, 2006), modelled different scales of communities (Figure 8.47).

Suitable controls and metering systems will need to be developed to integrate various generation technologies between users and the local grid and to enable metering of both imported and exported power to be achieved (Gardiner et al., 2008).

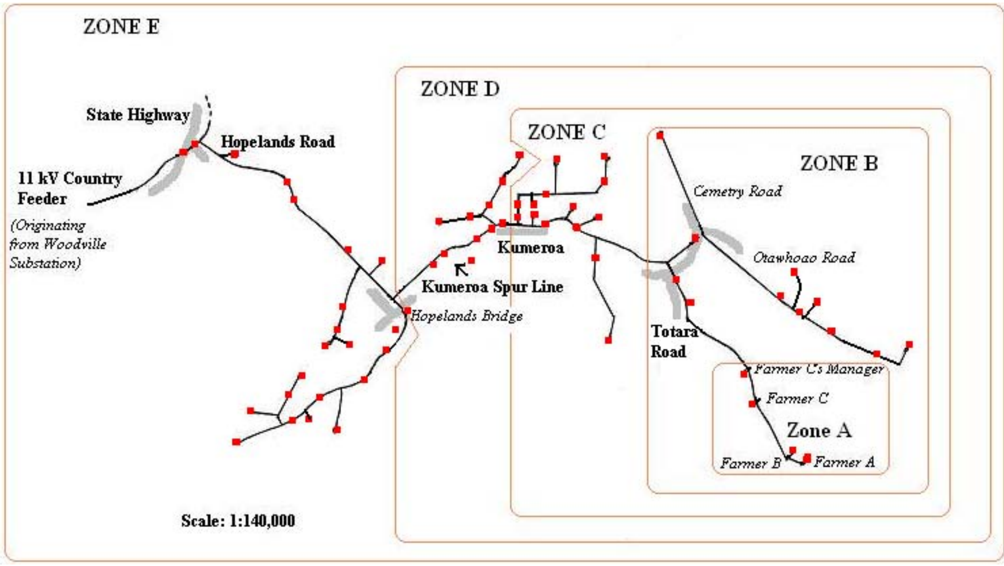


Figure 8.47: The power distribution feeder reaching Totara Valley (Zone A) is the end of the line. Larger community scales using their local RE resources (Zones A, B, C, D or E) could show greater economic benefits. (Farm and other building clusters with power loads are shown as red squares).

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 9

Renewable Energy in the Context of Sustainable Development

Chapter:	9				
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(Sub)Section:	All				
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COMMENTS BY TSU TO EXPERT REVIEWERS

Yellow highlighted – original chapter text to which comments are referenced

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

Chapter 9 has been allocated a total of 68 pages in the SRREN. The actual chapter length (excluding references & cover page) is 59 pages: a total of 9 pages below.

Expert reviewers are kindly asked to indicate where the Chapter could be shortened by 4-11 pages in terms of text and/or figures and tables to reach the mean length.

In addition, all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 9: Renewable Energy in the Context of Sustainable Development

CONTENTS

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 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. For most nations, increasing sustainability will be about navigating through an unexplored and evolving landscape.

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. 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, reduce hunger, increase access to safe drinking water, allow lighting that permits home study, increase security, etc. Moreover, efficient use of energy sources and good management can help to achieve sustainable use of natural resources and reduce deforestation.

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 being generally diffuse, not fully accessible, sometimes intermittent and regionally variable. To weigh the positive effects against the negative ones can be a lengthy and complex task, e.g., small vs. large hydro power. An expedient way out of the controversy was to define small hydropower as being renewable, and eligible for government support, and excluding large hydropower from subsidies or other incentive measures. 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.

9.1 Introduction

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” (WCED, 1987; Bojo et al., 1992).

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 et al., 2003; MA: Millennium Ecosystems Assessment, 2005).

Renewable energy applications are essential to deliver genuine results on Millennium Development Goals and all five World Summit on Sustainable Development 2002 (WSSD) development 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.

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 (Intergovernmental Panel on Climate Change), 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.

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[1].

The goal of this chapter is thus to summarize and consolidate the material reported in the other chapters. It begins by highlighting the two-way relationship between SD and renewable energy in Section 9.2. The discussion focuses on the impacts of renewables on the environment in Section 9.3 and on socio-economic aspects in Section 9.4. Section 9.5 describes the implications of sustainable development pathways for renewables and finally Section 9.6 synthesizes the above material particularly the policy implications including socio-economic and environmental considerations on the renewable potential.

[1] This material will be clarified and expanded after the zero order drafts are received

9.1.1 The Two-way Relationship between Sustainable Development and Renewables

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. Table 1 describes the positive and negative impacts of renewables, fossil fuels ands nuclear energy technologies on a variety of selected SD indicators. 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. The use of bioenergy and efficient cook stoves can enhance productivity, and promote social harmony and gender equality. 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 (Section 9.3), and economic and social (Section 9.4). 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 reverse implications of SD paths 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. The two-way relationship between SD and renewables thus is a key feature which is described in Section 9.4.1 and Table 2.

Climate change is 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 SRES, 2000) and cause changes in regional and severity of precipitation patterns, sea level rise and flooding, regional temperature increases, wind storms, and sea level rise. 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 on sea level rise, 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 adaption strategies. Micro grids using PV technologies for instance can serve as a means of electricity in cyclone shelters.

9.1.2 Energy Indicators of Sustainable Development

To make development 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, Najam, 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. 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 generation, (6) lack of storage facilities, (7) inadequate capacity to build and monitor performance of renewables, and (8) impact on agricultural land use.

Higher first cost of renewable energy technologies compared to conventional generation options hinders their large scale adoption particularly in developing countries, where cost is a prime concern. Since environmental and social costs of conventional generation options are not monetized, renewable energy does not have a level playing field given that it has advantages over conventional generation on these fronts. Subsidies to fossil fuel technologies are common across many countries which makes it difficult to justify the cost-effectiveness of renewable technologies in remote areas for instance.

Wind energy can be very seasonal which can lead to a low capacity factor. In addition, data on off-shore wind resources is often limited. Solar thermal (and photovoltaic) generation, some of which does not have significant storage potential, will not match the evening peaking system in most countries thus reducing the value of its generation. Such characteristics of renewable resources hinder their large scale adoption.

Other renewable energy options such as biomass/biogas and small hydro face many constraints related to scale, cost, institutional capacity, and integration policies. Access of renewable generation to the grid is an issue. A rational tariff setting framework, appropriate and simple interconnection for small RE, and solutions for the inter-state transfer of RE are ways that grid integration can be enhanced.

International opportunities for transfer of funds and technologies are being pursued on several fronts. These include the use of the Clean Development Mechanism, Clean Technology Fund established recently by the IBRD, and many bilateral activities. In addition, in many countries, renewable portfolio standards have been promulgated, and are being implemented in the US and India for example. Innovative financing mechanisms are being pursued in Bangladesh by the Grameen Bank to support the introduction of solar technologies at the village level.

Ultimately capacity building is a key barrier to the rapid transfer of technologies across and within countries. Lack of capacity to set 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 energy

9.2.1 Past and present roles of renewable energy for development

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, 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 et al., 1984), and governments are considered responsible for meeting this fundamental human need, along with 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 for sustainable development in the near to mid-term.

Central issues for renewable energy in the modern context include all three of the dimensions of energy services for development:

- Abundance. Based on currently available 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. Clearly, Brazil stands out as a sizeable economy built to a considerable degree on hydropower, plus significant attention to biofuels but realistic 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 use of wind power as an electricity source.

- Reliability. 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.

- 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. 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. For example, where kerosene is important for cooking and lighting in lower-income rural areas in developing countries, or where electricity is becoming important for job creation, interventions in energy markets in order to make renewable energy sources more competitive with fossil sources could have severe development impacts in some areas.

9.2.2 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 in the colonial period, 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:

- Rural settlements. 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). One focus for this effort became the World Summit on Sustainable Development in 2002, which confirmed that energy is a basic human need and supported such initiatives as the UNEP Global Clean Energy Network and the Global Village Energy Partnership, along with adding support for sustained attention to rural energy needs by the World Bank (World Bank, 1996). 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.

- Urban settlements. 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, 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.

9.2.3 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. 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).

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

9.2.4 Energy security as an aspect of sustainable development

Where reliability of energy services is important to sustainable development, which is nearly always the case, threats to that reliability – 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 Banks, 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 Environmental Impacts: global and regional assessment

9.3.1 Introduction

Development and exploitation of renewable energy have increasingly been 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. They are relatively cleaner in terms of GHG emissions, environmental pollution than the fossil energy sources Apart from hydropower, windpower (White, 2007) and bioenergy (Blanco-Canqui and Lal, 2009; Liska et al., 2009; Luo et al., 2009), literature on the impacts of other renewables-direct solar, geothermal and ocean energy sources on environment is rather limited. In this section, environmental impacts of renewable energy sources on land, water, air, ecosystems and biodiversity, human health and built environment are discussed for bioenergy, direct solar and hydropower sources.

9.3.2 Bioenergy

9.3.2.1 Land

Bioenergy from crops is an important source of renewable energy and large-scale land use changes due to bioenergy production 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 et al., 2009; Searchinger et al., 2008).

To help alleviate potential conflicts over land use, 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.

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 et al., 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 et al., 2007).

9.3.2.2 Water

The expansion of land for growing bioenergy crops can impact the quantity and quality of surface water and groundwater through nitrate pollution from the applied fertilizers (Lovett et al., 2009).

9.3.2.3 Air

The chemical structures of bioenergy resources make them a potentially renewable and 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 et al., 2007). However, in practice some biofuel chains 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). 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 CO_2, using bioenergy leads to smaller emissions of SO_2 compared with the use of coal. Biomass such as municipal organic waste contains small quantity of sulphur and SO_2 can be released into the atmosphere through the combustion process for biogas manufacturing. Note that emissions of SO_2, CO, and NO_x from biogas are considered trivial (Fan et al., 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.

9.3.2.4 Ecosystems and Biodiversity

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 is likely to eliminate niches for some species living on that land through conversion processes, but can create niches for a new suite of species (Firbank, 2007). One of the major negative impacts of bioenergy production on biodiversity 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). Another major negative impact occurs through introduction of invasive crop species, e.g., switchgrass, giant reed, and miscanthus (Barney and DiTomaso, 2008). Another 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, 2007).

9.3.2.5 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.

9.3.2.6 Built Environment

Growing energy 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). Poor people are usually settled in marginal and degraded lands. Any expansion for bioenergy plantation to these lands could result in displacement of these rural poor (Johansson and Azar, 2007).

9.3.3 Direct Solar Energy

Most sources of renewable energy are related to the Sun and are dependent on it in one way or another. The heat from solar energy sets up the differences in temperature and pressure that cause wind and waves, provides rainfall and melts snow. These will in turn generate the mechanical energy that is required to drive water mills and turbines to produce hydroelectical energy. Therefore, solar energy can be converted into two main forms of energy: as a source of heat, and by converting the radiation into electricity (Springer Netherlands, 2008).

Solar energy can be used for thermal applications such as water and space heating. Currently, these applications mainly use electricity, fossil fuels and traditional or modern biomass as their energy source. Solar hot water systems are a widely available technology in today's world and can be used to satisfy the hot water requirements of typical homes (Torrie et al., 2002). Installing solar water heaters can reduce the electricity or fossil fuels commonly used for water heating by 40% to 50%, hence reducing the energy bills of residents by the same amount (Etcheverry et al., 2004). Due to the popular concept of energy conservation measures, the demand for hot water through fossil energy in a typical home will likely be reduced. This reduction may result in solar hot water heaters providing an even larger share of a typical home's hot water needs. In addition, mass production of solar hot water systems e.g., in apartment houses and multi-storied office buildings could cause a significant reduction in the price (Torrie et al., 2002). Aside from thermal applications to heat water, solar energy can be used to heat spaces. In addition to heating purposes, solar energy can be used to generate electricity using solar photovoltaic (PV) systems.

9.3.3.1 Land

Solar energy can be used as a non-chemical alternative to soil disinfection. During intensive agriculture, agricultural lands can deteriorate and become infected with pathogens, insects, and weeds, which negatively affect the quality of crops (Camilo et al., 2007). Currently, methyl bromide is the common pesticide that is used to disinfect agricultural lands but its gaseous toxins deplete the stratospheric ozone layer. Steam soil disinfection is a highly efficient method and a safe alternative that 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).

Typically, large land areas are not required to produce solar energy. This is especially of concern in urban environments where there is likely shortage of available land. 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 (Guen and Steemers, 2008).

9.3.3.2 Water

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).

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. This method uses readily available chemicals and materials salvaged from waste streams, and eliminate the use of specialized laboratory equipment (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).

9.3.3.3 Air

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).

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). The pollution produced in the manufacturing stage of the solar collectors is estimated by calculating the energy invested in the manufacture and assembly of the collectors and estimating the pollution produced by this energy (Kalogirou, 2008).

9.3.3.4 Human Health

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.

9.3.3.5 Built Environment/Visual Aspects

As was mentioned before, solar energy technologies such as 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, “solar chimneys” that are used to produce electricity using solar radiation could be as high as 1 km with turbines near the base, which can affect visual aspects of the built environment (Springer Netherlands, 2008).

9.3.4 Geothermal Energy

Geothermal fuels have considerably higher potential (up to 75%) for reducing GHG emissions compared to fossil fuels used for power generation (Etcheverry et al., 2004). In addition to existing natural wastes, they produce limited additional local pollution with some exceptions (e.g., waste heat stream), but depending on the technology used, they may have some adverse environmental impacts. Technologically, three types of geothermal power plants- dry steam; flash steam and binary-cycle are now operating.

9.3.4.1 Water

Any release of polluted water from the geothermal plant 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).

9.3.4.2 Air

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 (U.S. Department of Energy, 2009).

9.3.4.3 Ecosystems and biodiversity

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.

9.3.4.4 Human health

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 (Mariita, 2002). With established monitoring systems in potential areas of water and air pollution, the geothermal plants become practically safe for people.

9.3.4.5 Built environment (visual aspects, infrastructural aspects, transmission lines, settlement etc.)

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.

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.

9.3.5 Hydropower

Hydropower generation is currently contributing slightly over 16% to global energy supply (IHA, 2005) and is the highest contributor among all the renewable energy technologies. Because hydropower requires storage of vast amount of water, in many ways it interacts with environment, ecology and livelihoods.

9.3.5.1 Land Submergence

Dams have been built for thousands of years throughout history for irrigation, flood control, management of water supply and for mechanical power and electricity generation for more than a hundred years. Despite the benefits however, 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). In addition, 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).

9.3.5.2 Water-quantity/quality

Constructing hydropower dams and reservoirs can dramatically affect the quality of water. 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. Additionally, reservoirs provide for fisheries because of the storage of high amount of nutrients in the water (Kaygusuz, 2009).

Hydropower dam construction and operation 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).

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, aka river fragmentations, occur (Anderson et al., 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 et al., 2008).

9.3.5.3 Emissions and Air Quality

Hydropower is considered a green technology, as it has very few greenhouse gas emissions compared with other large-scale fossil energy options. It produces 60 times less greenhouse gas emissions than those from coal-fired power plants, and 18-30 times less than natural gas power plants (Canadian Hydropower Association, 2009). 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 (Government of Canada).

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 buildup and release of methane gas, a potent greenhouse gas (US EPA). 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).

9.3.5.4 Ecosystems and biodiversity

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; Craig, 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 et al. 1996). These losses could occur over extensive spatial and temporal scales. Rancourt and Parent (1994) documented loss of biodiversity for the La Grande development project in Canada which operates a chain of reservoirs. Fearnside (2001) listed loss of forests which led to loss of natural ecosystems in the Tucuruı´ Dam in Brazil.

9.3.5.5 Human health

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 (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 1) .

Table 1: 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 Food security affected on flood plains and estuaries (farming and fishing), water related diseases, dam failure and flooding
Downstream river	Changes in food security, vector borne and water related diseases

Irrigation areas	Water related diseases, sexually transmitted diseases, HIV/AIDS, accidents and occupational injuries
Construction activities	Communicable diseases, violence and injury, water related diseases, loss of food security
Resettlement areas	Macro-economic impacts on health, inequitable allocation of revenue, health impacts of climate change
Country/regional/global	

Source: Oud and Muir, 1997.

9.3.5.6 Built environment (visual aspects, infrastructural aspects, settlement etc.)

Hydropower projects usually create adverse as well as positive 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. Similar damages also reported from the Three Gorges Dam in China. 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 centers. The reservoirs are usually used for recreational purposes.

9.3.6 Ocean energy

The ocean energy technologies can have very different environmental effect, depending on the type of technology employed and its location (Pelc and Fujita, 2002). Following are the currently available technologies: Tidal and current power stations (in turn, there are two types of them: barrage systems and stream systems); wave energy stations (several types of devices); ocean thermal energy conversion (OTEC); and salinity gradient energy (SGE). However, our current understanding of the effects of intervention through the ocean energy technology on the marine environment is limited because for now, ocean energy production is mostly at experimental stage, and, except for few tidal installations, there are no industrial power stations based on ocean energy.

9.3.6.1 Land

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. The OTEC technology requires small surface area; if located in a platform, only land is required for the cable and connecting to the station. 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).

9.3.6.2 Water

The barrage tidal stations can increase some water pollution above of them. Brackish water waste and polluted polyethylene membranes from the 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.

9.3.6.3 Air

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 (Cohen et al., 1982).

9.3.6.4 Ecosystems and biodiversity

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 (Tidal power, 2009). Colwell (1997) argued that problems would arise during quantification of environmental capital of the recreated environment compared to the original one, which possesses a wide array of values.

Sea streams (including tidal ones) are not as severe as those for a tidal barrage. They are positioned in the sea bed and this might have an effect on the aquatic life in that particular area. This site-specific can be avoided or minimized through proper environmental impact assessments (Tidal power, 2009).

The SGE 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, Lay, 1993).

Organisms impinged by an OTEC 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).

9.3.6.5 Human health

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. However, the risks are not larger than those for other industrial applications involving these chemicals.

9.3.6.6 Built environment

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. The result, for example, of an oil tanker colliding with an array may have consequences for colonies of seabirds in the locality (Thorpe, 1999).

9.3.7 Wind Energy

Wind is the fastest growing source of renewable energy in the world (Etcheverry et al., 2004). Beyond the process of production of power-generating and storage devices, it does not result in any emissions. Nevertheless, wind power plants can affect the environment in other ways.

9.3.7.1 Land

Compared to other types of power production, the wind power plants occupy less space (Canadian Wind Energy Association, 2009). 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.

9.3.7.2 Water

Except for making the wind farm equipment and cleaning the rotor blades, water is not used during the wind energy production. Wind energy is one of the technologies least influencing the water sources (U.S. DOE, 2009).

9.3.7.3 Air

Once again, except for making the wind farm equipment, the wind energy production is one of the most environment-friendly technologies. The wind energy plant itself does not produce any emissions to the air.

9.3.7.4 Ecosystems and biodiversity

Fatalities of birds by flying into wind 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. 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 et al., 1996).

There are many ways to minimize risks to local and migratory birds. 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 with birds. They consider the location of common migratory bird routes and, wherever possible, avoid those areas for wind farms.

9.3.7.5 Human health

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. 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 et al., 2006).

9.3.7.6 Built environment

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. Experience in Europe and U.S. has shown that wind turbines can easily and safely coexist with all types of radar and radio installations (Canadian Wind Energy Association, 2009).

9.3.8 Assessment and comparison of environmental impacts

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 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 (CEC 2009) and the U.S. EPA's Renewable Fuel Standard (U.S. 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 9.2. 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.

9.4 Socio-economic Impacts: global and regional assessment *(energy supply security)*

9.4.1 Sustainable Development Links to Renewable Energy Options

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 described in Table 2: 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, allow education during the night period. Local pollution and health benefits are improved.

In some cases, there are also impacts associated with these technologies – as shown in Table 2 – 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.

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).

Table 2: RE and conventional technologies and impact on selected SD indicators (Draft quantitative data)

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 is provided where data are available.

Selected SD Indicators	**RE Technologies**						**Conventional Fossil Fuel Technologies**			**Nuclear**
	Bio-Energy	***Direct Solar***	***Geothermal Energy***	***Hydro Power***	***Ocean Energy***	***Wind***	***Oil***	***Gas***	***Coal***	
Environmental										
Emissions and Air Quality Unit: gCO_2e/kWh	Sustainable GHG emissions, but there is a risk of unsustainable harvesting. Emissions contribution to air quality. Indoor PM, CO from fuelwood. PM, CO, NOx from harvest burning and land clearing (including deforestation). 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) Wood 120 [1]	Minor emissions during operations. Lifecycle emissions are more important. 90 [2] PV (9.4 – 300) [3] 60 [1] Solar Thermal (36.2 – 202) [3]	Site specific emissions, including sulfur compounds. Lifecycle emissions. 170 [2]	Methane emissions from reservoirs, very high range, site specific. Lifecycle emissions, mainly in construction phase. 41 [2] Small Hydro (18 - 74.9) [3]	No emissions during operations. Lifecycle emissions. Neutral [4]	No emissions during operations. Lifecycle emissions. (20 - 25) [2] [3]	Significant emissions of pollutants (PM, SOx, NOx, VOCs, heavy metals) and GHGs, some of which can be mitigated Oli 870 [1] Diesel 730 [1]	Significant emissions of pollutants (less than oil and coal, except NOx in some cases) and GHGs, some of which can be mitigated 543 [2] Natural Gas 650 [1] Natural Gas CC 440 [1] Gas 590	Significant emissions of pollutants (PM, SOx, NOx, VOCs, heavy metals) and GHGs, requiring controls for reduction. 1,004 [2] Lignite 1,240 [1] Hard Coal 1,060 [1]	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. 30 [1] (in the complete nuclear power chain)

Water Quantity and Quality Unit: m^3/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 m^3/MWh [5] Biodiesel-perennials 1200000 m^3/MWh [5] Biomass (1134 - 1814) Lt/MWh [6] Wates (residuums) (756 - 1814) Lt/MWh [6] Fossil/Biomass steam turbine Open Loop (200 – 300) Gal/MWhe [7] Closed Loop (300 – 480)	Limited water usage and pollution during manufacturing and utilization Can be utilized to disinfect biologically contaminated water 10 [2] Concentrating Solar 740 Gal/MWhe [7] PV 0.0 Gal/MWhe [7] Solar Thermal 311 Gal/MWha [8] Large Solar Thermal (800 - 1000) Gal/MWha [8] PV < 1 Gal/MWha [8] Water Footprint Solar Thermal 0.3 m^3/Gj [9]	Minor water usage in the binary-cycle plants Sulfur emission could be transformed into acid and acid rain (12 – 300) [2] Geothermal 1350 Gal/MWhe [7] < 5 Gal/MWha [8]	Possibility for water storage; limited water pollution in the reservoirs from biomass rotting Release of sediment free water can cause downstream erosion. 36 [2] 715 - 3145 Lt/MWh [6] Water footprint 22 m^3/Gj [9]	N/A	Limited water usage and pollution during manufacturing and utilization 1 [2] Water Footprint 0.0 m^3/Gj [9]	Risk of spills (1216 - 1814) Lt/MWh [6] Water Footprint 1.1 m^3/Gj [9]	N/A 78 [2] Natural gas (0.94 - 39.6) m^3/MWh [5] Gas (684 - 1814) Lt/MWh [6] Cycle Combined Open Loop 100 Gal/MWhe [7] Close Loop 180 Gal/MWhe [7] Natural Gas Open Loop 492 Gal/MWha [8] CC 350 Gal/MWha [8] Water Footprint 0.1 m^3/Gj [9]	Water usage for washing; pollution due to this 78 [2] (756 -1815) Lt/MWh [6] 548 Gal/MWha [8] Water Footprint o.0 m^3/Gj [9]	Water usage for cooling; risk of high pollution 4.1 m^3/MWh [5] (1512 - 2722) Lt/MWh [6] Nuclear Steam Turbine Open Loop 400 Gal/MWhe [7] Closed Loop (400 - 720) Gal?MWhe [7] 785 Gal/MWha [8] Water Footprint 0.1 m^3/Gj [9]

	Gal/Mwhe [7] Biomass 351 Gal/MWha [8] Water Footprint (24 – 143) m^3/Gj [9]									
Land and soil Unit: km^2/TWh unless noted otherwise	Agricultural land occupation for growing, possible soil pollution Biodiesel-wastes 0.04 Biodiesel-vegetables 25,069 m2/kW [5] Biodiesel-perennials 4,200 m2/kW [5] (101 - 193) m^2/Gj [10]	Land occupation for large solar thermal power but usually unused for other purposes (28 -64) [2] 50 m^2/kW [5] Solar Thermal 3561 m^2/GWh [11] PV 3237 m2^/GHW [11] PV (164 - 549) m^2/GWH [10] Solar Thermal Tower 552 m^2/GWh [10] Solar Thermal Parabolic Trough 366 m^2/GWh [10]	Limited land occupation; some risk of soil pollution (18 - 74) [2] 404 m^2/GWh [11]	Land occupation for reservoirs, including most productive soils (73 – 750) [2] Reservoirs (2,350 - 25,000) m^2/GWh [10] Run of River 3 m^2/GWh [10] (130 - 1050) hectares/MW [12]	Minor land occupation on coasts Sealand Tidal 7.5 km^2/kW [13] Wave 34.3 km^2/kW [13]	Limited land occupation 72 [2] 1335 m^2/GWh [11] (1030 – 3230) m^2/GW [10]	Land occupation for mining and processing; possibility of soil contamination (2.2 -17.2) km^2/kW [14]	Land occupation for developing gas fields and processing and supply installations Natural Gas 0.222 m^2/kW [5]	Significant land occupation for mining, processing and wastes 5.5 Km^2/kW [15] 3642 m^2/GWh [11]	Land occupation for mining, processing and wastes 1.74 m^2/kW [5]

Hazardous Waste Risk Unit: tons	Possibility for waste from by-products	N/A	Risk of pollution by toxic water and air	Large scale supply of sediments and nutrients during failure of a dam or sudden release of flood water	N/A	N/A	Risk of spills Fossil Fuel Plants 8.5 billion metric tons of carbon directly into the atmosphere [1]	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 [1]
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	Biodiversity loss from inundation of forests 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	Risk of collision for birds and bats; infrasound effects.	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
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 chimneys can affect visual aspect of built environment.	Not so large installations	Can cause Damage to existing built environment like settlements; New structures can add positive impacts Dams and reservoirs can be used for recreation purpose	Sometimes large structures (dams, barriers, etc.)	Complaints from some people; good for other people	Very large mining and processing structures; chimneys with fire	Large mining and processing structures	Large waste fields, sometimes large structures	Large constructions and chimneys

Economic										
Employment Opportunities Unit: Employment/ Power or Energy Include: construction, installation, operation and maintenance.	Increased job opportunities, particularly in rural areas 6 [16] 0.32 Employment/kToe [17] Biodiesel-wastes 30 jobs/MWh [5] Biodiesel-vegetables 98.6 Jobs/MWh [5] Biodiesel-perennials 9.76 Jobs/MWh [5]	Jobs in rural and urban areas PV (6.4 – 10.6) [16] Employment ratio/MWa Solar Thermal (5.9 – 6.8) [16] Solar Thermoelectric 46.4 [16] PV 7.69 Employment/kToe [17]	High compared to natural gas (5.7 – 19.2) [16]	Medium 20 [16]	Not developed	High (2.8 – 22) [16] (0.3-1.0) Employment ratio/MWp [16] 0.36 Employment/kToe [17] (20 - 45) Jobs/MWh [5]	High	High	High	Small
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 – loss of productive assets v. increase in energy	Not developed	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
Energy Generation/Supply Costs Unit: US cent/ kWhe	Opportunities for co-generation – reducing cost (•) (62 - 85) current US/MWh (49 – 123) year 2050 US/MWh	Still relatively high- but becoming more competitive PV (19 - 20) [3] (•) CSP (125 - 225) US/MWh	Capital-intensive, with low variable costs and no fuel costs (•) Hydrothermal (33 - 97) current (30 - 87) year 2030.	High-capacity, low-cost means of energy storage (•) Large Hydro (30 –120) year 2005. (30 – 115) year 2030.	Not developed (•) Tidal Barrage (60 – 100) year 2005 (50 – 80) year 2030. (45 - 70) year	Competitive with other sources (5-74) [3] (•) Onshore Low average wind speed (8.9 - 13..5) US cents/kWh Low average wind	Fluctuating Price; competitive but subsidized for some uses	Competitive – but subsidized for some uses	Competitive – but subsidized for some uses	Competitive – but subsidized (•) (62 - 88) US/MWh

		Year 2020 CSP (43- - 62) US.MWh Tower (35 - 55) Us/MWh	(29 - 84) year 2050. Hot dry rock (150 – 300) year 2005. (80 – 200) year 2030. (60 – 150) year 2050	(30 - 110) year 2050. Small Hydro (56 – 140) year 2005. (52 – 130) year 2030. (49 -120) year 2050.	2050. Tidal Current (150 -200) year 2005 (45 -90) year 2030. (40 – 80) year 2050. Wave (200 -300) year 2005 (45 -90) year 2030. (40 - 80) year 2050.	speed (6.5 – 9.4) US cents/kWh Year 2015 (43 -5.3 Low 6.3 Hihg Ofshore 20 US cents/kWh Year 2015 16 US cents/kWh Year 2030 15 US cents/KWh				
Price of energy generated/supplied Unit: USD/kWh Average price of electricity	Potential for cheap, locally produced power	On grid costs high, off-grid more competitive 0.24 [2]	Competitive with some fossil fuel facilities 0.07 [2]	Cost competitive 0.05 [2]	Not developed	Competitive with other sources 0.07 [2]	Fluctuating Price; competitive but subsidized for some uses	Competitive – but subsidized for some uses 0.048 [2]	Competitive – but subsidized for some uses 0.042 [2]	Competitive – but subsidized
Investment Unit: US $/kW Ref. IEA, 2008 (•)	Potential for large and small scale investment (•) Biomass Integrated Gasifier / Combined Cicle 2,500 (Current)	Large potential for investors - solar growth 30% every year from 2000 to 2005 (•) PV 5,500 (current) 1,900 (year 2035)	Asian countries urging large investment in geothermal (•) Hydrothermal (1,700 – 5,700) (1,500-5,000) year 2030.	Large and small projects still expanding (•) Large Hydro (1,000 – 5,500) year 2005.	Developing market (•) Tidal Barrage (2,000 – 4,000) year 2005 (1,700 –	Capital investment is high – but world's fastest growing energy source (•) Onshore 1,200 (current) 900 (year 2025)	Demand increase – Mainly in upstream – risk because of uncertainty over remaining reserves	Demand increase Acts as driver Uncertainty of remaining reserves is risk (•) Gas - IGCC 1,800 (current)	Large potential because of expansion in the coal sector – China, India, US	Heavily promoted to combat climate change – re-emerging investment opportunities (•) III+ 2,600 (current) 2,100 (year

		CSP 4,500 (Current)	(1,400 – 4,900) year 2050. Hot dry rock (5,000 – 15,000) year 2005. (4,000 – 10,000) year 2030. (3,000 – 7,500) year 2050	(1,000 – 5,400) year 2030. (1,000 - 5,100) year 2050. Small Hydro (2,500 – 7,000) year 2005. (2,200 – 6,500) year 2030. (2,000 -6,100) year 2050.	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. Wavw (6,000 - 15,,000) year 2005 (2,500 - 5,000) year 2030. (2,000 – 4,000) year 2050.	Offshore 2,600 (current) 1,600 (year 2030)		1,400 (year 2035)		2025) IV 2,500 (year 2030) 2,000 (year post 2050)
Social										
Displacement of people Unit: persons/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	Very unlikely to cause displacements. Providing decentralized energy enhances access and thus better dwellings in isolated areas, relieving populational pressure in urban	Case specific, but people displacement may be very rare and in small scale. Improves decentralized energy and settlements close to the	Case, site, technology specific. Risks of significant displacements, requiring adequate assessments and compensation.	Very unlikely to cause displacements. Providing decentralized energy enhances access and thus better dwellings in isolated areas, relieving	Unlikely to cause displacements, but some onshore projects can cause nuisances such as noise with effects in local communities.	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.

	therefore additional settlements.	areas.	energy source.	(61 – 120) persons/MW [12]	population pressure in urban areas.					
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.	Improved systems enhance lifestyles. Decentralized energy have potential to provide more and gender friendly jobs.	Gender neutral.	Gender neutral.	Gender neutral.	Gender neutral.	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.	Usually gender neutral, but primitive use of this solid fuel causes domestic health impacts, affecting mainly women, children and the elderly.	Gender neutral.

9.4.2 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 et al., 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 et al., 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 et al., 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 et al., 2009).

9.4.2.1 Overview on resources and technologies

Most of the literature makes a qualitatively assessment of the impact and the use of resources by renewable technologies. The following Table 3 summarizes both the qualitative and quantitative information available on the use of resources and the impact of different renewable technologies on sustainable development. For comparison purposes, conventional fossil fuel and nuclear technologies are also included.

Table 3: Sustainable Development ←→ Renewable Energy

Selected SD Goals	*Renewable Energy Technologies*						*Conventional Fossil Energy Fuels*			*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
Water Security	Water usage, wastewaters	Medium	Low	High	Too early to know	Medium	Spills	NA	Coal washing, water contamination	Potential high contamination
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

9.4.3 Requirements for increased RE deployment

9.4.3.1 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 et al., 2008).

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 is already in use quite widely for information campaigns, corporate promotion, direct marketing
- 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
- Different types of publications from newspaper articles to leaflets to simple slogan statements and many more
- Public meetings, talks and quiz games
- Inclusion in education curriculum from kindergarten level and upwards
- Direct demonstration plants with public access

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 counter information and lobby policy makers. A recent report from the US based Centre for Public Integrity concluded that both developed and developing countries are under heavy pressure from fossil fuel industries and other carbon-intensive businesses to slow progress on negotiations and weaken government commitments. The clash cannot simply be framed as one between richer and poorer nations

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 REN 21 may play important roles, on a broader international scale, for augmenting deployment of RE technologies. 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. However, 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.

9.4.3.2 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 [REN21, 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). See Box from Agenda 21.

> **Agenda 21, Chapter 37:**
>
> **Creating Capacity for Sustainable Development**
>
> A country's ability to develop more sustainably depends on the capacity of its people and institutions to understand complex environment and development issues so that they can make the right development choices.
> People need to have the expertise to understand the potential and the limits of the environment. They will face difficult policy choices when dealing with such complex problems as global climate change and protecting biodiversity. This will require scientific, technological, organizational, institutional and other skills.

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. 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 (EIA, 2000). 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, et al., 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. [REN21, 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 et al. (2002)

Table 4: 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)

9.4.3.3 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 & Vedovello, 2002, 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

This 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.

- 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 from investment

- 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]. 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 before COP 15 to have new dedicated efforts as part of a possible new agreement [needs to be revised after COP 15!!] and this is expected to among other issues to focus on:

- Development of effective policy frameworks to accelerate the transfer, deployment and dissemination of existing and new technological solutions;
- Strengthen investment, research, innovation, information and skills sharing, dissemination and uptake of clean technologies, through bilateral and multilateral partnerships;
- Promote sustained and joint efforts between government and the private sector, including the financial sector, to promote the market for new technologies;
- 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;
- Develop international energy management standards to increase the efficient use of existing and future technologies in industry and other sectors.

9.5 Implications of (sustainable) development pathways for renewable energy

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 et al, 2003).

We need to measure progress by how quickly we can build a renewable energy platform, meet basic human needs, discourage wasteful consumption, and invest in rather than deplete natural and cultural capital (State of the World, 2008 – The World watch Institute).

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 sustainable energy:
Availability of resources
Security of supply
Environmental compatibility
Economic compatibility
Social compatibility
Production associated with low risks

9.5.1 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, and biofuels provide transportation fuels. 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, 2007).

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 (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.

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).

9.5.1.1 Development pathways for renewable energy in different regions

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. 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. 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:

- Clean Development Mechanism (CDM)
- Dealer-Credit Model (Grameen Shakti)
- Consumer Credit Model
- Supplier Credit Model
- Energy Service Company Model
- Revolving Fund
- Global Environment Facility (GEF)

9.5.1.1.1 Developing Countries

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).

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).

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 (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.

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 (see subchapter 9.2.1.3 for more detail on leapfrogging and microenergy) [TSU: No section has currently been dedicated to cover leapfrogging and microenergy]. 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).

9.5.1.1.2 Developed Countries

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.

- Establish renewable friendly laws and regulation
- Promote renewable friendly building codes and standards
- Stimulate long term financing
- Provide sustained financial support for projects

According to PEER (2009) the following should happen to stimulate increased energy market by renewable energy:

- Climate-based subsidies and budget allocations could be increased or new ones introduced;
- Subsidies and taxes with harmful climate impacts could be removed or redesigned;
- Budget allocations and taxes with favourable side effects from a climate point of view could be increased;
- 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 Report No 2, 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).
5. Support research and development for shifting the use of fossil fuels from bulk electricity to balancing power production (balancing power focus) (TREC, no date)

9.5.1.2 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.

9.5.1.2.1 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 hence the total of direct and indirect emissions in this sector amounts to 75%. 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, no date).

9.5.1.2.2 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:

- Urban planning, changing lifestyles and production patterns to reduce the need for transport at the source;
- 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;
- 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:

- The improvement of urban planning to promote inter-modality;
- The diffusion of cleaner technologies and the deployment of relevant policies that drive them to reduce environmental impacts,
- 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. 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[2] 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.

9.5.1.2.3 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 (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.

9.5.1.3 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 CO_2 neutral energy. 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).

[2] 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/)

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 9.1: Biogas from human Waste – the case of Rwanda
(Copied from Ashden Award Pdf)
Kigali Institute of Science, Technology and Management (KIST), Rwanda, 2005 (on line) Available:
http://www.ashdenawards.org/files/reports/KIST%20Rwanda2005%20Technical%20report.pdf

The Kigali Institute of Science, Technology and Management (KIST*), Rwanda, has developed and installed large-scale biogas plants in prisons in Rwanda to treat toilet wastes and generate biogas for cooking. After the treatment, the bio-effluent is used as fertiliser for production of crops and fuelwood.

Large prisons, each housing 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.

Using biogas digesters to manage animal or human sewage is not a new idea, but in Rwanda has been applied on an enormous scale, and with great success. Each prison is supplied with a linked system of underground digesters, so the sight and smell of the sewage are removed. KIST staff manage the construction of the system, and provide on-the-job training to both civilian technicians and prisoners. The biogas is piped to the prison kitchens, and halves the use of fuelwood. The fertiliser benefits both crop production and fuelwood plantations.

The first prison biogas plant started operation in 2001, and has run with no problems since then. Biogas plants are now running in six prisons with a total population of 30,000 people, and KIST is expecting to install three more each year.

Technology and use

Biogas systems take organic material such as manure into an air-tight tank, where bacteria break down the material and release biogas - a mixture of mainly methane with some carbon dioxide. The biogas can be burned as a fuel, for cooking or other purposes, and the remaining material can be used as organic compost. The systems installed in Rwanda have an impressive international heritage: the original design came from China, was modified by GTZ, and finally scaled up and refined by a Tanzanian engineer working in Rwanda.

The biogas system uses a number of individual digesters, each 50 or 100m3 in volume and built in an excavated underground pit. Toilet waste is flushed into the digesters through closed channels, which minimize smell and contamination. The digester is shaped like a beehive, and built up on a circular, concrete base using bricks made from clay or sand-cement. The sides taper gradually and eventually curve inward towards a half-meter diameter man-hole at the top. It is crucial to get the bricks laid in exactly the right shape, and to make the structure water-tight so that there is no leakage of material or water out of the digester. Biogas is stored on the upper part of the digester.

The gas storage chamber is plastered inside with waterproof cement to make it gas-tight. On the outside, the entire surface is well plastered and backfilled with soil, then landscaped. The biogas system is finally inspected and, when approved, it is certified for operation.

From the manhole cover, the gas is piped underground towards the kitchen where it is used for cooking porridge, beans and maize in enormous (500 liter) pots, and in stoves that are insulated with a brick lining. 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.

A particular feature of the plant design is a compensating chamber that acts as a reservoir of methane bacteria for enhanced gas generation. At first, gas pressure displaces the liquid to the compensating chamber. Consumption of gas leads to backflow of the waste from the compensating chamber into the bio-digester; this agitates the waste, circulates the bacteria, and releases trapped gas.

The continuous input of waste, and the gas pressure, push digested effluent out of the bio-digester to a stabilizing tank, and from there, to a solid/liquid separation unit. The stabilizing tank allows additional gas production. The solids are composted for three months and then used as fertilizer in the prison gardens and woodlots. Great care is taken to ensure that the effluent is safe to use in this way, with regular laboratory checks on samples for viruses, bacteria and worms. As an additional precaution, the fertilizer is used only for crops that stand above ground, such as papaya, maize, bananas, tree tomato and similar tree crops.

The scale of these biogas systems is enormous: 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.

How users pay

The biogas plants are purchased for the prisons by the Ministry of Internal Security. The cost of a 500m3 plant is about 50 million Rwandan francs (£50,000). A system of phased payments is used, with the final 5% paid only after 6 months of satisfactory operation.

Training and support

There is great emphasis on quality and reliability in the design and construction of the biogas plants, and they are expected to last for at least 30 years. Prisoners are trained to operate the systems, with support from the KIST team, and are very diligent in this task. Their work includes regular checks on the digester seals, emptying condensate bottles, guiding the flow of the bioeffluent, and application of the compost on the farm. It is also advisable to completely de-sludge the digesters every seven years.

Benefits of the project

The initial reason for using biogas systems was to improve the sanitation in prisons, reducing health risks and smell for both prisoners and the neighbouring residents. The Ashden judge who visited this project noted the overflowing septic tanks and dreadful odour at a prison where the biogas plant was still being installed, and the remarkable lack of odour (even from the output effluent) at a prison with an operating plant. Some prisons have used the effluent to make gardens over their underground biogas system.

Large institutions put enormous demands on fuelwood for cooking, and can cause local deforestation even in a generally well-wooded country like Rwanda. A prison of 5,000 people consumes about 25 m3 (approximately 10 tonnes) of fuelwood per day. Using all the biogas from their sewage system can save about half of this fuelwood. The overall prison population served by biogas plants is now about 30,000 people, so the annual fuelwood saving is about 27,000 m3.

The project saves greenhouse gas emissions by reducing the unsustainable use of fuelwood, and also by preventing the uncontrolled emission of methane from overloaded septic tanks and sewage pits. Both these savings are site-specific and difficult to quantify. As an indication of savings, if 50% of the fuelwood saved is unsustainable, then the greenhouse gas saving from the current systems is about 10,000 tonnes of CO_2 equivalent per year. Similarly if 20% of the biogas production would have occurred with unmanaged sewage disposal, then an additional 1,000 tonnes of CO_2e per year would be saved.

A significant benefit from the project is the technical and business training that is provided to the civilian technicians, prisoners, and even KIST graduates on-the-job at each installation: the technicians often come from the neighbouring population. To date, over 30 civilians and 250 prisoners have received training, and three private biogas businesses have been started. CITT has employed one of the released prisoners as a trainee.

Through their training programmes, CITT have started the development of private biogas companies in Rwanda. These will install plants with CITT acting as the certification body, and thus keeping quality standards high. Failures (as have occurred in other countries) 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. Many other large institutions which are remote from mains sewage services also have problems with sewage disposal, and housing developments could also benefit. CITT has already undertaken smaller installations in three residential schools: here the percentage of fuelwood replaced is less (around 20% rather than 50%, because more cooked food is provided) but still a significant benefit

Management, finance and partnerships

When a biogas system is requested, a team from CITT make a site inspection along with a representative of the Ministry for Internal Security and the Director of the Prison. Technical and financial staff at CITT produce a detailed specification and contract. All site work is managed by a manager and site engineer from CITT, with materials supplied through a tender system, often from local sources. The Ministry also has a project controller on site, to supervise installation.

The International Committee of the Red Cross (ICRC) has been a key partner throughout the biogas programme, because they see the benefits which it brings to health and welfare in prisons. Both the ICRC and the government of the Netherlands have assisted the government of Rwanda in financing the programme.

The project won an Ashden Award for Sustainable Energy

*KIST is a public Institute of Higher Learning, which was established in 1997 to replace professional manpower that had been lost from Rwanda. The main focus is on technology and management.

Note: this is more or less an ad verbatim copy from the Ashden Award document

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 et al, 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 9.3.3 for more detail on direct solar).

Electrical production from geothermal results in an order of magnitude less CO_2 per kilowatt-hour of electricity produced compared to burning fossil fuels (Bloomfield et al (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 9.3.4. 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 9.3.5. 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 9.3.6. 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 9.3.7 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.

9.5.2 Policy framework for renewable energy in the context of sustainable development

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).

1. 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 et al. (1997), Nieuwenhout et al. (2000), Taylor (1998) and 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).

2. 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.

9.5.2.1 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. Feed-in tariffs and mandatory targets [TSU: here is text missing]

At the national level a mix of command and control or regulatory instruments, as well as market based incentives is required. The two main instruments are feed in tariffs and certificate markets. These two policy instruments in combination are necessary to achieve the desired transformation towards sustainable development in the context of the global climate challenge. The 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).

In addition, defining national targets and setting bidding systems, establishing markets for tradable permits for CO_2 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.

9.6 Synthesis *(consequences of including environmental and socio-economic considerations on the potential for renewable energy, sustainability criteria)*

9.6.1 RE policies and sustainability - background

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.

Since the early 1960´s, the SD concept that 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.

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 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 et al., 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 et al., 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 et al., 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. Several voluntary energy initiatives (called "Type 2", contrasting 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 et al, 2005).

9.6.2 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 et al., 2004 and Spalding-Fecher et al, 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).

9.6.3 Sustainable renewables

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 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’’, and they had to decide which particular technologies or organizations would be eligible for subsidies and tax concessions, and which others would be excluded. Not infrequently, a considerable amount of lobbying would precede the passage of such laws and regulations, and the resulting definitions of ‘‘renewable’’ and ‘‘sustainable’’ are often different than their original meaning (Frey and Linke, 2002). According to Spalding-Fecher et al (2005), at CSD9 in 2001 a strong fault-line arose around the national recommendations, either favoring the term ‘‘sustainable energy’’ (more prescriptive) or ‘‘energy for sustainable development’’, addressing particularly the need to bring access to energy to more people and to use locally available energy resources). 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 (Frey and Linke, 2002).

Renewable energy technologies are ones that consume primary energy resources that are not subject to depletion. Non-consumptive renewable technologies include solar power and wind power. Included in the family of renewable energy technologies are hydropower (considering water supplies replenished in the hydrologic cycle), geothermal (an abundant resource) and biomass (when capable of replenishing itself rapidly). 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). 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. The overall benefits of renewable energy technologies are often fully assessed, leading to such technologies often being assessed as less cost-effective than the traditional ones. Renewables may cause local impacts which give rise to concerns and opposition to the development. The risk of public opposition increases if the benefits of the proposed development are not clear to the local people. That is further fuelled by uncertainties, lack of information and media amplification. The provisions of capital grants and regulatory reforms alone are not sufficient to make such energy development successful (Upreti and van der Horst, 2004).

To weigh the positive effects against the negative ones can be a lengthy and complex task. For example, there are many laws or regulations which define ‘‘small hydro’’ as renewable and sustainable, whereas ‘‘large hydro’’ is labeled by some of the legislators as being either not renewable or not sustainable. To further complicate matters, the definition of ‘‘small hydro’’ varies widely from jurisdiction to jurisdiction, from as little as 1MW capacity to as much as 100MW capacity. It has become apparent to policy makers that large hydro projects can attract opposition and become controversial, whereas smaller ones usually do not. An expedient way out of the controversy was to define small hydropower as being renewable, and eligible for government support, and excluding large hydropower from subsidies or other incentive measures. Some organizations opposed to hydropower call for a moratorium on the construction of new dams, or the decommissioning of some dams which interfere with salmon migration, or even the decommissioning of many more dams for a variety of environmental reasons. Eliminating these facilities will not reduce power demand, since most of the world electric energy comes from thermal, nonrenewable and in the majority unsustainable resources. The question for policy makers and decision-makers of this generation is whether the impacts created by this hydropower facility are a reasonable tradeoff for the benefits generated according to the current value system and importance attached to both the positive and negative effects. (Frey and Linke, 2002).

The demand for bioenergy is growing due to the climate policies of various countries that search for 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. This happened in northern Europe in the 1990s with the introduction of biomass in district heating. There are different reasons for international biomass trade, but the most important drivers are the lower prices (nowadays also true when sea transport is included) and enhanced supply security. Energy balances and subsequent greenhouse gas balances show that international bioenergy trade is possible against a modest energy loss. Bioenergy exporting countries benefit from trade, in terms of market access and enhanced socio-economic development. However, concerns arise on the potential negative impacts of the rising 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, indicators for sustainable development and indicators to assess the sustainability of projects (Lewandowski and Faaij, 2006).

9.6.4 Assessment tools and policy implications

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).

9.6.5 Sustainability criteria for the Clean Development Mechanism

Under the Kyoto Protocol, host countries for the Clean Development Mechanism decide whether a project meets its sustainable development needs. 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 CDM Executive Board agreed to consider a recommendation on documentation regarding the written approval of voluntary participation from the designated national authority of each Party involved, including confirmation by the host Party that the project activity assists it in achieving sustainable development (Decision EB 12). This confirmation would have the form of a statement issued by the designated national authority (DNA) of a Host Party involved in a proposed CDM project activity (Decision EB 16). Revision to the crediting period must not alter the project's contribution to sustainable development (Decision EB 24). The statement has a form of a letter of approval (Decision EB 25). Developing countries, especially those in sub-Saharan Africa, should to improve their level of participation in the CDM, further promoting sustainable development, mitigation of climate change and poverty alleviation (Decision EB 35). Renewable energy policies may establish mandatory targets, which can conflict with the additionality criteria of CDM projects; nevertheless Decision EB 16 states 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). This is clarified by Decision EB 22, by which a baseline scenario shall be established taking into account relevant national and/or sectoral policies and circumstances, such as sectoral reform initiatives, local fuel availability, power sector expansion plans, and the economic situation in the project sector. As a general principle, national and/or sectoral policies and circumstances are to be taken into account on the establishment of a baseline scenario, without creating perverse incentives that may impact host Parties' contributions to the ultimate objective of the Convention..

9.6.6 Sustainable energy policies in the developing and in the developed world

The world's primary energy system was in 2004 at least a 1.5 trillion dollars per year market dominated by fossil fuels, subsidized with over $US 240 billion per year. Subsidies 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. Renewable Portfolio Standards (RPS) represent bottom-up approaches at regional or country level, policies that States may use to remove market barriers to renewable energy. In their simplest form, RPS specify shares from certain renewable energy sources (Goldemberg, 2006).

National renewable energy policies in South Africa, Egypt, Nigeria and Mali were analyzed by Bugaie (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. 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. The Board of the Swiss Institutes of Technology suggests pathways to the 2000W per capita society (Marechal et al, 2005).

9.6.7 Existing RE-SD policies

The Organization for Economic Cooperation and Development, together with the International Energy Agency (OECD and IEA, 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 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 Table 3. 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 Table 1, 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 aren’t 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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INTERGOVERNMENTAL PANEL ON climate change

Chapter 10

Mitigation Potential and Costs

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COMMENTS ON TEXT BY AUTHORS/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: ….]

Length

Chapter 10 has been allocated a total of 68 pages in the SRREN. The actual chapter length (excluding references & cover page) is 90 pages: a total of 22 pages over target.

The Executive Summary exceeds its allocation by 2 pages as it shall not exceed 1.5 pages.

Expert reviewers are kindly asked to indicate where the Chapter and Executive Summary could be shortened in terms of text and/or figures and tables.

Structure

In light of the very successful IPCC WG III Expert Meeting 'Modelling Renewable Energies; Coherence Between Model Assumptions and Latest Technological Knowledge', new data and new literature the structure of Chapter 10 has been improved to follow a more logical order. This new structure is subject to IPCC plenary approval. Please note that all content from the chapter outline has been retained. Expert Reviewers are kindly invited to comment on these amendments.

The content of the original 10.2 (Methodological Issues) is now integrated in each relevant sub-section, where appropriate. Similarly, the content of the original 10.7 (Gaps in knowledge and uncertainties) now appears at the end of the relevant sub-sections, where appropriate. The original 10.3 (Assessment and synthesis of scenarios for different renewable energy strategies (top-down and bottom-up)) is shifted to section 10.2 and deals as before with an overview of medium to long-term global, aggregated models. The original section 10.4 (cost curves for mitigation with renewable energy) is split apart into the new sections 10.3 and 10.4. The new 10.3 (Assessment of representative mitigation scenarios for different renewable energy strategies) investigates those models further that have greater technological detail. The new 10.4 (regional cost curves for mitigation with renewable energy) extends on the old 10.4 and goes into further technical detail dealing with regional resource cost curves and mitigation cot curves.

References

References highlighted in yellow are either missing or unclear.

Tables & Figures

The Numbering of tables & figures is not continuous and its structure differs between the numbers attached to the table & figure and the one in the text. That is, numbering of tables & figures starts new with every subsection 10.x and is structured 10.x.1, 10.x.2, … Numbering in the text starts with 1 in every subsection 10.x. Therefore, each reference can be clearly identified by the last digit. For example, in section 10.2, Figure 10.2.5 is referred to as Figure 5 in the text.

Currencies

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

Abbreviations

RE, RES	Renewable Energy Sources
OMC	Operation and Maintenance Costs
CHP	Combined Heat and Power

Chapter 10: Mitigation Potential and Costs

CONTENTS

EXECUTIVE SUMMARY

The evolution of future greenhouse gas emissions is highly depending on the availability of mitigation technologies and their implementation, triggered, amongst others, by cost effects or specific policy incentives. The uncertain future is reflected in the wide, and growing, range of emissions pathways across emission scenarios in the literature, as was well reflected in the most recent IPCC assessment report (IPCC, 2007). 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, together with energy efficiency, 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 an integrative perspective, interactions with other technologies and the overall energy system have to be considered.

As such, it is most important to appraise the mitigation potentials and costs of RE technologies based on the assessment of the most recent scenario and deployment pathways literature available on the subject, as well on potentials and costs of specific technical analyses of different RE technologies.

Following the comprehensive scenario analysis (investigation of 137 scenarios) performed in this chapter, increasing demand for energy, and for low-carbon energy in particular, if the world chose to reduce greenhouse gas emissions, could lead to RE deployments many times, or even orders-of-magnitude larger than those of today. Indeed, even without climate mitigation, many scenarios include RE deployments by the end of the century larger than the total global energy system today simply by virtue of growing energy demand. However, there are several challenges RE are facing in the context of climate mitigation. In the near-term, the challenge is achieving deployment increases at a rate that is consistent with meeting very ambitious longer-term levels. There are many objectives in energy policy other than climate change mitigation, such as increasing energy security, reducing energy import dependence, pollution levels or creating job opportunities, that RE contribute to and that served as reasons for establishing incentive schemes to support RE deployment in the recent past. Although the potential is quite large and other reasons are relevant to push market penetration of RE, tremendous uncertainty surrounds the role of RE in climate mitigation. This uncertainty is manifest in the wide range of RE deployments in the scenarios reviewed in this section. The range is a reflection of uncertainty in: energy demand growth; the degree to which the development and deployment of high-efficiency energy end-use technologies mitigates this growth; the degree of climate mitigation; the ability of RE technologies to overcome their costs, performance, and other barriers; and the ability of competing supply technologies, most notably nuclear energy and fossil energy with CCS, to overcome cost and performance, social acceptance, environmental, and other barriers.

However, given the still high unexploited technical opportunities of RE, although without having reached their full technological development limits so far, it can be concluded that technical potentials are not the limiting factor to the expansion of the renewable energy generation.

If the renewable industry could maintain the growth rates between 2000 and 2009 for the next decades, all combined power technologies could achieve an electricity share of 39% by 2020, 58% by 2030; and before 2050 the entire electricity could come from renewable power sources, if in the same time period global power demand showed only a moderate growth rate (69% increased by 2050 compared to 2005 level).

Similar to the more aggregated scenario overview presented in this chapter, the more in depth look on selected scenarios and in particular on the possible contribution of RE in different sectors or for different applications show a substantial range of different results. The total share of renewable heating systems in all scenarios by 2050 varies significantly between 21%, if combining a high power demand and a low RE market development case, and 69%, anticipating the advanced market development and low demand case. A medium range market development and medium increase of heat demand would lead to a renewable heat share of 27% by 2020 and up to 47% by 2050.

In the most optimistic case, which is a combination of a high market development for renewable energies and a successfully implemented energy efficiency strategy, renewable energies could provide 61% of the world energy needs by 2050. While there is a potential to supply the entire global power demand with renewable energies and 69% of global heating and cooling demand, the most problematic sector for renewable energy to supply substantial shares is the transport sector. Even the energy scenarios with the most ambitious growth rates for renewable energy did not exceed an exhaustion rate of the technical potential of 3.2% (China, 2020) on a regional level and 0.58 % (2050) on a global level.

Based on the selected scenarios and calculated with the status quo specific emission factors for electricity generation, heat and fuel as an orientation mark, the total annual CO_2 reduction potential varies significantly between the low, medium and high cases. While the low case abatement potential for renewable is only 5.8 Gt CO_2/a by 2050, which represents the business as usual pathway, the medium case achieves a total of 15.4 Gt CO_2/a by 2050. The annual high case CO_2 savings lead to 33.3 Gt CO_2/ a, which is equal to a 70% reduction of energy related CO_2 emissions of the analysed reference scenarios.

To follow the scenario pathways is of course quite challenging. A strategic increase of the production capacity of 50 to 100 GW/a for each technology (in the power sector) within the next decade is required to achieve drastic emission cuts - but also to achieve cost reductions in order to become independent from support programs. However, this does not seem to be impossible, as annual growth rates from RE have been constantly underestimated in the past decades.

This chapter also focuses on the concept of supply curves of RE and therefore adds regional cost aspects to renewable energy potentials. The concept of abatement, energy and conservation supply curves nowadays is a 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 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

The reviews of the existing regional and national literature on RE as well as mitigation potential literature as a function of cost show a very broad range of results. In general, it is very difficult to compare data and findings from renewable energy supply curves as there have been very few studies using a comprehensive and consistent approach and detailing their methodology; and most studies use different assumptions (technologies reviewed, target year, discount rate, energy prices, deployment dynamics, technology learning, etc.). Concerning the analyzed regional/country studies[1] it is worth to mention that they attribute fairly low abatement potential to renewable energies under USD100/tCO_2 – typically in the single digit range, with their highest contribution of 13% of emissions foreseen in Australia in 2030. The findings translated in terms of the potential role of RE for mitigation pathways from the analysed studies are somehow quite different from answers given through other methods (even such as scenario based RE supply curve analysis conducted in this section).

In this chapter, the renewable power cost curves for 10 world regions have been reviewed for 2030 exemplary for two scenarios - World Energy Outlook (IEA, 2008b) and Energy [R]evolution scenario (Krewitt et al, 2009a) - and one for 2050 (Energy [R]evolution scenario). The calculated cost curves represent dynamic deployment potentials rather than static technical or economic ones. Although the curves are based on different deployment paths as a result of the two selected scenarios, a few general regional and technological trends are shown by these curves. Most typically, on- and offshore wind power prove to be the most cost-effective in many regions, both in the shorter and longer terms. Hydropower is often close to wind in cost-effectiveness in 2030, especially in the WEO scenario, but it looses parts of its competitiveness in many regions by 2050. While these two technologies dominate many of the curves at reasonable costs (e.g. under USD 150/MWh) in 2030, by 2050 a more balanced portfolio of technologies appears in most regions, with many other technologies taking a large share of the available low-cost potential, including CSP, PV, and geothermal. Ocean energy is also projected to compete successfully with other technologies in regions with access to the seas, but its overall contribution to the potential remains limited everywhere. In 2050, geothermal, hydropower and CSP become the least attractive options from the perspective of costs in most regions, although CSP is projected to be among the most cost-competitive options and also supplying very large potentials in Africa and the Middle East in both the shorter and longer term, and is very cost-competitive in North America over both periods.

With regard to temporal dynamics of potential size, the curves underline the importance of a long-term perspective and a consequent market introduction policy. Many regions see a several-fold increase in their low-cost renewable energy potential between 2030 and 2050, including an almost doubling in Latin-America, other Asian countries and other transition economies, over a doubling in China and OECD Pacific, 2.5 times increase in Africa, and over a triplication in India and the Middle East.

Although some of the technologies applied in the field of renewable energy usage are already competitive, at least in niche market applications, a review of energy generation costs reveals that most of them are still not competitive. As most of these 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 by learning by doing (resulting from capacity expansion programs) effects, however, this might result in considerable lower costs in the future.

In the past, the energy generation costs of the most important innovative renewable energy technologies showed a significant decline. In general, the cost decrease is well described by empirical experience curves with learning rates between 8 and 32% (wind onshore), 13 to 26 % (photovoltaic), 2 to 15% (concentrating solar power), and up to 30 % for biomass.

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, annual investment needs in the order of 100 billion USD are expected in case that ambitious climate protections goals (e.g., the 2°C mean temperature change limit) are pursued. This number allows assessing future market volumes and resulting investment opportunities. Due to avoided fossil fuel costs and

[1] available in the public domain as of Summer 2009

decreased investment needs for conventional technologies, the additional costs (learning investments) might be considerably lower than the deployment costs.

Learning by research and learning by doing can be facilitated by suitably designed research and development programs (intended to result in a technology push) and capacity expansion promotion programs (intended to establish a market pull). Due to market failures, the internalization of the external costs of carbon (e.g., via emission trading schemes) might not suffice to design emission mitigation strategies that are cost-effective from a long-term perspective. In addition, a technology specific support for selected innovative technologies (e.g., via feed-in tariffs) might be recommended to cover the specific characteristic of RE systems in a suitable manner.

Although social and environmental external costs vary heavily amongst different energy sources and are still connected with an 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 assessed on life-cycle basis. However, the uncertainty and variability by energy chains is considerable. Some RE production cases can cause considerable external impacts as well. The increase of RE in the energy system typically reduces the overall external costs of the system which produces external benefits. The increase of RE decreases also 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. However, 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.

10.1 Introduction

The evolution of future greenhouse gas emissions is highly depending on the availability of mitigation technologies and their implementation triggered amongst others by cost effects or specific policy incentives. The uncertain future is reflected in the wide, and growing, range of emissions pathways across emission scenarios in the literature, as was well reflected in the most recent IPCC assessment report (IPCC, 2007). 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, together with energy efficiency, 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 an integrative perspective, interactions with other technologies and the overall energy system have to be considered.

Behind that background this chapter assesses the mitigation potentials and costs of RE technologies taken as a whole based on an assessment of the most recent scenario literature available on the subject, as well at least for some sections on inputs (in particular deployment pathways) coming from previous technology chapters (chapters 2-7) in this report.

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 more than a hundred 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.

The section that follows (Section 10.3) complements the review with a more detailed and near-term-focused review based on a selected part of the global scenarios. This sections 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.

Then the purpose of the section that follows (Section 10.4) is to go to a next level of detail with regard to regional potentials as a function of costs. The section first of all assesses the strengths and shortcomings of supply curves for RE and GHG abatement, and then reviews the existing literature on regional RES [TSU: Renewable Energy Sources] supply curves as well as abatement cost curves as they pertain to mitigation using RE. The section comes out with a consistent set of regional cost curves for RE. For the calculation data are used from a subgroup of scenarios which have already been discussed in the previous sections and covering different future pathways.

The next section (Section 10.5) deals with the costs of RE commercialization and deployment. The idea is to review the present RE technology costs, as well as the 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 will present historic data on R&D funding as well as on observed learning rates. In order to allow an assessment of future market volumes, the investment in RE will be discussed which is required if ambitious climate protections goals are to be achieved.

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. 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.

Gaps in knowledge and uncertainties associated with RE potentials and costs are discussed in each of the sections of the chapter.

10.2 Synthesis of mitigation scenarios for different renewable energy strategies [TSU: deviation from structure agreed by plenary: "Methodological issues"]

This section provides context for understanding the role of RES in climate mitigation through the review of medium- to long-term scenarios from large-scale, integrated, energy-economic models. In particular, the section is motivated by four strategic questions at the heart of RES mitigation cost and potential. First, what sorts of RES deployment levels are consistent with different climate change mitigation targets? Second, over what time frames and where will RES deployments occur? Third, how are the costs of mitigation tied to RES deployments? Finally, what factors influence the answers to all of the above?

The scenarios explored in this were developed using large-scale energy-economic and integrated assessment models. The benefit of large-scale, integrated models is that they capture the interactions with other technologies, other parts of the energy system, other relevant human systems (e.g., agriculture), and important physical processes associated with climate change (e.g., the carbon cycle), that serve as the environment in which RES technologies will be deployed. In addition, they explore these interactions over at least several decades to a full century and often at a global scale. This degree of coverage is critical for establishing the strategic context for RES. However, this degree of coverage puts limits on the degree of detail that these scenarios can represent. The section that follows, Section 10.3, complements the review here with a more detailed and near-term-focused review of a smaller set of scenarios; it provides a next level of detail for exploring the role of RES in climate change mitigation.

Several important themes emerge from the review in this section. First, increasing demand for energy, and for low-carbon energy in particular if the world chooses to reduce greenhouse gas emissions, could lead to RES deployments many times, or even orders-of-magnitude, larger than those of today. Indeed, even without climate mitigation, many scenarios include RES deployments by the end of the century larger than the total global energy system today simply by virtue of growing energy demand. Second, there are both a near-term and long-term contexts for considering the challenges facing RES in climate mitigation. The longer-term challenge will increasingly be one of scale, as the total deployment of low-carbon energy, including RES, nuclear power, and fossil energy with CCS, could reach several times the total global energy system today. In the near-term, the challenge is achieving deployment increases at a rate that is consistent with meeting these longer-term levels. However, there are objectives in energy policy other than climate change mitigation, such as reducing energy import dependence, pollution levels or creating job opportunities, that RES contribute to and that served as reasons for establishing incentive schemes to support RES deployment in the recent past. Finally, although the potential is quite large, tremendous uncertainty surrounds the role of RES in climate mitigation. This uncertainty is manifest in the wide range of RES deployments in the scenarios reviewed in this section. The range is a reflection of uncertainty in: energy demand growth; the degree to which the development and deployment of high-efficiency energy end-use technologies mitigates this growth; the degree of climate mitigation; the ability of RES technologies to overcome their cost, performance, and other barriers; and the ability of competing supply technologies, most notably nuclear energy and fossil energy with CCS, to overcome cost and performance, social acceptance, environmental, and other barriers.

10.2.1 State of scenario analysis

Scenarios are a tool for understanding, but not predicting, the future. Scenarios 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, 2007). They are thus a means to explore the potential contribution of RES to future energy supplies and to identify the drivers of their deployment. In a climate stabilization regime, RES must compete with other options, such as nuclear energy, carbon capture and storage (CCS), energy efficiency and behavioural changes, to reduce GHG emissions the future energy system. Therefore, it is important to put renewable energy sources into the larger context of the energy system and the economy as a whole, in particular when thinking about the longer-term perspective to 2030, 2050 or even beyond.

The climate change mitigation scenario literature largely consists of two distinct approaches: quantitative modelling on the one hand and qualitative narratives on the other hand (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 analysis in this section relies exclusively on scenarios that provide a quantitative description of the future. These scenarios are valuable because of they provide quantitative 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 note, however, that there is enormous variation in the models used to construct the quantitative scenarios. Many authors have attempted to categorize these models as either bottom-up and top-down. For several reasons (see Box 1) [TSU: Box 10.1], this review will not rely on the top-down/bottom-up taxonomy. Instead, the characteristics of “technology detail” and “level of integration” will be used to help define modelling approaches.

Box 10.1: 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 models. While 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, while being 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.*, 2009a).

In addition, the terms top-down and bottom-up can be misleading, because they are strongly context dependent: they are used differently in different scientific communities. For example, in previous IPCC assessments (RS: Provide precise references), all integrated modelling approaches were classified as top-down models regardless of whether they included significant technology information (van Vuuren *et al.*, 2009a). 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.

To avoid the confusion borne by the top-down/bottom-up taxonomy, this section will organize modelling approaches along two axes: "technology detail" and "level of integration". By "technology detail" on the one hand the number of individual technologies and corresponding resource grades (e.g. wind on-/offshore) included in the models and on the other hand the adequate representation of their technical characteristics (e.g. fluctuating electricity generation from RES) is captured. While the former might lead to an over- or underestimation of the (technical and economic) potential, the latter can have significant impacts on the competitiveness of technologies. The "level of integration" in energy studies varies significantly from single technology and sectoral assessments to energy-economic and integrated assessment modelling where the latter also includes interactions of the energy sectors with the biosphere, the climate system, etc.

A total of 150 scenarios from the recent literature are reviewed in this section. Although this set of scenarios is by no means exhaustive of the recent work on mitigation scenarios, it is large enough and extensive enough to provide robust insights into the role of RES in climate change mitigation. In addition, although the level of integration and technology detail varies considerably across the underlying modelling frameworks, they all share an energy systems view; that is, no scenarios/studies that only look at single sectors or technologies are included. In addition, at least basic coverage of socio-economic variables (population, GDP) and climate indicators (atmospheric CO_2 concentration) was required. Included in this set are a number of scenarios from three co-ordinated studies: the Energy Modeling Forum (EMF) 22 international scenarios (Clarke et al., 2009), the ADAM project (Edenhofer et al., 2009b) and the RECIPE comparison (Edenhofer et al., 2009a; Luderer et al., 2009) that harmonize some scenario dimensions, such as baseline assumptions or climate policies across the participating models. The whole set of scenarios covers a large range of climate stabilization levels (350-1050 ppm atmospheric CO2 concentration by 2100) and time horizons (2050, 2100). The majority of the scenarios are global in scope.

This set of scenarios has several distinguishing characteristics that make is most appropriate for the consideration of RES. First, the scenarios represent the most recent work of the quantitative modelling community, and therefore reflect the most recent understanding of key underlying parameters. Second, the scenario set includes a relatively large number of selected 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). While traditionally 1st-best scenarios used to dominate the mitigation scenario literature, more recently 2nd-best scenarios have received growing attention (Clarke et al., 2009; Edenhofer et al., 2009a). As shown in Table 1, the share of 2nd-best scenarios is decreasing towards lower CO2 concentration levels, indicating that attainability of the lower targets gets increasingly difficult under 2nd-best assumptions. Finally, in developing the database for this section, RES information was collected at a level of detail beyond that found in most published papers or existing scenario databases, e.g. those compiled for previous IPCC reports (Morita et al., 2001; Hanaoka et al., 2006; Nakicenovic et al., 2006). For example, many scenario databases represent renewable energy technologies as either bioenergy or non-biomass renewables (e.g., Clarke et al., 2009).

Table 10.2.1: Number of long-term scenarios categorized by CO2 concentration levels in 2100 (categories as defined in the IPCC AR4, WGIII, see (Fisher et al., 2007)), assumptions on participation in a global climate regime and technology availability. The assumptions regarding delayed participation vary considerably, but are mostly taken from two harmonized studies (see (Clarke et al., 2009; Luderer et al., 2009)). Similarly, technology availability is not defined homogenously across all scenarios in the analyzed set. Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Alban Kitous et al., 2009; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009). [TSU: No reference in text]

	CO2 concentration by 2100 [ppm]	all scenarios	mitigation scenarios		
			1st-best	2nd-best (del. participation)	2nd-best (limited tech. portfolio)
Cat I+II (350-440ppm CO2)	350 - 440	39	24	3	12
Cat III+IV (440-570ppm CO2)	440 - 570	81	36	17	28
references (>600ppm CO2)	> 600ppm	30	-	-	-
Total	-	150	60	20	40

Figure 1 [TSU: Figure 10.2.1] shows the development of global fossil and industrial CO2 emissions in the medium- to long-term scenarios over the century, grouped by different categories of atmospheric CO2 concentration in 2100. Similar to previous assessments (e.g. (Fisher et al., 2007)) and as illustrated by the broad range of emissions in the baseline scenarios (without climate policies) as well as the different emission trajectories in the intervention cases, there is considerable uncertainty about the future evolution of the energy system. This uncertainty is reflected in the different assumptions used to develop scenarios and, as a result, in the aggregate characteristics of the energy system. For instance, fossil and industrial CO2 emissions by 2050 in the baseline scenarios cover a range of 43 to 84 GtCO2, leading to CO2 concentration levels of 490-570 ppm by 2050 and further to concentrations of 610-1050 ppm by 2100.

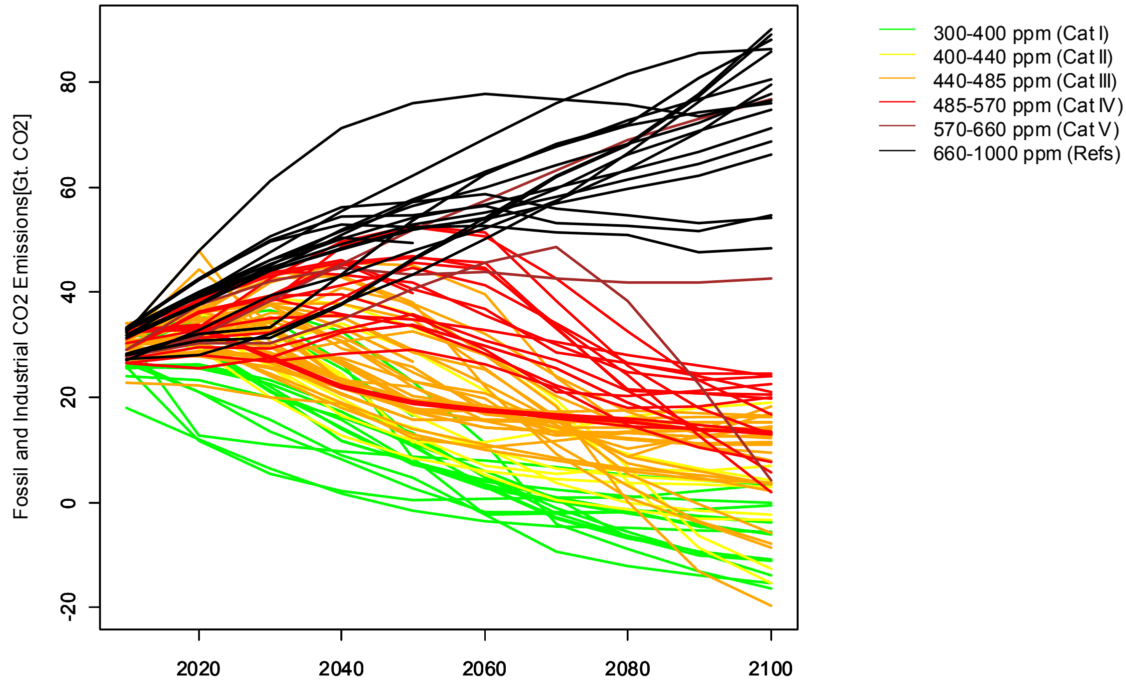


Figure 10.2.1: Global fossil and industrial CO2 emissions of long-term scenarios between 2010 and 2100(colour coding is based on categories of atmospheric CO2 concentration level in 2100). Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b). AUTHOR COMMENT: [include historical CO2 emissions since approx. 1950, add SRES, post SRES, AR4, etc. ranges as bars on right-hand-side for continuity with previous IPCC work]

10.2.2 The role of RES in scenarios

The potential deployment of renewable energy depends on a number of factors. One set of factors sets the scale for the deployment of low-carbon energy generally. This includes both the mitigation goal and the fundamental drivers of energy demand, such as population growth, economic growth, the evolution and emergence of end-use technologies that convert energy into useful services such as lighting, cooling, transportation, and industrial processes, along with energy policy choices. The factors that set the scale of the energy system are discussed in Section 10.2.2.1. Within this broader context, RES deployments depend on factors such as the competition between technologies that provide low-carbon energy (e.g., RES, nuclear energy, and fossil energy with CCS), and energy and mitigation policy approaches. In addition, the distribution of deployments over time and space depends on the relative level of mitigation among countries and the particular manner in which countries take action on climate mitigation and other energy-related issues (e.g., energy security). These issues are discussed in Section 10.2.2.2. Finally, the role of RES in moderating the costs of mitigation is discussed in Section 10.2.2.3.

10.2.2.1 Setting the Scale of Renewable Energy Deployment: Energy System Growth and Long-Term Climate Goals

It is useful to begin the discussion of RES deployments by first considering the broad forces that drive the need for low-carbon energy, which includes RES, nuclear energy, and fossil energy with CCS. Two forces are of particular importance: the scale of the energy system, here represented by primary energy demands, and the long-term climate goal.

Although there is some degree of correlation between primary energy demands and long-term mitigation goals in the scenarios, there is also a great deal of variation (Figure 2) [TSU: Figure 10.2.2]. One reason for this variation is simply our lack of knowledge about how key drivers of energy demand, such as economic growth, might evolve over the coming century. To some degree, the variation increases with the stringency of the long-term climate goal. The baseline scenarios are less varied because few scenarios envision primary energy demands decreasing over the coming century without emissions constraints. The constrained scenarios are more varied because these scenarios may assume abundant low-carbon options (leading to high primary energy demands) or approaches to mitigation based on reducing the demand for energy (leading to low primary energy demands).

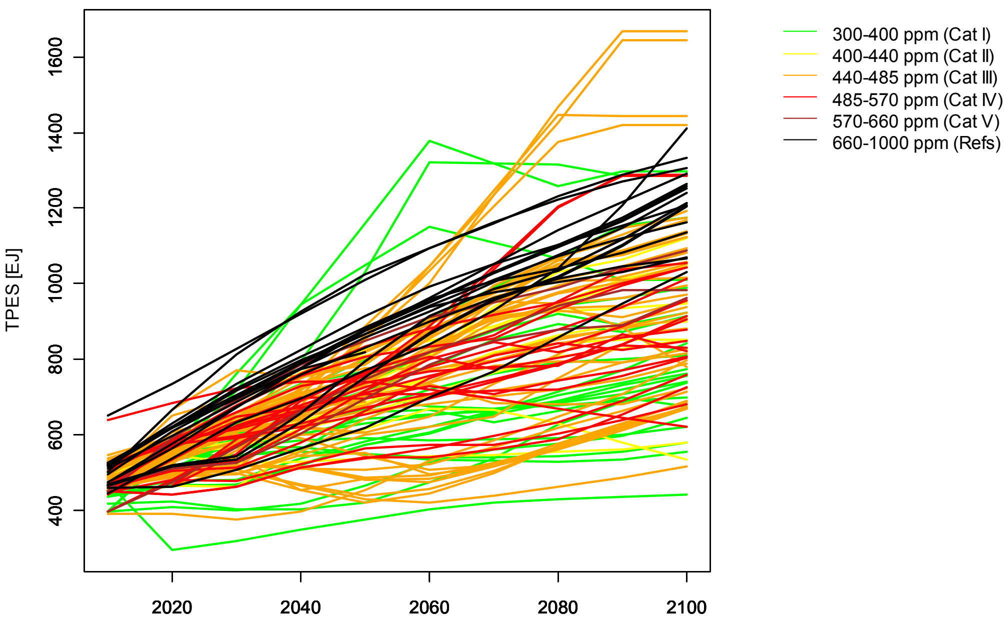


Figure 10.2.2: Primary energy consumption (direct equivalent) across both baseline and mitigation scenarios (colour coding is based on categories of atmospheric CO2 concentration level in 2100). Note the large range of primary energy consumption. Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b).

In contrast to the variation in total primary energy, the production of freely-emitting fossil energy is tightly constrained by the long-term climate goal (Figure 3) [TSU: Figure 10.2.3]. Meeting long-term climate goals requires a reduction in the CO2 emissions from energy and other anthropogenic sources. Physical systems, such as the global carbon cycle, put bounds on the levels of CO2 emissions that are associated with meeting any particular long-term goal. This puts limits on the amount of energy that can be produced from freely-emitting fossil energy sources. The tighter the climate constraint, the tighter are the near- and mid-term constraints on both CO2 emissions and freely-emitting fossil energy. Looser constraints imply greater flexibility over the coming decades, although CO2 emissions must necessarily be reduced toward zero, or beyond in some scenarios, in the longer term. Note that there is some degree of flexibility in the limits on freely-emitting fossil energy, as reflected by the ranges shown in Figure 3. Factors that lead to this flexibility include: the ability to switch between fossil sources with different carbon contents (e.g., natural gas has a lower carbon content than coal); the potential to achieve negative emissions by utilising e.g. biochar, bioenergy with CCS or forest sink enhancement, which allows for greater emissions of freely-emitting fossil energy; 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.

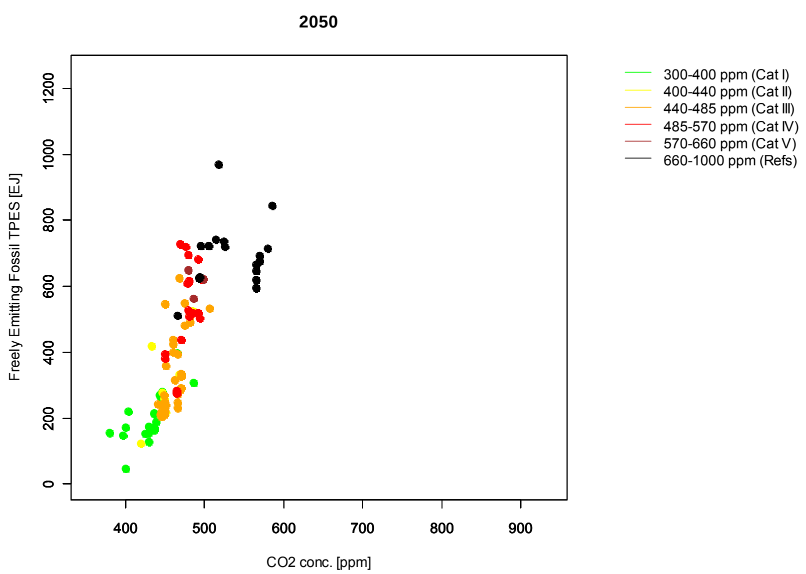


Figure 10.2.3: Freely emitting fossil primary energy consumption in the long-term scenarios by 2050 as a function of atmospheric CO2 concentrations in 2050 (colour coding is based on categories of atmospheric CO2 concentration level in 2100). Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b).

The demand for low-carbon energy, including not just RES, but also nuclear power and fossil energy with CCS, is the difference between total primary energy demand, reductions from end-use efficiency improvements notwithstanding, and the production of freely-emitting fossil energy that meets the long-term climate goal (the left panel in Figure 4) [TSU: Figure 10.2.4]. It follows that the low-carbon energy production is correlated to the long-term climate goal: as the stringency increases, CO2 emissions must decrease, and low-carbon energy increases (O'Neill et al., 2009). At the same time, because of the wide uncertainty in the magnitude of the energy system, the variation in low-carbon energy among scenarios to meet any long-term goal is large. Given the variability in low-carbon energy deployments more generally, it is not surprising that there is also great variation in the deployment of renewable energy deployments among scenarios, even for specific long-term climate goals (the right panel in Figure 4) [TSU: Figure 10.2.4].

Despite the variation in RES deployments, the actual levels of RES deployment are dramatically higher than those of today in the vast majority of the scenarios. In 2007, total global RES deployment stood at 62.4 EJ/yr (IEA, 2009).[2] In contrast, by 2050, deployments in many of the scenarios reach 200 EJ/yr or up through 400 EJ/yr. This is an extraordinary expansion in RES energy. The ranges for 2100 are substantially larger than these, reflecting continued growth throughout the century.

It is also important to note that although deployments of RES technologies in the baseline scenarios are not in general as large as those in the more aggressive mitigation scenarios, these baseline deployments are also quite large in many instances. These large deployments are simply a matter of energy system scale and assumptions about the relative competitiveness and resource base for RES technologies. As discussed earlier, there is a large increase in primary energy consumption over the coming century in most of the scenarios. This demand will need to be met by both CO2-emitting and non-CO2-emitting sources. Those scenarios that assume relatively strong competitiveness from RES technologies exhibit RES deployments that can be dramatically larger than those of today.

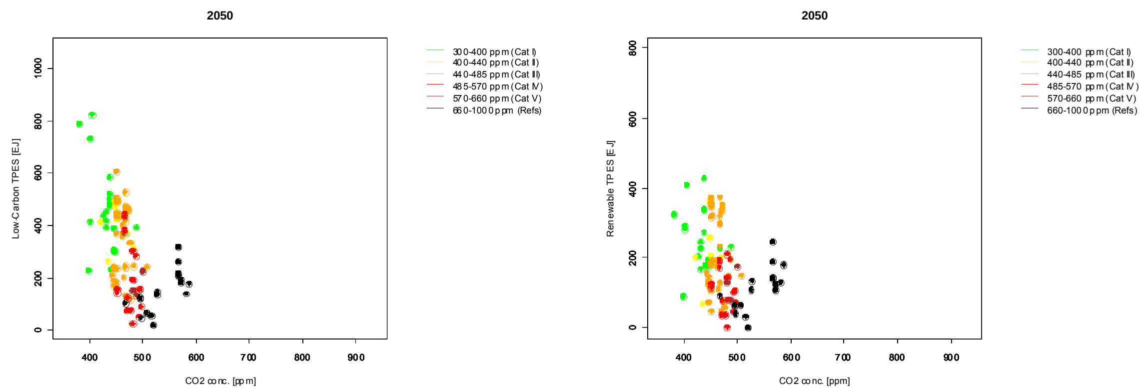


Figure 10.2.4: Global low-carbon primary energy consumption (left panel) and renewable primary energy consumption (right panel) in the long-term scenarios by 2050 as a function of atmospheric CO2 concentrations in 2050 (colour coding is based on categories of atmospheric CO2 concentration level in 2100). Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b).

Another additional uncertainty affecting RES deployments is the competition with other options for reducing carbon emissions. RES are only one option for meeting the energy demands while reducing carbon emissions. The others are nuclear energy, fossil energy with CCS, and reductions in total energy demand through more efficient end use technologies or reductions in end use demand. All other things being equal, RES deployments will be lower if these other options are more competitive.

It follows that the presence or absence of competing low carbon supply technologies, nuclear power and fossil energy with CCS, has an important influence on the deployment of RES. Scenarios such as these are often referred to as 2nd best scenarios because they reflect a less than full set of technology options. All other things being equal, when these competing options are not available, RES deployments will be higher because RES technologies must carry more of the load associated

[2] IEA 2009 Energy Balances report this value for 2007, but note that geothermal and solar thermal is accounted for differently by IEA (factors 10 and 2 respectively for electricity and heat generation) which is not so easily converted to direct equivalent because of CHP (at most 2 EJ deviation).

with mitigation. In addition, because the costs of mitigation are higher in these cases, total primary energy consumption is also lower as end use options – increased efficiency or reduced demand – become increasing economically attractive with higher CO_2 prices. In the scenarios reviewed here, it is clear that for individual models the absence of competing low-carbon supply technologies such as nuclear power and CCS leads to higher RES deployments (Figure 5) [TSU: Figure 10.2.5]. Although the extent to which the RES contribution to primary energy greatly varies across the models, in almost all available examples the unavailability of CCS has a stronger impact on the RES share than the unavailability of nuclear power. One possible explanation for this is that CCS affords, in many scenarios, for the production of energy that couples bioenergy and CCS, leading to negative emissions. There is no such possibility for nuclear power. An additional explanation may be that models have assumed greater environmental, security/proliferation, and safety limits on the possible deployment of nuclear power. These dynamics are not explored here. Instead, it simply noted that these 2nd best scenarios clearly demonstrate the influence of competition between low-carbon options.

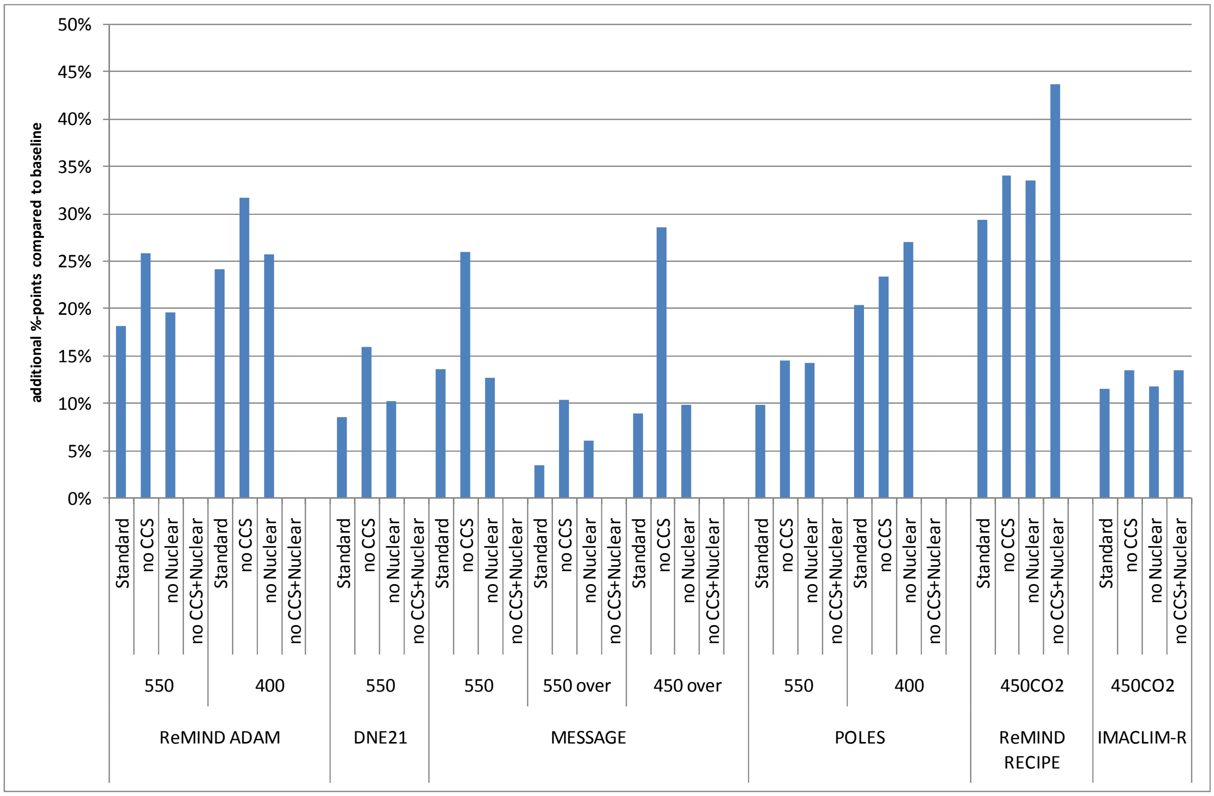


Figure 10.2.5: Increase in renewable primary energy share by 2050 in 1st- and 2nd-best mitigation scenarios in percentage points compared to the respective baseline scenarios. Note that the exact definition of the "no CCS", "no Nuclear" and "no CCS+Nuclear" cases varies across models. Moreover, the magnitude of the increase shows a large spread, mostly because the deployment in the respective baselines differs significantly between the models.Scenarios from (Akimoto et al., 2008; Edenhofer et al., 2009a; Kitous, 2009; Krey and Riahi, 2009; Leimbach et al., 2009).

At the same time, although it is tempting to attribute the variation in RES deployments across scenarios to the character of the competing options, the discussion to this point should make clear that 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 RES technologies themselves are equally critical drivers of RES deployments (Figure 6) [TSU: Figure 10.2.6]. There appears to be little solid correlation between the availability of CCS and the degree of renewable energy deployment considering all the scenarios reviewed here. In other words, the presence or absence of large-scale deployments of CCS or nuclear are not the only or perhaps even the most critical determinants of future RES deployments to address climate change.

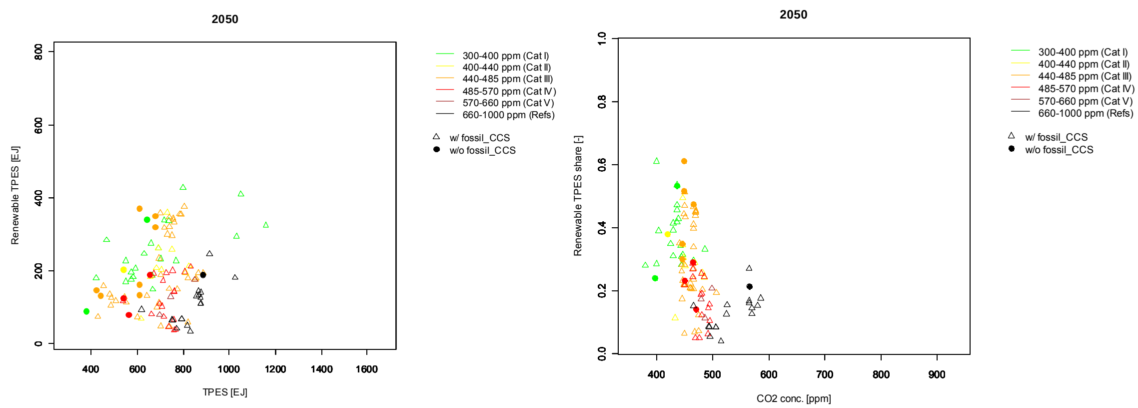


Figure 10.2.6: Global renewable primary energy consumption in the long-term scenarios by 2050 as a function of total primary energy consumption, grouped by different categories of atmospheric CO_2 concentration level in 2100 (left panel) and renewable primary energy share as a function of atmospheric CO_2 concentrations in 2050 (colour coding is based on categories of atmospheric CO_2 concentration level in 2100) (right panel). The availability of CCS in scenarios is indicated by triangles while unavailability by filled circles. Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b).

In summary, the scenarios literature to date indicates several broad elements of future RES deployments. First, the scale of these deployments could be quite large, if climate change is to be addressed. They may, in fact, be quite large even without addressing climate change simply due to the increasing demand for energy and other challenging environmental, public health, or security issues associated with competing technologies such as coal, nuclear energy, natural gas, and petroleum. Second, besides the general expectation of a significant increase there is little consensus on just how large these deployments should be to meet any particular climate goal, given uncertainties about the demand for primary energy in the future, the cost and performance of RES technologies, and the cost of competing technologies such as nuclear and fossil energy with CCS, and the long-term mitigation goal.

10.2.2.2 RES Deployments by Technology and Region

Within the context of total RES deployment, there is great variation in the deployment characteristics of individual technologies (Figure 7) [TSU: Figure 10.2.7]. 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 renewable energy technologies. 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 RESs (Figure 7 and Figure 8) [TSU: Figure 10.2.7 and Figure 10.2.8], 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 bioenergy 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 renewable energy 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 (Figure 7) [TSU: Figure 10.2.7] 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 bioenergy from advanced feedstocks, such as cellulosic feedstocks.

Third, the deployment of some renewables in the scenarios is driven mostly by climate policy (e.g. solar, geothermal, commercial biomass) whereas others are considerably deployed irrespective of climate action (e.g. wind, hydro, direct use of bioenergy) (Figure 8) [TSU: Figure 10.2.8]. 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.

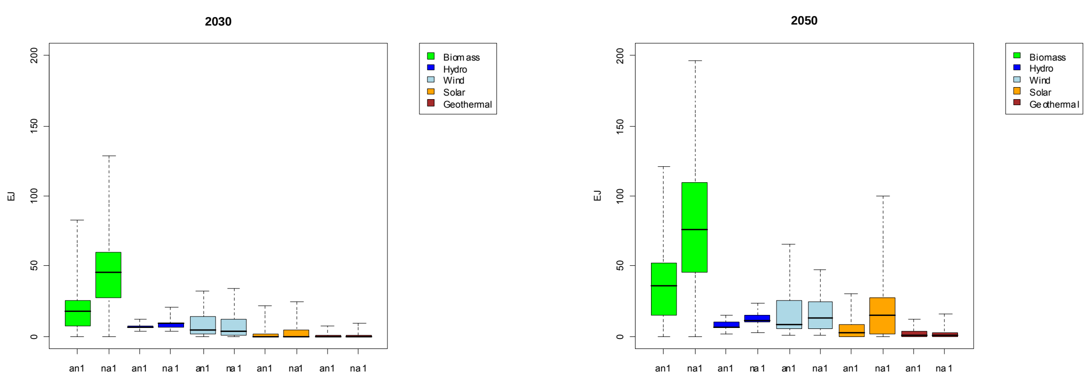


Figure 10.2.7: Renewable primary energy consumption by source in Annex I and Non-Annex I countries in the long-term scenarios by 2030 and 2050.[3] Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b).

[3] In these and all following box-plots 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.

Finally, the distribution of RES 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 RES 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 RES supplies are large enough to support this growth. All other things being equal, higher energy demands will require greater deployment of renewable energy sources. This is important in the sense that it highlights that RES in climate mitigation is both an Annex 1 and a non-Annex 1 issue.

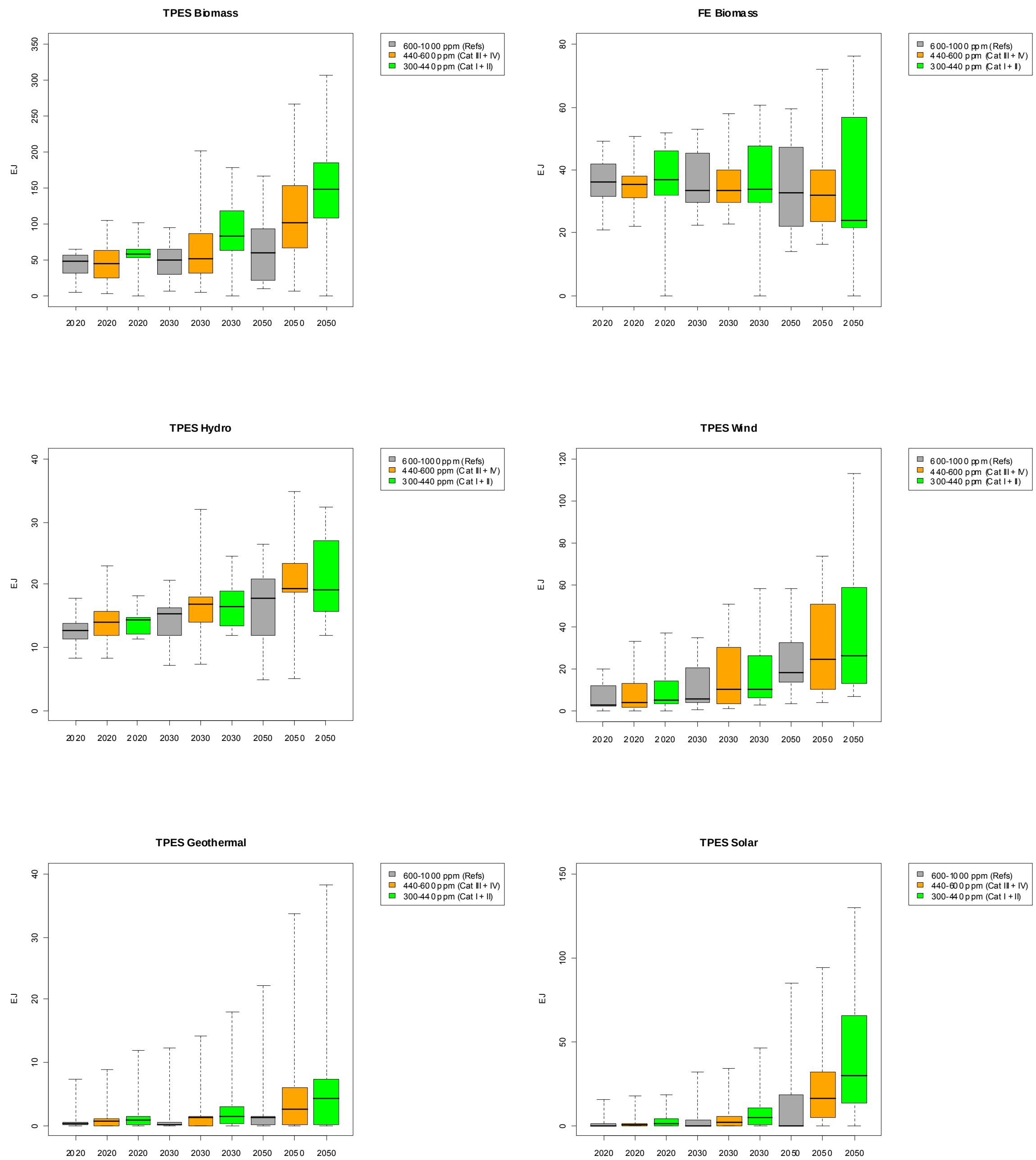


Figure 10.2.8: Global energy consumption of biomass, hydro, wind, solar and geothermal in the long-term scenarios by 2020, 2030 and 2050, grouped by different categories of atmospheric CO_2

concentration level in 2100. Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b).

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, near- to mid-term mitigation efforts may differ substantially across regions, with some regions taking on larger commitments than others. In this real-world context, the distribution of renewable energy deployments in the near-term would be skewed toward those countries taking the most aggressive action. As an example, Figure 9 [TSU: Figure 10.2.9] shows the change in RES deployment in China in 2020 and 2040 from the Energy Modeling 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. The figures show that RES deployments are influenced by the variation in mitigation among regions. When China delays mitigation, the relative deployments of RES are lower. The impact is generally more severe for tighter constraints, because the degree of mitigation is higher in these cases. Delay clearly decreases deployment during the period when China is taking on no mitigation (2020). The effect of delay on RES deployments is ambiguous in the period after China has begun mitigation (the right panel in Figure 9) [TSU: Figure 10.2.9]. In some cases, deployments are larger in 2050 and in some cases they are lower. This ambiguity is in part because China 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. It is also important to note that there is some degree of RES deployment in every region even in the absence of mitigation. This is the reason that there is little effect on RES deployment in some scenarios in 2020.

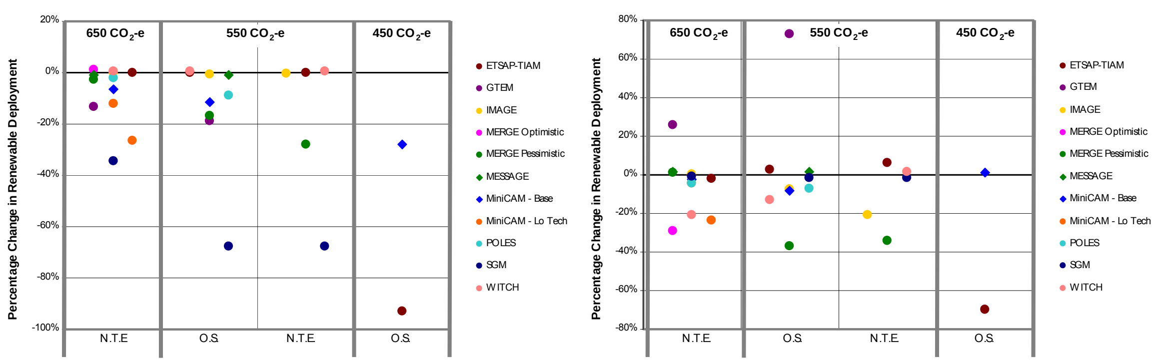


Figure 10.2.9: Change in RES deployment in China across EMF 22 scenarios as a result of delayed accession in 2020 (left panel) and 2040 (right panel) (Clarke et al., 2009).

10.2.2.3 Renewable energy and the costs of mitigation

One way that researchers characterize the challenge of mitigation is to quantify the economic consequences of mitigation. Technological improvements that reduce costs or improve performance will make it easier to address climate change. It is therefore useful to explore the relationship between RES deployments that the economic indicators of mitigation cost.

A first point to note is that the scenarios literature generally demonstrates that although mitigation reduced GDP, the other forces that drive GDP exert a larger influence. This means that RES deployments in response to climate mitigation will not be largely linked to total global GDP. Figure 10 [TSU: Figure 10.2.10] shows global GDP across the scenarios analyzed in this study (left panel) and the correlation between carbon prices and RES deployments (right panel). There is little correlation between GDP and stabilization level. Although mitigation following most of the scenarios will reduce economic output, the uncertainty in underlying drivers of economic growth swamps this effect. Moreover, a minor part of the literature finds that climate mitigation could lead to increased economic output (cf. e.g. (Barker et al., 2006)).

Nonetheless, mitigation should have a real cost. The CO_2 price is one of several metrics that has been used to characterize the economic implications of mitigation. The right panel in Figure 10 [TSU: Figure 10.2.10] demonstrates that higher RES deployments are generally associated with higher CO_2 prices, but that there is a great deal of variation in this correlation. There are several interacting, and some degree counteracting forces at work here. First, more aggressive mitigation generally calls greater deployment of low-emissions energy sources. CO_2 prices are higher with higher RES deployments because these low-emissions sources are generally more costly then their emitting counterparts. Larger energy demands will also require greater deployments of low-emissions sources (see the discussion above), and this may further increase the CO_2 price. The second dynamic is that, to the extent that RES technologies have higher performance, larger supplies, or lower cost, they will both have higher deployments and make mitigation cheaper. This effect would tend to correlate larger RES deployments with lower CO_2 prices. 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 RES deployments and carbon prices.

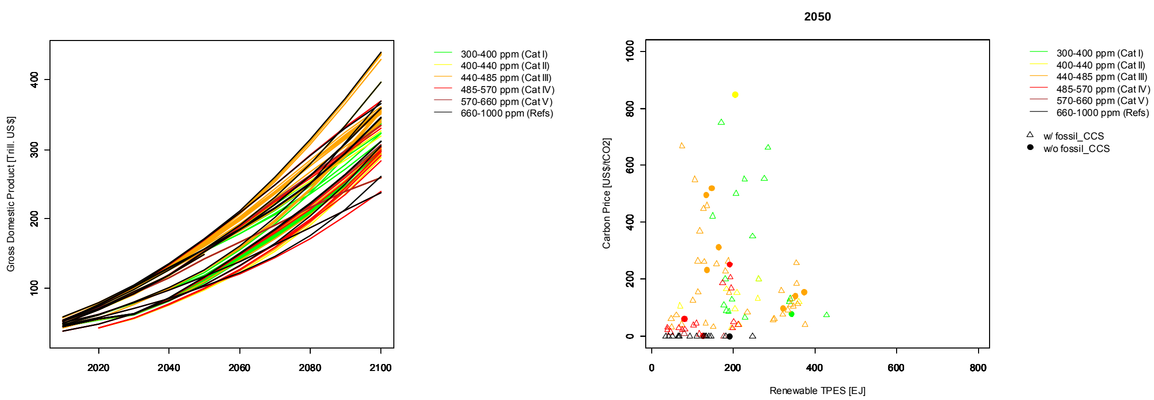


Figure 10.2.10: Gross World Product development and carbon price by 2050 as a function of renewable primary energy consumption grouped by different categories of atmospheric CO_2 concentration level in 2100. Scenarios from (Kurosawa, 2006; van Vuuren et al., 2007; Akimoto et al., 2008; IEA, 2008; Shukla et al., 2008; Bosetti et al., 2009a; Bosetti et al., 2009b; Calvin et al., 2009; Gurney et al., 2009; Kitous, 2009; Krewitt et al., 2009; Krey and Riahi, 2009; Leimbach et al., 2009; Loulou et al., 2009; Luderer et al., 2009; Magne et al., 2009; van Vliet et al., 2009; van Vuuren et al., 2009b).

10.2.3 The deployment of RES in scenarios from the technology perspective

This section summarizes the results of the deployment sections from the individual technology chapters and puts the deployment levels from the reviewed scenarios into context. AUTHOR COMMENT: [Information from several chapters has been summarized, but additional iterations will be needed to make this section really coherent with the deployment sections of [TSU: the technology] Chapters 2-7 and the systems integration chapter 8. It will be completed for the Second-Order Draft of this report.]

All scenarios report global primary energy biomass consumption levels by 2050 that are compatible with corresponding biomass resource potentials which take into account key sustainability criteria and amount to more than 400 EJ, also by 2050. However, due to the complexity of bioenergy production and the variety of fuel chains involved, much more than a simple comparison of total bioenergy potentials is needed to provide a coherent and integrated picture. This includes potential conflicts with food production (e.g. first generation biofuels), land-use change and environmental and socio-economic impacts of bioenergy deployment (see Chapter 2.8).

The contribution of solar PV in 2020 and 2030, being lower than 7 EJ in the majority of scenarios (75^{th} percentile) is considered to be relatively low. On the other hand, the PV growth rates after 2030 which lead to sizeable deployment levels by 2050 are judged to be on the high side (see Chapter 3.9).

Global and regional availability of geothermal resources do not pose a constraint on the deployment of geothermal energy in the scenarios. Even under the most optimistic assumptions which foresee a contribution of geothermal energy at the primary energy level of up to 38 EJ globally by 2050 market penetration seems to be reasonable. However, in particular the median deployment levels which are much lower than that (up to 4.5 EJ by 2050) are considered to be on the conservative side and considerably lag behind the deployment levels as projected by technology experts (see Chapter 4.8.3).

For hydropower, currently only about a third of the economically feasible potential is developed, corresponding to about 3000 TWh electricity generation or 11 EJ in primary energy units. In the most optimistic scenarios this - under current conditions – economically feasible potential is exploited by 2050 (about 35 EJ) while in the median case only a doubling a current electricity generation is projected. Compatible with the assessment of the technology experts is the finding that most of the hydropower expansion will most likely happen in the non-Annex I countries, because in many Annex I countries the largest part of the potential has been developed in the past. However, both the scenarios and the technology experts still project significant hydropower capacity expansion also in Annex I countries (see Chapter 5.9.1).

Compared to previous IPCC estimates in the AR4 (based on literature available until 2005), which assumed a contribution of wind power in the order of 8 EJ by 2030 (7% of global electricity supply) the role of wind has increased in the recent scenario literature where the median by 2030 ranges between about 6 EJ under baseline conditions and more than 10 EJ under modest to more stringent climate mitigation scenarios. The large diversity of results reflects on the one hand the underlying uncertainties (see Section 10.2.2) and on the other hand the diversity of modelling approaches used to generate these scenarios. In particular, more modelling tools with less technological detail do not adequately reflect "technical and economic viability" of high wind penetrations which are relevant at geographical and temporal scales way smaller than most existing modelling tools are capable of addressing. As for the other RES, the technical potential is unlikely to pose a constraint on the wind deployment levels as reported by the scenarios and also upscaling of wind industry production capacities is not considered to be a problem even under the most aggressive wind penetration levels of up to 100 EJ globally by 2050, provided that adequate policy frameworks will be in place. To realize these higher global wind deployment levels, however, a greater geographic distribution of deployment will be necessary. In any case, to ensure sufficient investments over the long term, incentive policies (carbon price or other, see Chapter 11) that provide adequate economic attractiveness as well as stability are likely to be required (see Chapter 7.9).

From a systems integration perspective, dealing with fluctuating RES in electricity generation (wind, solar, wave, tidal and run-of-river hydropower) is most challenging, but a broad portfolio of technologies including quickly dispatchable plants is available that can help address these challenges. In addition, a wider geographical distribution and improved forecasting of variability can lead to a smoothing of total electricity output over time. More generally speaking, the ability to integrate larger shares of fluctuating RES into the electricity generation system depends on the architecture and flexibility of the overall power supply system. At higher deployment levels of fluctuating RES, backup generation may be needed to maintain reliable grid operation. Moreover, load management and more flexible market instruments can help dealing with higher RES shares while reducing the need for investments into power plants, storage systems and other infrastructure (see Chapter 8).

10.2.4 Strengths and weaknesses of scenario analysis

Scenario analysis is used to explore alternatives of how the future might unfold. The focus here is on the contribution of RES to the energy supply against the background of avoiding dangerous anthropogenic interference with the climate system. The scenarios reviewed in this section are not meant to be predictive. Their greatest value lies in setting up thought experiments that generate robust insights into the issues of interest rather than creating large sets of numbers. The analysis presented here emphasizes this view by showing a very rich future for RES that spans - depending on a number of determining factors - a spectrum from essentially negligible up to the dominant energy sources in the medium-term.

The strength of global scenarios is to provide an integrated view on the role of RES, but they might not accurately cover all details that govern decision making at the national or even company scale, in particular in the short-term. 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, other tools, such as market outlooks or shorter-term national analysis that explicitly address all existing policies and regulations might be more suitable sources of information. Section 10.3 provides a shorter-term view of RES deployments using scenarios, and is therefore complementary to this section.

Important features of the scenarios included in this review are plausibility, internal consistency and a certain level of integration that covers the interaction of RES with the energy system, the economy and the climate system. The emphasis of different aspects greatly differs across the scenarios covered in this assessment with some having a much more detailed representation of individual renewable and other energy technologies and aspects of systems integration of RES while others focus on the implications of renewable deployment for the economy as a whole. Whereas for certain questions one or the other approach might be preferable, including different methods and modelling approaches in the assessment provides us with a representation of the deep uncertainties associated with future dynamics of the energy system, the role of RES therein and the resulting GHG emission trends.

10.3 Assessment of representative mitigation scenarios for different renewable energy strategies [TSU: deviation from structure agreed by plenary: "Assessment and synthesis of scenarios for different renewable energy 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 renewable energies and the specific role of these technologies in mitigation paths, in this chapter a more detailed view should be given on the specific renewable energy technologies. Behind that background several scenarios from the given general overview have been selected to build the basis for a more in-depth analysis. The primary data for this analysis has been provided by the scenario authors and/or institutions.[4] Besides that, additional data has been taken from chapter 2 till 7.

All analysed scenarios used a 10-region global energy system model environment and represent with the exemption of the reference scenario of the IEA World Energy Outlook which is a typical forecasting approach target oriented scenarios based on a back-casting process. The 10 regions correspond to the world regions as specified by the IEA's World Energy Outlook 2007 (Africa, China, India, Latin America, Middle East, OECD Europe, OECD North America, OECD Pacific, Rest of Developing Asia, Transition Economies). The Energy [R]evolution (ER2008) as well as IEA World Energy Outlook and ETP are based on IEA energy statistics (DLR 2008, IEA 2007, IEA 2008).

10.3.1 Technical Potentials from renewable energy sources

Before looking on the role renewable energies is given by different scenarios, it is worth to know about the upper application limit. The overall technical potential for renewable energy – 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. The assessment about the total (global) technical potential for all renewable energies sources varies significantly from 2.477 EJ/a (Nitsch 2004) up to 15,857 EJ/a (UBA 2009)[5]. Based on the global primary energy demand in 2007 (IEA 2009) of 503 EJ/a the total technical potential of renewable energy sources at the upper limit would exceed the demand by a factor of 32. However barriers to the growth of renewable energy technologies may rather be posed by economical, political, and infrastructural constraints. That's why the technical potential will never be realised in total.

Assessing long term technical potentials is subject to various uncertainties. The distribution of the theoretical resources is not always well analysed, e.g. the global wind speed or the productivity of energy crops. The geographical availability is subject to issues as land use change, future planning decision on where technologies are allowed to be installed and accessibility of resources, e.g. for geothermal energy. The technical performance will develop on the long term and the rate of development can vary significantly over time. Next to these inherent uncertainties, one is confronted with uncertainties regarding the definition and the transparency of literature sources. The data provided even in the cited studies is not always consistent, and underlying assumptions are often not explained in detail. Similarly, not all studies use well-established potential definitions, or the definitions are not stated explicitly, which results in uncertainties when comparing potentials between different literature sources (UBA 2009).

The 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 renewable energy 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, 2004), and studies that only focus on one source, for instance

[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] 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.

(Hofman et al, 2002) and (Fellows, 2001)[6]. The study compared for each renewable energy 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 renewable energy source.

Table 10.3.1: Technical Potential by technology for different times and applications.

		Technical potential EJ/yr electric power							Technical potential - heat - EJ/a		Technical potential – primary energy – EJ/a		Total
		solar PV	solar CSP	hydro-power	wind onshore	wind offshore	ocean energy	geothermal electric	geothermal direct uses	solar water heating	biomass residues	biomass energy crops	
World	2020	1125,9	5156,1	47,5	368,6	25,6	66,2	4,5	495,5	113,1	58,6	43,4	7.505
	2030	1351,0	6187,3	48,5	361,7	35,9	165,6	13,4	1486,6	117,3	68,3	61,1	9.897
	2050	1688,8	8043,5	50,0	378,9	57,4	331,2	44,8	4955,2	123,4	87,6	96,5	15.857
World Energy Demand 2007: IEA 2009 [EJ/a]	502,9												
Technical Potenial in 2050 versus World primary energy demand 2007		3,4	16,0	0,1	0,8	0,1	0,7	0,1	9,9	0,2	0,2	0,2	32

Source. 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 versus World energy demand: S. Teske

The complexity to calculate renewable energy 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 already 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. Considering the huge dynamic of technology development, many existing potential studies are based on data which cover from a nowadays perspective quite old technology characteristics. The results and estimates of this study have to be converted using more recent numbers (e.g. significantly increased average wind turbine size, suitability factor) which would increase technical potentials even further[7]. Given the high unexploited potentials already although without having reached the full technological development limits so far it can be concluded that technical potential is not the limiting factor to expansion of renewable energy generation.

10.3.2 Regional and sectoral breakdown of renewable energy sources

To exploit the entire technical potential is neither needed nor unproblematic. Implementation of renewable energies has to respect sustainability criteria in order to achieve a sound future energy supply. Public acceptance is crucial to the expansion of renewable energies. Due to the decentralized character of many renewable energy 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

[6] 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.

[7] The wind speed is converted to output in terms of full-load hours using a linear relation. A suitability factor was applied in order to quantify maximum area for wind electricity production. At these suitable areas, a power density of 4 MW/km2 was assumed. The output of a wind turbine was calculated assuming an average wind turbine size of 1 MW for 2005 and 3 MW for 2050, with a linear increase from 2020 to 2050. While there were no 5 MW or even 6 MW turbines on the market, in 2009 those turbines are already available. Turbines with higher capacities do have a higher hub height (above 100 m). This results in higher wind speeds and therefore an increased output when assuming a roughness length of 0.1 m of 10%.

have a huge influence on the overall market 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 [TSU: in the Glossary to the report], but often used in different manner. Often the general understanding is that market potential is the total amount of renewable energy 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 renewable energy 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 renewable energy sources. An approximation of what can be expected for the future markets can be achieved via using the results of in particular bottom up energy scenarios delivering an in depth view on renewable energy technologies from an overall system perspective taking relevant interaction into consideration.

Behind that background the goal of the chapter is to come out with a range of possible futures, described here as high, medium and low market penetration of renewable energy technologies. Therefore, in this section an analysis of selected "bottom up" global energy scenarios have been conducted which have substantial information on a number of technical details. The selected eight global scenarios represent a wide range of emission categories; from up to 1000ppm – as a reference case - , via category IV + III (>440 – 660ppm) down to category I + II (<440ppm). While there are a relative huge number of category III and IV scenarios, global energy scenario from category I and II with greater technical details were not available for this analysis and might be added if published. This indicates that more research is needed in category I and II scenarios.

Table 10.3.2: Overview: Different demand projections of the analysed scenarios. (ETP Data to come). [TSU: no reference in text]

Categories	Scenario name	Energy demand [EJ/a]		Renewable energy share	
		2030	2050	2030	2050
References (>600ppm)	World Energy Outlook 2008 World Energy Outlook 2009 ETP Base 2008	721 712	868 (1) No data	14% 14%	13% (1) No data
Categories III + IV (> 440 – 660 ppm)	ETP ACT ETP BLUE IEA 550ppm (2008) IEA 450ppm (2008 /2009)	648 601 / 602	No data No data	24% / - 18% / 22%	no data no data
Categories I + II (< 440 ppm)	Energy Revolution [DLR / EREC GPI]	526	481	31%	56%
(1) DLR 2008					

Besides the discussion of mitigation scenarios the subchapter considers the findings of the technical chapters 2 – 7 as well and summarizes the different technology parameters and energy potentials and their deployment over time from their perspective. Also "Technology Roadmaps" and "Market Development Reports" have been analysed if suitable. The possible market penetration for each sector, region and time horizon depends on a number of assumptions. Especially the assumptions of current and future costs for different renewable energy 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. In fact the level of detail for the cost development in the heating and cooling is so poor, that a cost analysis was not possible. This is particularly problematic as renewable heat shows not only a huge technical potential, but is in many cases already cost effective (ISES 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. The outcomes of the energy scenarios depend on many assumptions which can vary significantly between the considered studies. Most important are of course assumptions for market developments, costs and other scenario relevant technical details.

10.3.2.1.1 Factors for market development in the renewable power sector

The biggest variations in the cost development assumptions can be found for younger technologies such as solar photovoltaic, concentrated solar power plants and ocean energy (cf. table 4). Among these technologies, in particular the cost projections for solar photovoltaic vary significantly, which leads in the scenarios to very different market development pathways. For 2020, the highest costs projection was US$ 5960 /kW and the lowest projection at US$ 2400/kW[8]. The upper limit was so far even higher than the current market price. 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 renewable energy 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.

10.3.2.1.2 Annual market potential for renewable power

Annual market growth rates in the analysed scenarios are very different, 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 2009). The wind industry experienced 30% annual growth rate over the same time period (GWEO 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 and decline to between 20% and 10% between 2020 and 2030 and below 10% after 2030. In contrast, all analysed integrated energy scenarios assume much lower annual growth rates for all renewable power technologies in the range of about 20% till 2020 further declining to 10% or lower afterwards. Only concentrated solar power had higher annual growth rate projections.

Based on the energy parameters of the analysed scenarios, the required annual production capacity has been either calculated (IEA scenarios) or has been provided by the scenario authors. Table 4 [TSU: Table 10.3.3] provides an overview about the required annual manufacturing capacities

[8] 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)[8] for households, larger photovoltaic parks in the MW-range achieved significant lower prices.

(annual market volume) in order to implement the given renewable energy generation within the analysed scenarios. These calculated manufacturing capacities do not include the additional needs for repowering.

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: DLR/GPI/EREC: Energy [R]evolution 2008 / IEA WEO 2008, ETP 2008, information from chapter 2-7, Sven Teske (scenario analysis).

	Energy parameters								Market development					
	Generation			% of Global Demand % of Global Demand				Capacity factor (average)	Annual market growth			Annual market volume		
	Twh/a			**Max:** Low global demand (3)	High global demand (1)	Medium global demand (2)	**MIN:** low global demand (3)	%	%/a			GW/a		
	high	medium	low	Market development high	Market development: high	Market development medium	Market development low		high	medium	low	high	medium	low
Solar (A)														
PV - 2020	459	87	70	2%	1,7%	0,3%	0,3%	18%	39%	18%	16%	27	4,5	4
PV - 2030	2792	1351	142	8%	8,4%	4,5%	0,8%	18%	21%	18%	7%	159	65,2	5
PV - 2050	4754	2584	142	15%	9,4%	6,5%	0,4%	18%	22%	12%	5%	199	121,0	72
CSP - 2020	355	115	11	1%	1,3%	0,4%	0,2%	65%	40%	21%	10%	8	1,7	0
CSP - 2030	1732	971	24	5%	4,5%	3,2%	2,2%	68%	30%	15%	8%	26	14,2	10
CSP - 2050	7878	2731	24	26%	15,6%	6,8%	2,2%	75%	17%	15%	3%	118	63,8	4
Wind (B)	TWh (el./ therm)			% of Global Generation										
On+Offshore-2020	3.333	1.740	970	13%	12%	7%	4%	28%	24%	16%	9%	122	55	22
On+Offshore-2030	6.019	3.484	1.490	18%	18%	12%	6%	26%	9%	7%	4%	157	71	17
On+Offshore-2050	10.100	4.819	1.208	33%	20%	18%	3%	29%	5%	3%	1%	157	41	4
Geothermal [C]	TWh (el./ therm)			% of Global Generation										
> for power generation														
2020	392	231	128	2%	1%	1%	0%	78%	17%	11%	5%	5	2	1
2030	611	488	199	2%	2%	2%	1%	80%	9%	8%	3%	4	3	1
2050	1.059	934	264	3%	2%	3%	1%	79%	8%	6%	2%	8	7	1
> heat & power (CHP)														
2020	322	65	6	1%	1%	0%	0%	62%	49%	29%	1%	5	1	0
2030	908	191	9	3%	3%	1%	0%	62%	11%	11%	4%	10	2	0
2050	657	191	17	2%	2%	1%	0%	61%	13%	0%	6%	9	0	0
Bio energy (D)	TWh (el./ therm)			% of Global Generation										
> for power generation														
2020	836	690	343	3%	3%	2%	1%	63%	21%	17%	9%	13	9	3
2030	1.523	866	423	5%	5%	3%	1%	64%	9%	5%	2%	17	10	3
2050	1.571	1.274	670	5%	5%	3%	2%	82%	4%	3%	1%	8	4	3
> heat & power (CHP)														
2020	1.020	741	272	4%	4%	3%	1%	50%	15%	13%	3%	15	13	2
2030	2.066	1.403	367	6%	6%	5%	1%	58%	7%	5%	0%	21	10	0
2050	2.858	1.736	613	9%	7%	6%	2%	64%	11%	8%	5%	34	19	4
Ocean (E)	TWh (el./ therm)			% of Global Generation										
2020	58	25	4	0%	0,21%	0,10%	0,02%	35%	33%	23%	3%	2	1	0
2030	151	69	10	0%	0,45%	0,23%	0,03%	40%	19%	10%	7%	3	1	0
2050	677	413	10	2%	1,34%	1,03%	0,03%	38%	20%	16%	0%	15	11	0
Hydro (F)	TWh (el./ therm)			% of Global Generation										
2020	4.547	4.010	3.521	18%	16%	15%	14%	38%	4%	2%	1%	39	20	8
2030	6454	4425	3955	19%	19%	15%	14%	39%	3%	2%	1%	54	19	12
2050	6027	5348	4590	20%	17%	15%	12%	40%	2%	2%	1%	31	27	16
Total Renewables	TWh (el./ therm)			% of Global Generation										
> for power generation														
2020	9.980	6.898	5.047	39%	36%	26%	20%		25%	15%	7%	215	92	39
2030	19.282	11.654	6.243	58%	58%	39%	19%		14%	9%	4%	418	183	47
2050	32.066	18.103	6.908	104%	63%	45%	22%		11%	8%	2%	536	275	101
> heat & power (CHP)														
2020	1.342	806	277	5%	5%	3%	1%		32%	21%	2%	21	14	2
2030	2.974	1.594	376	9%	9%	5%	1%		9%	8%	2%	31	12	0
2050	3.515	1.926	630	11%	7%	5%	2%		12%	4%	6%	43	19	4

References:	Analysed scenarios and technical roadmaps – annual market growth rates + required manufaction capacity for all IEA scenarios are calculated based on provided informations	[E]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI;+ information from Chapter 6
[A]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI;EPIA Roadmap + SolarGeneration V (reference, medium, advanced), WETO 2050, ESTELA CSP Outlook 2009 (reference, medium, advanced), + information from Chapter 3	[F]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (B/
[B]	ACT); Energy [R]evolution 2008 – DLR/EREC/GPI; GWEC- Global Wind Energy Outlook	[1]	Global High demand Projection: IEA WEO 2008 – reference case
[C]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GP + information from Chapter 4	[2]	Global Medium demand Projection: Calculated (WEO -ER)
[D]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI; + information from Chapter 2	[3]	Global Low demand Projection:Energy [R]evolution 08, DLR/EREC/GPI

Besides the expectations for renewable energies the specific numbers for the overall electricity demand are decisive for specifying the resulting role of renewable energies. High power demand and high market development projections are not necessarily from the same scenario. The IEA World Energy Outlook assumes a rather high demand development while the projections from renewable energy markets are among the lowest of all analysed scenarios and vice versa. The Energy [R]evolution scenario has the lowest demand projection of all analysed scenario, but the renewable market projections (in absolute numbers) are under the medium or even in low case (hydro, biomass). Therefore table 10.3.4 provides for each market projection (low, medium, high) three possible market shares – under low, medium and high demand projections. As the data combination are not a strong result of the scenarios, these calculations should be seen more as a theoretical exercise, but nevertheless as a important orientation about the possible range renewable energies could cover.

The lower case projections for solar photovoltaic, wind power and concentrated solar power represent the reference case and assume a lower global manufacturing capacity in 2020, 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. The World Energy Outlook 2008 for example representing the lower range assumed a shrinking manufacturing capacity for wind from about 25 GW/a in 2008 (GWEC 2009) down to 22 GW/a in 2020 only 4 GW/a in 2050.

This has been somehow revised in the World Energy Outlook 2009 which assumes a annual manufacturing of around 50 GW/a in 2015 and 80 GW/a in 2030 and is therefore in line with the moderate development pathway over that timeframe expected by the respective industry (GWEC 2009).

The high case projections for wind require an annual production capacity of 157 GW by 2020 – which would represent a 6-fold increase of production capacity on a global level. This would lead to a global wind power share of 33 % under the low demand projection. A combination of the low market development and high demand projection would mean that the global wind share would be only 3% by 2050.

The medium case assumes a doubling of production capacity by 2020 (55GW/a) and tripling by 2030 (71 GW/a) – for 2050 the annual additional capacity would drop to 41 GW/a, but significant manufacturing capacity would be needed for repowering at the time.

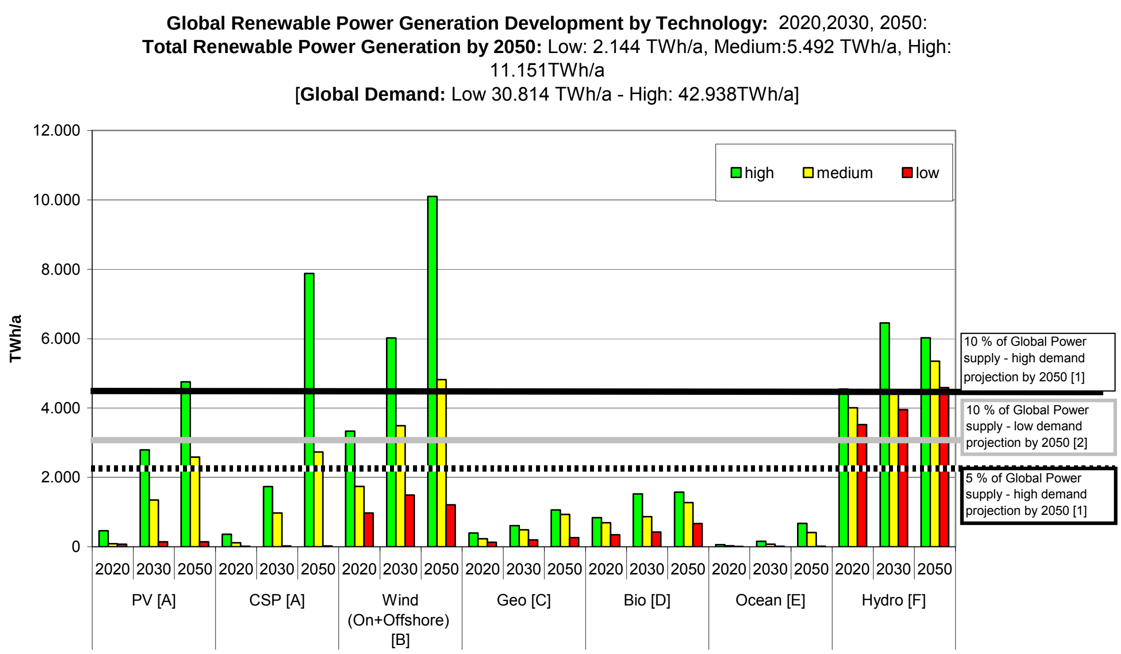
The expected role of CSP as another example is very different within all scenarios and has a wide range from 2.2% of the world's electricity production by 2050 under the high demand and low or now market development case and up to 25.6% under the advanced market development and low demand case. The advanced case assumes that annual manufacturing capacity will go up to 118 GW/a which is still well under the advanced case of the wind industry (157 GW/a).

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 17 GW/a on the level of the global wind power market in the year 2000 (17.4 GW/a). This represents only 0.7% of the global technical potential for geothermal power generation, which indicates that further research in the development of a larger market potential is required. The highest geothermal electricity share (incl. CHP) will be achieved with a combination of the low demand and advanced market development case with 5.6%.

The bio energy share in all analyses is – relative to other technologies – low as well. The advanced case estimates an annual market volume and a required manufacturing capacity of 38 GW/a. Similar to geothermal power generation; bio energy plays in most scenarios a rather low role and achieves an electricity share of maximum 9.3%.

Figure 10.3.1 summarizes the resulting range electricity generation of renewable energies reflecting the selected scenarios distinguishing between the different technologies and compares it with different demand projections. 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 the high (1905 GW) and low case (1055 GW) indicates a high correlation of projections. The total renewable power market potential in the low case is 7% above the 2008 level with 22% by 2050.

This will happen if the low market projection correlates with the highest growth in electricity demand. A medium range renewable market growth and a medium demand development, would lead to a renewable electricity share of 26% in 2020, 39% in 2030 and 45% by 2050. More than half of the worlds electricity demand could be supplied under the assumption that the market volumes for all renewable power generation technologies will continue to grow according to the renewable industry's moderate market projections. If the renewable industry can maintain the growth rates between 2000 and 2009 for 5 more years, while the global power demand will not grow more than 67% by 2050 (base year 2005), all combined power technologies could achieve an electricity share of 39% by 2020, 58% by 2030 and before 2050 the entire electricity could come from renewable power sources.



[A]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI;EPIA Roadmap + SolarGeneration V (reference, medium, advanced), WETO 2050, ESTELA CSP Outlook 2009 (reference, medium, advanced), + information from Chapter 3
[B]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI; GWEC- Global Wind Energy Outlook 2008,Lemming *et al.* 2008 (Riso high wind), + information from Chapter 7
[C]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GP + information from Chapter 4
[D]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI; + information from Chapter 2
[F]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI; + information from Chapter 5
[1]	Global High demand Projection: IEA WEO 2008- reference case
[2]	Global Medium demand Projection: IEA WEO 2009-550ppm scenario
[3]	Global Low demand Projection: Energy [R]evolution 08; DLR/EREC/GPI

Figure 10.3.1: Global Renewable Power Development Projections by Technology.

10.3.2.2 Market potential for the renewable heating and cooling sector

Renewable heating technologies can be used for cooling as well, which offers a huge new market opportunity for countries with Mediterranean, subtropical or tropical climate. None of the analysed scenarios provide detailed information about renewable heating or cooling technologies. Renewable cooling could be used for air-conditioning and would therefore reduce electricity demand for electric air-conditioning significantly. While the cost reduction potential for geothermal and bio energy share is relatively low as it is already a 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 is huge for market development of renewable 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 have 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.

10.3.2.2.1 Factors for market development in the renewable heating and cooling sector

The renewable 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 chapter 10.3.2.1 under renewable power generation.

Even in the most advanced scenario, solar heating systems will need until 2030 till toady's bio energy production level will be reached. However the market growth rates for solar collectors in all scenarios between 2010 and 2020 are 21% in the low case and 54% in the high case.

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 of fuel volume. 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.

10.3.2.2.2 Annual market potential for the renewable heating and cooling

The market potential for renewable heating technologies such as solar collectors, geothermal heat pumps or pellet heating systems overlaps with the market potential analysis of the renewable 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 there operation and therefore increase the demand for electricity. Renewable heating and cooling is even more dispersed and decentralized than renewable power generation, what explains to a certain extend that the statistical data is still quite poor and needs 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 10.3.5 [TSU: Table 10.3.4] provides an overview about the annual market volumes in order to implement the given renewable heating capacities within the analysed scenarios. These calculated annual market volumes do not include the additional needs for repowering. Even with relatively low growth rates manufacturing capacities for all renewable heating and cooling technologies must be expanded significantly in order to implement the projected renewable heat production in all analysed scenarios. The annual market volume for solar collectors until 2020 must be expanded from less about 35 PJ/a in 2008 to 109 PJ/a in 2020 in the low case and up to 1224 PJ/a in the high case. 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 specific market size data by technology.

Table 10.3.4: Projected renewable heat production, possible market shares, annual growth rates and annual market volumes.

	Energy parameters						Market development					
	Generation			% of Global Demand % of Global Demand			Annual market growth			Annual market volume		
	PJ/a			High global demand (1)	Medium global demand (2)	**MIN:** low global demand (3)	%/a			PJ/a		
	high	medium	low	Market development: high	Market development medium	Market development low	high	medium	low	high	medium	low
Solar (A)												
Solar Thermal - 2020	12.244	5.837	1.091	8%	4%	1%	54%	43%	21%	1224	583,7	109
Solar Thermal - 2030	36.577	17.231	614	6%	3%	0%	12%	11%	6%	2433	1139,4	86
Solar Thermal - 2050	41.867	21.387	907	7%	4%	0%	9%	6%	4%	2464	170,3	29
Geothermal [C]	PJ/a			% of global heating demand						PJ/a		
2020	3.844	2.477	1.110	2%	2%	1%	36%	28%	20%	367	-	93
2030	7.793	4.882	1.970	5%	3%	1%	7%	7%	6%	395	-	86
2050	19.021	11.182	3.342	12%	7%	2%	9%	7%	5%	1.123	-	137
Bio energy (D)	PJ/a			% of global heating demand						PJ/a		
2020	36.945	35.925	34.905	24%	23%	22%				228	-	24
2030	37.421	36.779	36.137	24%	23%	23%		Not avaiable		48	-	123
2050	47.764	43.612	39.460	30%	28%	25%				1.034	683	332
Total Renewables > heating	PJ/a			% of Global heating demand						PJ/a		
2020	53.033	44.239	37.106	34%	27%	23%	30,0%	23,6%	13,6%	1.819	584	227
2030	81.791	58.891	38.721	52%	36%	24%	6,3%	6,0%	4,0%	2.876	1.139	295
2050	108.652	76.180	43.709	69%	47%	27%	6,2%	4,6%	3,1%	4.621	854	499

References:	Analysed scenarios and technical roadmaps – annual market growth rates + required manufaction capacity for all IEA scenarios are calculated based on provided informations		
[A]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI;EPIA Roadmap + SolarGeneration V (reference, medium, advanced), WETO 2050, ESTELA CSP Outlook 2009 (reference, medium, advanced), + information from Chapter 3	[1]	Global High demand Projection: IEA WEO 2008 – reference case
[C]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GP + information from Chapter 4	[2]	Global Medium demand Projection:
[D]	IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI; + information from Chapter 2	[3]	Global Low demand Projection:Energy [R]evolution 08, DLR/EREC/GPI

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[9]. The total share on renewable heating system in all scenarios by 2050 varies significantly between 21% if combining the high demand und low market development case to 69% anticipating the advanced market development and low demand case. A medium range market development and medium increase of heat demand would lead a renewable heat share of 27% by 2020 and up to 47% by 2050.

10.3.2.3 Market potential for renewable energies in the transport sector

[AUTHOR COMMENT: The quality and quantity of data submitted at the deadline for the 1st order draft was not comprehensive enough to provide an overview about the estimated market potential. However the data collection will continue and an analysis will be part of the second order draft.]

There are two categories of RE used in scenarios.

Direct renewable energy drives:

- Biodiesel
- Ethanol

[9] See also Chapter 2.1.1.

- Marine Wind energy use:
  - Sails
  - Other marine wind energy systems such as second generation sails

Indirect renewable energy drives: (in competition with stationary use)

- Electricity from RE
- Hydrogen production from RE

10.3.2.4 Global renewable energy primary energy contribution [TSU: unclear]

The total contribution of renewable energy sources to the world global primary energy demand is the summary of the scenario outcomes for all sectors: power generation, heating/cooling and transport. Figure 10.3.3 provides an overview of the projected primary energy production by source and in the selected categories low, medium, high for 2020, 2030 and 2050 and compares the numbers as a numerical exercise with different global primary energy demands. Bio energy has the highest market share both in the medium and the low case, followed by geothermal. This is due to the fact, that bio energy can be used across all sectors (power, heating & cooling as well as transport) while geothermal can be used for power generation and heating / 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. Cogeneration power plants use bio energy most efficiently to a level of up to 90%.

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.[10]

The high case ranks bioenergy first, with a possible primary energy share of 19.7% by 2050, solar energy with 18.2% second and geothermal and wind with 10.4% and 7.6 % third and fourth. About 59% of the needed global primary energy could come from only three renewable energy sources.

The total renewable energy share by 2050 has a huge variation across all scenarios. With only 17.1% by 2050 – about 5% more than in 2007 – the combination of a low renewable energy development and high demand will mean only a very moderate increase of the global renewable energy share. The medium case – a combination of a rather moderate market development for RE and a moderate increase of the global energy demand, renewable energy provides 21% of the energy needs in 2050. This shows once more the meaning of combining both strategies extension of renewable energies on the one hand and substantial increase of energy efficiency on the other hand to contribute effectively to mitigation targets.

In the most optimistic case, which is a combination of a high market development for RE and a successfully implemented energy efficiency strategy, RE could provide 61% of the world energy needs. While there is a potential to supply the entire global power demand with REs and 69% of global heating and cooling demand, the most problematic sector for renewable energy to supply substantial shares is the transport sector.

[10] The International Maritime Organization (IMO) published a study in April 2009 which estimated the emissions from shipping are at 1.046 million tonnes of CO2 in 2007, which corresponds to 3.3% of the global emissions during 2007. Modern wind drives such as sails for containerships are estimated to save up to 35% of the annual needed fuels. More research is needed to identify the future technical and market potential for wind power use in modern vessels.

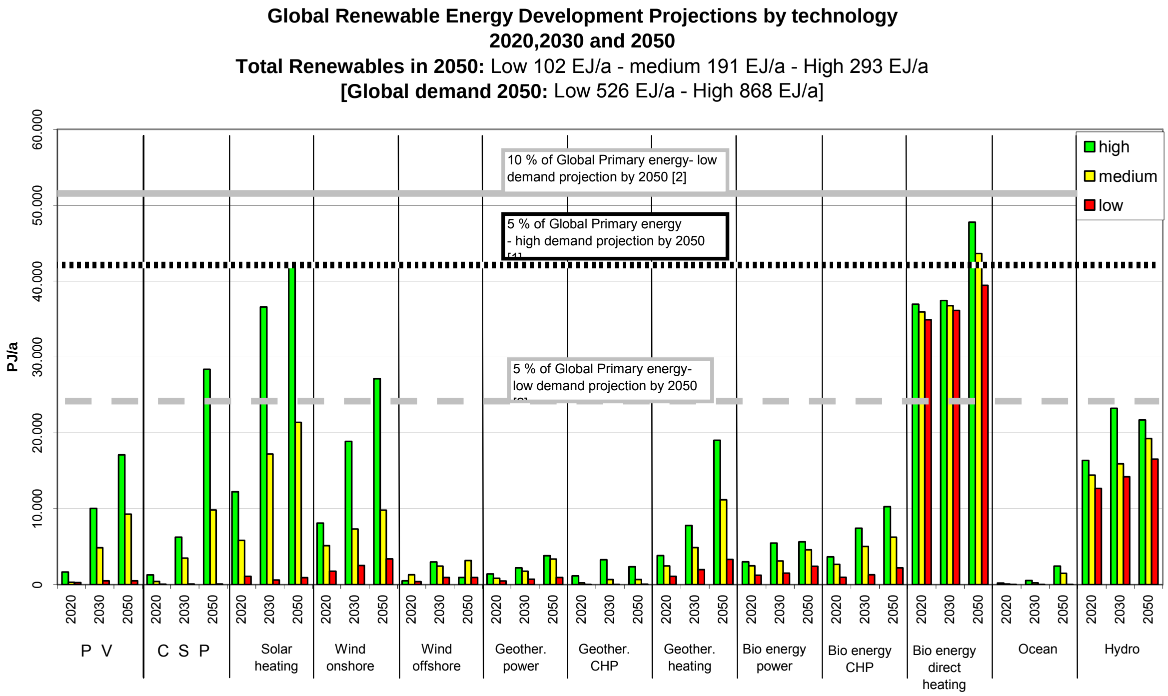
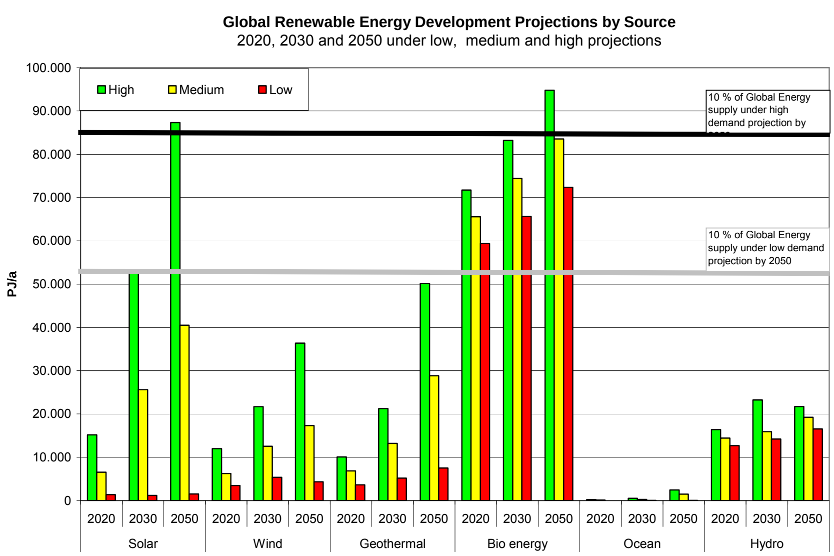


Figure 10.3.2: Summary: Global Renewable Energy Development Projections by Technology. [TSU: No reference in Text; No Source]



	Energy parameters			
	% of Global Demand			
	Max: Low global demand (3) Market development high	High global demand (1) Market development high	Medium global demand (2) Market development medium	**MIN:** low global demand (3) Market development low
	Solar – Primary energy			
2020	2,8%	2,4%	1,1%	0,3%
2030	10,1%	7,3%	4,1%	0,2%
2050	18,2%	10,1%	3,8%	0,3%
	Wind – Primary energy			
2020	2,2%	1,9%	1,1%	0,6%
2030	4,1%	3,0%	2,0%	1,0%
2050	7,6%	4,2%	1,9%	0,9%
	Geothermal – Primary energy			
2020	1,9%	1,6%	1,2%	0,7%
2030	4,0%	2,9%	2,1%	1,0%
2050	10,4%	5,8%	2,0%	1,6%
	Bioenergy – Primary energy			
2020	13,3%	11,3%	11,2%	11,0%
2030	15,8%	12,5%	11,9%	11,5%
2050	19,7%	15,0%	11,0%	10,9%
	Ocean energy – Primary energy			
2020	0,0%	0,0%	0,0%	0,0%
2030	0,1%	0,1%	0,0%	0,0%
2050	0,5%	0,3%	0,0%	0,0%
	Hydro – Primary energy			
2020	3,0%	2,6%	2,5%	2,3%
2030	4,4%	3,2%	2,6%	2,7%
2050	4,5%	2,5%	2,4%	3,4%
	Total Renewable – Primary energy			
2020	23,2%	19,8%	17,0%	14,9%
2030	38,6%	28,1%	22,8%	16,5%
2050	60,9%	33,7%	21,0%	17,1%

Figure 10.3.3: Global Renewable Energy Development Projections by Source and Global renewable primary energy shares by source. [TSU: No Source]

10.3.3 Regional Breakdown – technical potential versus market potential

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 [TSU: 10.3.5] compares the maximum value (high case- of this scenario analysis) with the technical potential in order to calculate the maximum deployment rate of the technical potential. Within this survey, the bio energy potential was devided by energy crops and residuals, but not by technology and/or sector.

10.3.3.1 Renewable Power sector by Region

The quality of the regional data is not as comprehensive as global scenario data. This is partly due to the fact, that the number of available regional scenarios and/or regional technology roadmaps is very limited, especially for developing regions. In some cases there are only specific country scenarios available (e.g. USA) but no further regional scenarios are given. In general there are many specific energy scenarios available for Annex I countries, but very little data can be used for developing countries. Besides that, another major obstacle for a precise discussion of national energy scenarios for developing countries e.g. in Central Africa, is the lack of exact energy statistics and the lack of data for regional specific renewable energy potentials.

Table 10.3.5: Overview of achieved potential shares (high case scenario based market growth versus technical potential – power sector, by technology).

	Highest Market potential in PJ/A versus Technical potential - electric power in 2050												Total in [EJ/a]	
	solar PV [1]	% of average Tech. Potential	solar CSP [2]	% of average Tech. Potential	Hydro-power [3]	% of average Tech. Potential	Wind [4]	% of average Tech. Potential	Ocean energy [5]	% of average Tech. Potential	geothermal electric -incl. CHP [6]	% of average Tech. Potential	Total max. RE market potential – electricity [EJ/a]	Maket Potential vs Tech. Potential [%]
Africa	1.260	0,18%	2.700	0,06%	1.363	20,5%	713	2,4%	54,0	0,3%	14	0,3%	6,10	0,12%
China	810	0,83%	3.564	5,96%	5.594	103,0%	5.324	96,2%	936,0	12,7%	12	0,3%	16,24	9,00%
India	1.728	5,16%	2.268	2,13%	1.901	102,1%	2.164	101,4%	90,0	2,2%	2	0,1%	8,15	5,45%
Latin America	576	0,49%	720	0,24%	5.004	55,5%	2.840	6,1%	90,0	0,2%	18	0,4%	9,25	1,77%
Middle East	1.512	1,19%	4.536	0,39%	210	20,8%	853	15,8%	18,0	0,2%	12	1,7%	7,14	0,55%
OECD Europe	1.476	4,44%	450	11,02%	2.621	35,6%	5.065	16,2%	194,4	0,8%	31	1,7%	9,84	9,57%
OECD North America	3.665	4,36%	3.881	1,12%	2.963	49,5%	6.628	4,0%	630,0	1,4%	86	1,3%	17,85	2,72%
OECD Pacific	1.012	0,45%	169	0,01%	641	53,1%	3.053	5,4%	259,2	0,9%	21	0,5%	5,15	0,28%
Rest of Asia	1.170	0,86%	576	6,25%	1.493	23,0%	3.128	17,0%	57,6	0,0%	104	1,8%	6,53	2,00%
Transition Economies	342	0,30%	54	0,03%	2.214	46,0%	3.647	4,9%	108,0	7,8%	24	0,4%	6,39	1,57%
World	1.332	0,12%	962	0,02%	16.401	34,5%	9.565	2,4%	207	0,3%	134	3,0%	28,60	0,42%
World	4.371	0,32%	4.219	0,07%	22.399	46,2%	21.359	5,4%	544	0,3%	213	1,6%	53,11	0,65%
World	13.550	0,80%	18.918	0,24%	24.004	48,0%	33.415	7,7%	2.437	0,7%	324	0,7%	92,65	0,87%
References	**IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI;EPIA Roadmap + SolarGeneration V (reference, medium, advanced), WETO 2050, ESTELA CSP Outlook 2009 (reference, medium, advanced), + information from Chapter 2,3,4,5,6 and 7, technical potential from" Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply" -Commissioned by the German Federal Environment Agency - FKZ 3707 41 108 DLR/Wuppertal Institute/Ecofys, March 2009**													

The overall estimated market share for renewable power generation did not exceed 10% of global technical potential. For 2050, the highest deployment rate of the technical renewable power potential per region has been found in OECD Europe (9.6%), followed by China (9%), India (5.9%), OECD North America (2.7%) and Developing Asia (2%). The other remaining regions have rates below 2%. On a global level none of the analysed scenario exceeds a deployment rate of 1% of the total technical potential for renewable power generation.

10.3.3.2 Renewable Heating and cooling by sector and region

The quality of the regional data for heating and cooling is even less comprehensive than the regional data for power generation. Especially the statistical data for the current situation for heating and cooling is weak. While there is some data available for industrial (process) heat for developing countries there is very little data available for those regions for the residential heating and cooling sector. All statistical data for the heating sector is based on IEA Statics. This analysis can only provide a first overview about future potential exhaustion. In the following table [TSU: 10.3.6] numbers are given for geothermal energy and solar water technologies.

Table 10.3.6: Highest market potential versus technical demand by region and technology.

		Highest Market potential [PJ/a] versus Technical Potential - heating + cooling (excluding biomass)					
		geothermal direct uses [1]	% of average Tech. Potential	solar water heating [2]	% of average Tech. Potential	Total max. RE market potential – heating [EJ/a]	Maket Potential vs Tech. Potential [%]
Africa	2050	0,9	0,1%	2,8	27,1%	3,7	0,4%
China	2050	6,7	1,6%	7,2	41,5%	13,9	3,2%
India	2050	5,6	3,9%	3,7	62,2%	9,3	6,3%
Latin America	2050	3,2	0,4%	1,8	8,0%	5,0	0,7%
Middle East	2050	3,0	1,6%	5,9	32,3%	8,8	4,5%
OECD Europe	2050	5,3	0,9%	5,9	25,4%	11,2	4,2%
OECD North America	2050	12,5	1,8%	5,7	23,9%	18,2	2,5%
OECD Pacific	2050	1,9	0,6%	2,0	72,4%	3,9	1,2%
Rest of Asia	2050	5,4	1,0%	3,3	15,5%	8,7	1,6%
Transition Economies	2050	5,6	0,9%	3,0	53,1%	8,7	1,3%
World	2020	10,0	2,0%	6,5	5,8%	16,6	2,7%
	2030	21,2	1,4%	17,1	14,6%	38,3	2,4%
	2050	50,1	1,0%	41,3	33,5%	91,4	1,8%
References	**IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI), WETO 2050,+ information from Chapter 2,3,4,5,6 and 7, technical potential from“ Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply” -Commissioned by the German Federal Environment Agency - FKZ 3707 41 108 DLR/Wuppertal Institute/Ecofys, March 2009**						

By 2030, the highest market potential projection for direct geothermal heating uses only 1.4% of the available technical potential based on (UBA 2009) and 2.4% in the case of solar hot water heating. The joined technical potential for solar water heating and geothermal heating has be exploited to 2.4% in the analysed market potential projections.

The total technical potential for renewable heating and cooling systems has been exploited in the scenarios by any time to less than 3% until 2050. From the technical point of view, there is still a large potential for market potential improvement.

10.3.3.3 Primary energy by region, technology and sector

The maximum deployment share out of the overall technical potential for solar energy in 2050 were found in energy scenarios for OECD Europe with a total of 3.2%. The second and third biggest deployment rates were found in scenarios for India and China. All other analysed scenarios use less than 2% of the available technical potential for solar energy.

Wind energy has been exploited to a much larger extend in all regional scenarios than solar energy. As indicated in table 10.3.8 [TSU: Table 10.3.7], the wind potential has been fully exploited in scenarios for India and China. However the provided technical potential for wind within those regions is very low compared to other regions.

Geothermal energy does not play a mayor role in neither of the analysed scenarios. Both on a global and regional level the deployment rate of the available technical potential is far below 1%.

The established hydro power market on a global and regional level has exploited roughly half of the believed technical potential on a global level. Analysed scenarios for both China and India, exploited the entire technical potential which indicates, that the estimated capacity for 2050 represents the maximum possible capacity for hydro power in these countries.

Table 10.3.8 [TSU: 10.3.7] gives an overview about the overall renewable primary energy share on a global and regional level.

Table 10.3.7: High case market potential projections versus Technical Potential by technology and region.

		Primary energy: High Market Potential Projection (MP) versus Technical Potential (TP)											
		Solar MP [EJ/a]	% of TP	Wind MP [EJ/a]	% of TP	Geother. MP [EJ/a]	% of TP	Hydro MP [EJ/a]	% of TP	Ocean MP [EJ/a]	% of TP	Total RE MP [EJ/a]	% of TP
Africa	2020	0,2	0,00%	0,2	0,56%	0,004	0,004%	0,59	9,3%	0,01	0,2%	0,9	0,03%
	2030	0,7	0,02%	0,5	1,67%	0,011	0,004%	1,33	20,6%	0,02	0,2%	2,5	0,06%
	2050	4,0	0,08%	0,7	2,44%	0,015	0,001%	1,36	20,5%	0,05	0,3%	6,1	0,10%
China	2020	0,1	0,10%	1,8	38,57%	0,003	0,008%	3,81	73,8%	0,02	1,2%	5,7	3,19%
	2030	0,9	0,65%	4,0	83,01%	0,008	0,006%	5,59	106,1%	0,09	2,4%	10,6	3,68%
	2050	4,4	2,50%	5,3	96,16%	0,019	0,004%	5,59	103,0%	0,94	12,7%	16,3	2,62%
India	2020	0,1	0,09%	1,2	72,27%	0,001	0,010%	0,96	54,4%	0,02	1,8%	2,3	1,90%
	2030	0,5	0,42%	1,8	99,64%	0,002	0,005%	1,9	105,3%	0,02	1,2%	4,2	2,48%
	2050	4,0	2,74%	2,2	101,39%	0,008	0,005%	1,9	102,1%	0,09	2,2%	8,2	2,67%
Latin America	2020	0,1	0,03%	0,9	2,21%	0,006	0,008%	3,29	38,5%	0,01	0,1%	4,3	0,99%
	2030	0,4	0,12%	1,8	4,32%	0,015	0,007%	3,94	45,1%	0,01	0,1%	6,2	0,93%
	2050	1,3	0,30%	2,8	6,08%	0,021	0,003%	5	55,5%	0,09	0,2%	9,3	0,69%
Middle East	2020	0,1	0,02%	0,2	4,47%	0,003	0,014%	0,15	15,8%	0,00	0,2%	0,5	0,06%
	2030	1,3	0,13%	0,6	11,11%	0,007	0,013%	0,17	17,3%	0,01	0,1%	2,0	0,19%
	2050	6,1	0,47%	0,9	15,80%	0,015	0,008%	0,21	20,8%	0,02	0,2%	7,1	0,48%
OECD Europe	2020	0,5	1,06%	1,6	6,94%	0,016	0,066%	2,28	32,6%	0,01	0,2%	4,4	3,78%
	2030	1,0	1,87%	3,1	12,16%	0,026	0,035%	2,62	36,7%	0,05	0,4%	6,8	3,69%
	2050	1,9	3,19%	5,1	16,21%	0,036	0,015%	2,62	35,6%	0,19	0,8%	9,8	2,55%
OECD North America	2020	0,9	0,30%	2,2	1,41%	0,054	0,076%	2,55	44,8%	0,07	0,7%	5,8	1,02%
	2030	2,8	0,78%	4,6	2,93%	0,075	0,035%	2,96	51,0%	0,19	0,8%	10,6	1,35%
	2050	7,6	1,66%	6,6	3,99%	0,099	0,014%	2,96	49,5%	0,63	1,4%	17,9	1,26%
OECD Pacific	2020	0,2	0,10%	0,8	1,49%	0,013	0,039%	0,57	49,7%	0,01	0,2%	1,6	0,53%
	2030	0,4	0,03%	2,5	4,71%	0,018	0,018%	0,64	54,8%	0,05	0,3%	3,6	0,24%
	2050	1,2	0,07%	3,1	5,37%	0,023	0,007%	0,64	53,1%	0,26	0,9%	5,2	0,24%
Rest of Asia	2020	0,1	0,08%	0,5	4,23%	0,036	0,068%	0,79	12,8%	0,01	0,0%	1,5	0,64%
	2030	0,5	0,33%	1,9	12,97%	0,055	0,035%	1,02	16,2%	0,03	0,0%	3,4	0,85%
	2050	1,7	1,05%	3,1	16,95%	0,109	0,021%	1,49	23,0%	0,06	0,0%	6,5	0,75%
Transition Economies	2020	0,0	0,01%	0,1	0,17%	0,008	0,012%	1,41	30,9%	0,05	19,5%	1,6	0,44%
	2030	0,2	0,07%	0,8	1,11%	0,015	0,008%	2,21	47,4%	0,07	10,4%	3,2	0,59%
	2050	0,4	0,12%	3,6	4,89%	0,030	0,005%	2,21	46,0%	0,11	7,8%	6,4	0,59%
World	2020	2,3	0,04%	9,6	2,43%	0,144	0,029%	16,4	34,5%	0,21	0,3%	28,6	0,38%
	2030	8,6	0,11%	21,4	5,37%	0,234	0,016%	22,4	46,2%	0,54	0,3%	53,1	0,54%
	2050	32,5	0,33%	33,4	7,66%	0,374	0,007%	24	48,0%	2,44	0,7%	92,7	0,58%

References **IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI;EPIA Roadmap + SolarGeneration V (reference, medium, advanced), WETO 2050, ESTELA CSP Outlook 2009 (reference, medium, advanced), + information from Chapter 2,3,4,5,6 and 7, technical potential from" Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply" -Commissioned by the German Federal Environment Agency - FKZ 3707 41 108 DLR/Wuppertal Institute/Ecofys, March 2009**

Ocean energy is at a very early development stage and it is very difficult to estimate the potential market development for the coming years. Furthermore, the technical potential for some regions seems to be very limited. Especially the Transition Economies, but also China will reach – based on current knowledge – technical limits even with a modest expansion of ocean energy.

The overall technical potential for renewable energy exceeds current global primary energy by factor 32 (see chapter 10.3.2). Even the energy scenarios with the most ambitious growth rates for renewable energy did not exceed 3.2% (China, 2020) on a regional level and 0.58 (2050) on a global level.

The analysed regional and global scenarios show a wide range of the renewable shares in the future. In order to show the different ranges of deployment rates for renewable energy sources by sector and region, Figure 10.3.4 (see below) 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.

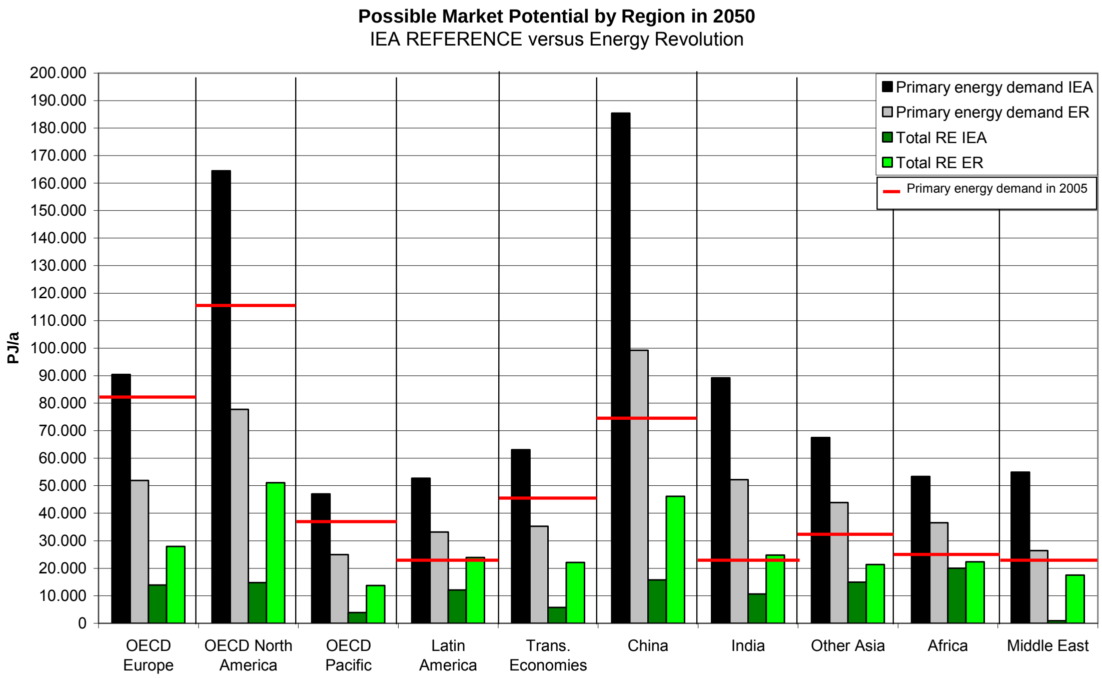


Figure 10.3.4: Regional breakdown from possible renewable energy market potential: Reference (> 600ppm) versus Category II (<440ppm) scenario.

10.3.4 GHG mitigation potential of single options and the effects of Climate Change on potentials

Based on the results of the bottom up scenario analysis and the identified market penetration rates projections for different renewable energy technologies, the GHG mitigation potential has been calculated. For each sector, a factor has been identified based on possible substituted fossil fuel or a mix of different fossil fuels. The calculation is based on simplified assumption and can only be indicative. For the power sector with the current global technology mix, the average specific CO_2 emissions are 0.603 kg CO_2 per kWh (IEA2009). In practice, it might be more sensible to calculate the emission reductions using the specific characteristic of new power plants as reference. The specific number of 0.603 kg CO_2 per kWh in that context represents a specific mix of coal and natural gas fire power plants. For the heating sector, the average specific global CO_2 emission is 71 kt t CO_2/PJ[11].

[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

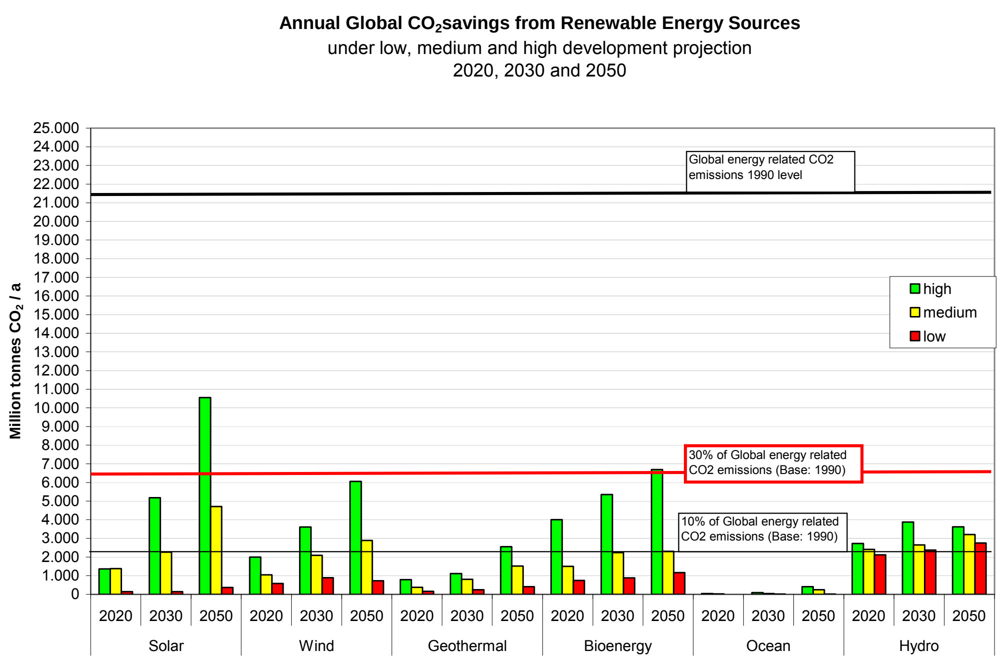
Figure 10.3.5 shows the annual CO_2 reduction potential per source 2020, 2030 and 2050, for the low, medium and high case projections. The red line at 6 Gt CO_2/a identifies 20% of the global energy related CO_2 emissions (Base year 2008), the line below represents 10%.

Solar energy has the highest CO_2 reduction contribution both in the medium and high case. The medium case projections will result 2.2Gt CO_2/a (2030) and 4.7Gt CO_2/a (2050), while the high case will reach 5 Gt CO_2/a 10 years earlier by 2020. By 2050, under a combined high market growth projection for photovoltaic, concentrated solar power and solar heating, results in a total annual reduction potential of 10.5 Gt CO_2/a.

Wind power has the second highest CO_2 reduction contribution from all power technologies. By 2030 both under the high and medium case, wind power could avoid around 10% of 2008 energy related CO_2 emissions. By 2050, this could go up to 20% under the high market growth projections.

As geothermal could play a significant role in the heating sector, the overall CO_2 reduction potential across all sectors is the second largest of all analysed renewable energy technologies under the high case. However, there is a huge range between the medium and high case projections, and the analysis of more scenarios is required.

In this analysis, bio energy contributes between 1169 million tonnes CO_2/a in the low case and 6.695 million tonnes CO_2/a in the high case by 2050. But one has to keep in mind that the uncertainties are significantly higher than at all other technologies. The use of unsustainable bio fuels or solid biomass would reduce this amount significantly and could even result into higher CO_2 emissions compared to fossil fuels.[12] (Sattler, Crutzen, Scharlemann et. al.). In addition all analysed scenario 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 CO_2 reduction emission calculation.



[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. 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.

Figure 10.3.5: Annual Global CO_2 savings from RE under low, medium and high development projection for 2020, 2030 and 2050 (NOTE: this is excluding transport). [TSU: No Source]

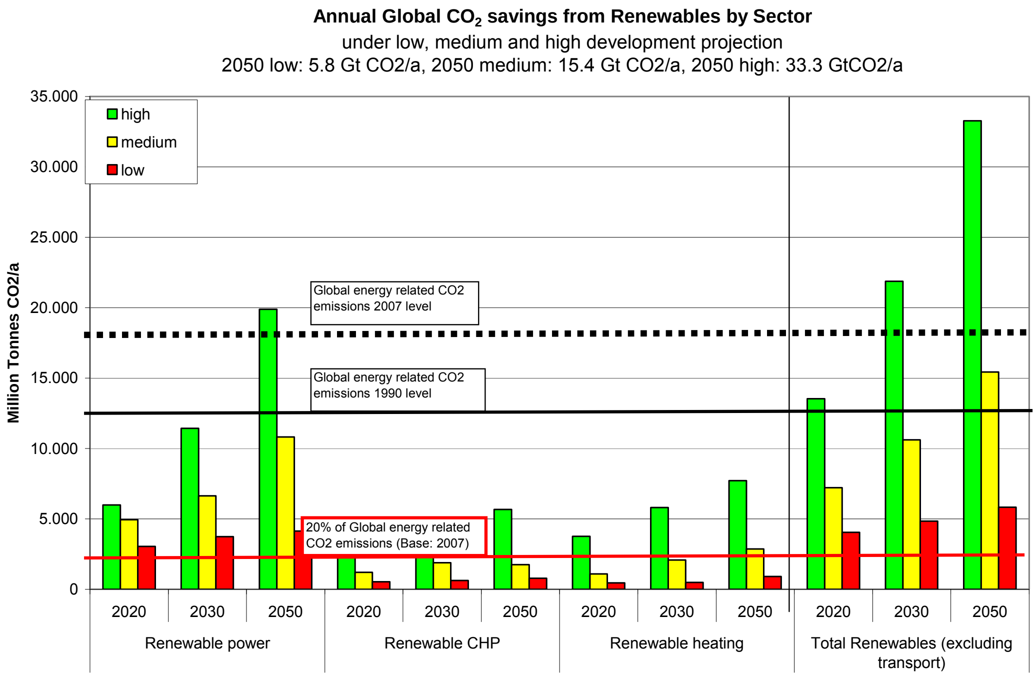


Figure 10.3.6: Annual Global CO_2 savings from RE by Sector and total; under low, medium and high development projection for 2020, 2030 and 2050.

[Analysed scenarios: IEA WEO 2008, 2009 (REF, 550ppm, 450ppm pathway) IEA ETP 2008 (BASE, BLUE + ACT); Energy [R]evolution 2008 – DLR/EREC/GPI;EPIA Roadmap + SolarGeneration V (reference, medium, advanced), WETO 2050, ESTELA CSP Outlook 2009 (reference, medium, advanced), GWEC- Global Wind Energy Outlook 2008,Lemming et al. 2008 (Riso high wind), + information from Chapter 2,3,4,5,6, 7,]

10.3.4.1 Global CO_2 mitigation potential from RE

Based on the analysed scenarios, the total annual CO_2 reduction potential varies significantly between the low, medium and high case. While the low case abatement potential for renewable is only 5.8 Gt CO_2/a by 2050 which represents the business as usual pathway, the medium case achieves a total of 15.4 Gt CO_2/a by 2050. The annual high case CO_2 savings lead to 33.3 Gt CO_2/ a which is equal to a 70% reduction of energy related CO_2-emission of the analysed reference scenarios.

10.3.4.2 Cumulative CO_2 reduction potentials form renewable energies until 2050

Cumulative CO_2 reduction potential from renewable energies between 2020 and 2050 has been calculated on the bases of the annual CO_2 savings shown in figure 10.3.5 and 10.3.6 and under the assumption of 10.3.4.. The analysed scenarios would due to a cumulated reduction of 148 Gt CO_2 under the low case, 333 Gt CO_2 in the medium case and 640 Gt CO_2 in the high case.

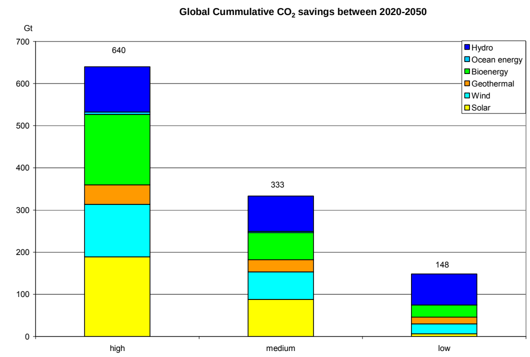


Figure 10.3.7: Global cumulative CO_2 savings between 2020 and 2050. [TSU: No Source]

10.3.5 Comparison of the results with scenario analysis

The deployment pathway of renewable energy sources from the mitigation scenario analysis of chapter 10.2 and the analysis of the "bottom up" scenario in chapter 10.3 differ significantly by source. Table 10.3.9 [TSU: 10.3.8] provides an overview about the different ranges from Low to high in both analyses.

While the figures for hydro are in the same range, the figures for geothermal and solar energy differ significantly. The technical scenarios expect a far higher market potential than the integrated models, especially for new renewable energy technologies. Biomass has significantly higher shares in the high and low case within the integrated models.

Table 10.3.8: Global renewable energy development projections by source – technical detail models ("bottom-up") versus integration model ("top- down") scenarios. [TSU: No Source]

[EJ/a]		High		Medium		Low	
		technical detail modells	integration modells [1]	technical detail modells	integration modells [2]	technical detail modells	integration modells [3]
Solar							
	2020	15	4	7	1	1	0
	2030	53	11	26	2	1	0
	2050	87	63	41	16	2	0
Wind							
	2020	12	14	6	1	3	2
	2030	22	26	13	2	5	4
	2050	36	56	17	16	4	14
Geothermal							
	2020	10	1	7	1	4	0
	2030	21	3	13	1	5	0
	2050	50	7	29	3	8	0
Bio energy							
	2020	72	65	66	46	59	0
	2030	83	117	74	52	66	4
	2050	95	184	84	101	72	22
Hydro							
	2020	16	15	14	14	13	11
	2030	23	19	16	17	14	12
	2050	22	26	19	19	17	12
[1] Categories I+II (<440 ppm), 75% case							
[2] Categories III+IV (440-600 ppm), 50% case							
[3] References (>600 ppm), 25% case							

10.3.6 Knowledge gaps

More research is needed amongst others for the coverage of global potential for CHP. In the scenarios especially the heating/cooling sector have a limited data base. A global reporting system for RE (market volume, production capacity, costs) as well as a better resource assessment (down to 10 x 10 km cluster) required to do more exact scenarios.

10.4 Regional Cost Curves for mitigation with renewable energies [TSU: deviation from structure agreed by plenary: "Cost curves for mitigation with renewable energy"]

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, as well as ranks these options in order of cost-effectiveness (see, for instance, Fig. 5) [TSU: Figure 10.4.5]. 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, Creyts et al. 2007, Dornburg et al. 2007, McKinsey and Company 2007). Two of the most widely used such efforts include the curves produced by the Energy Technology Perspectives initiative of the International Energy Agency (IEA 2008a), as well as the large number of country/regional and global studies by McKinsey[13] (e.g. McKinsey and Company 2008a, 2009b, 2009c).

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 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 renewable energy; (c) produce a consistent set of regional cost curves for renewable energy supply.

10.4.2 Abatement and energy cost curves: concept, strengths and limitations

10.4.2.1 Concept and Methodological aspects

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). The methodology has since been revised and upgraded, and the field of its application field extended to energy generation supply curves including renewable 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 with certain improvements.

[13] Colloquial nomenclature sometimes refers to abatement curves as the "McKinsey curves". However, it is important to recognize, as detailed below, that supply curves of energy and mitigation cost curves have been invented and used even decades earlier.

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, IEA (2008a) 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 et al. 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 renewable energy 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) hindering a higher rate of investments into renewable energy technologies as well, but even more importantly for untapped energy efficiency measures, potentially resulting in negative cost options (Novikova 2009).

A further concern about supply curves is raised by EEEC (2007), criticizing 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 IEA (2008a) 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.

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 renewable energy 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).

One of the key uncertainty factors is the discount rate used in the financial formula for the distribution of investment costs over the lifetime of a project, such as annualization. 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 renewable energy, 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. Junginger et al. (2004), in their methodology, set their internal rate of return (IRR)[14] expected by the investors and the support of government towards renewable energy investments according to the preferences of the stakeholders; however social and institutional settings are not taken into consideration, as the authors found it impossible to quantify those aspects.

[14] While the expected IRR is not equal to the discount rate, it is usually compared to it to evaluate an investment.

For greenhouse gas abatement cost curves, a key input that can largely influence the results is the carbon intensity, or emission factor of the country or geographical area to which it is applied, and the uncertainty in projecting this into the future. Emission factors depend largely on the technologies in place, and thus the abatement potential depends very strongly on the substituted fuel/technology in addition to the introduced abatement measure. This may lead to a situation where the option in one locality is a much more attractive measure 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 emission intensity of energy supply. This question can only be addressed using a dynamic approach on one hand and a system perspective on the other hand considering the relevant interdependencies (as also discussed below). Finally, Fleiter et al. (2009) also raise a number of issues about the cost assessment of boundaries that are often mishandled, such as lifetime of investments, external costs and co-benefits.

There are further 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 renewable energy technology in a future year largely depend 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 renewable energy option heavily depends also on the prices of fossil fuels, which are also very uncertain to predict.

Perhaps one of the key shortcomings of the cost curves are that they consider and compare mitigation options apply individually, whereas typically a package of measures are applied together, therefore potentially missing synergistic and integrational opportunities. Optimised, strategic packages of measures may have lower average costs than the average of the individual measures applied using a piecemeal approach. In particular the missing dynamic system perspective considering relevant interactions with the overall system behaviour can be problematic, although cost curves applying advanced methods are dynamic rather than static. In particular this is true for GHG mitigation cost curves where the question of substituted energy options plays a major role for the calculation of the mitigated CO_2-emissions.

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. In the effort we use in this chapter to construct regional cost curves, we attempt to alleviate as many of these limitations as possible, as described below.

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 regional cost curves for renewable energy and its application for mitigation. First, we review work that looks at energy cost curves, followed by a review of the role of renewable in abatement cost curves – since designated cost curves for renewable alone are rare.

10.4.3.2 Regional renewable energy cost curves

In an attempt to review the existing literature on regional cost curves, a number of studies were identified, as summarized in Table 10.1. [TSU: Table 10.4.1] As discussed in the previous section, the assumptions used in these studies have 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.

Table 10.4.1: 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
US (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			
Czech Republic	<100	101	19.93	4	- Only biomass production - Best case scenario where future yields equal the level of the Netherlands	RES data: Lewandowski et al. (2006) Baseline data: IEA (2005)
Germany	<100	160	24.24	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	26.76			
	<300	372	56.20			
Germany	<100	174	N/A	N/A	- Only wind and PV are included - PV available between 100 and 200 USD	Scholz (2008)
	<200	393	N/A			
Netherlands	<100	22	15.17	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;	Junginger et al. 2004
	<200	23	15.86			
	<300	24	16.55			
UK	<100	815	22.46	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	32.95			
United States	<100	3421	14.86	N/A	- Wind energy only	RES data: Milligan (2007) Baseline data: EIA (2009)

Country/Region	Cost ($/MWh)	Total RES (TWh/yr)	% of baseline	Discount rate (%)	Notes	Source
United States (WGA)	<100	177	0.77		- 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	1959	8.51			
	<300	1971	8.56			
Central and Eastern Europe	<100	3233	74.13	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) Baseline data: Solinski (2005)
Europe (Wind+PV))	<100	10310			- Only wind and PV included	Scholz (2008)
	<200	14730				
	<300	15904				
Europe (Wind+PV)	<100	13348			- Only wind and PV included - Wind reaches its maximum at around 200 USD - PV reaches its maximum at around 100 USD	Scholz (2008)
	<200	16534				
Global	<100	21000-83000	29-166	10	- Liquid transport fuel from biomass. All land suitable and available for plantations assumed to be used for transport fuel	de Vries et al. (2007) Baseline data for electricity: IEA (2003)
	<100	200000-300000	231-347	10	- Electricity from biomass, onshore wind, PV. Total global power supply potential, without supply-demand balance and other considerations taken into account.	
Global (Biomass)	<100	97200	N/A	10	- Target year is not specified - Study claims biomass production under this price can exceed electricity consumption multiple times	Hoogwijk et al. (2003)

In general, it is very difficult to compare data and findings from renewable energy 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 Table 10.1 [TSU: Table 10.4.1] need to be compared with caution, and for the same reasons findings for the same country can be very different in different studies.

In addition, most renewable energy cost curve studies focused on single, or just a few, renewable energy resources, and few have combined multiple technologies/resources applying a universal methodology (de Vries et al. 2007). Therefore the following discussion focuses on findings from largely single technology curves, but attempts to compare these where possible.

Nonetheless, certain trends can be observed. The most widely analyzed renewable energy sources for the future are wind, biomass and solar PV. Solar PV is typically attributed a large potential, however, with a large uncertainty since costs are very much dependent on the learning curve and the resulting investment and O&M costs. This phenomenon is best demonstrated by de Vries et al. (2007) where according to the scenario chosen, PV may have a bigger potential at around 100 USD/MWh than biomass and wind combined for the highest scenario by 2050, or according to their lowest scenario assumptions, not even starting to produce below 200 USD/MWh (still in the lowest scenario potentials may be large above that cost level).

Another example is the supply curve for Germany for 2030 (Scholz 2008), where PV only becomes available above 200 USD/MWh, whereas wind for example has a large potential even under 100 USD/MWh. Nevertheless, once we reach the cost level where PV starts to supply, available potential becomes large. This study also reinforces the significance of technological development in the case of PV as the supply curve for 2050 shows that at that point of time costs are expected to go down at a scale that its full potential becomes available under around 200 USD/MWh, while in the case of wind, the cost gap between 2030 and 2050 is considerably smaller and starts to widen only when approaching the maximum technical potential.

The same research (Scholz 2008) shows that in Europe as a whole the trend is very similar in terms of the characteristics of supply curves with regard to the gap between 2030 and 2050 cost curves for these technologies.

Projecting biomass energy potentials as a function of cost is a very complex task, depending on many other exogenous projections, including, land availability and competition with other land uses (as discussed in the previous sections), policies related to forestry, agriculture and other land uses; and future yield levels in a changed climate (de Vries et al. 2007). The uncertainty of many of these inputs as well as the significance of government policy choices, lead to the fact that most studies concerning biomass production work with several scenarios even with six or seven, like Lewandowski et al. (2006) and van Dam et al. (2007).

Biomass supply is the most thoroughly analyzed in the Central and Eastern European region from the perspective of cost curves. Although again showing a significant variation, according to the projections of van Dam et al. (2007), biomass may supply a significant share of TPES in that region. Their calculations suggest that around 3233 TWh/yr could be available by 2030, which may comprise over 70% of TPES according to the forecast. At the country level, Lewandowski et al. (2006) find a lower potential of 101 TWh/yr in the Czech Republic under the cost of 100 USD/MWh, but this still represents almost 20% of the TPES foreseen by the IEA (2005) for this year by biomass alone.

With regard to onshore wind, almost all studies agree that energy from this source may be produced in reasonable quantities even under 100 USD/MWh where there is a sufficient technical potential. On a global level de Vries et al. (2007) come to the conclusion that by 2050 at certain places electricity from wind can be generated from around 40 USD/MWh, which is even below the price of electricity produced from woody biomass as found in the study, and it will be possible to generate around 43 PWh/year electricity below the cost of 100 USD/MWh. Data from the United States show that even in the relatively short term, by 2015, almost 15% of TPES may come from wind energy under 100 USD/MWh. However, in this case the input data on the economic potential of wind from Milligan (2007) implies that 40% of the existing grid is available to transport wind energy which is in their case the best scenario. The report produced by Enviros in 2005 for the United Kingdom in 2015 also found that wind is the most promising renewable energy source for the country. It has by far the largest potential almost 75% of which can be realized under 100 USD/MWh while reaching the maximum potential below 200 USD/MWh. Junginger et al. (2004) in the case of the Netherlands finds that most of the technical potential may be reached by 2020, and even at inland locations most of the energy can be produced under a 100 USD/MWh with the best onshore places producing at around half of this cost. As mentioned before, in the case where multiple timeframes are compared for the same regions (Scholz 2008), the finding is that price decrease due to technology learning is not expected to be extremely steep.

The weakness of studies carried out concerning individual regions and/or energy sources 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). Only one study was identified among the examined ones that explicitly addressed this issue, de Vries et al. (2007). In their findings potentials seriously decline in case of exclusive land use, with solar PV suffering the worst losses both in technical and economic potential.

10.4.3.3 Regional carbon abatement cost curves

Table 10.2 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 typically have a different focus, goal and approach as compared to renewable energy supply curve studies, and are broader in scope. They typically examine renewables within a wider portfolio of mitigation options.

Table 10.4.2: Summary of carbon abatement cost curves literature.

Country/Region	Year	Cost ($/tCO$_2$e)	Mitigation potential (million tonnes CO$_2$)	% of baseline	Discount rate (%)	Notes	Source
Australia	2020	<100	74	9.46	N/A	- Costs are converted from Australian dollars[15]	McKinsey and Company (2008a)
Australia	2030	<100	105	13.43			
Australia (NSW region)	2014	<100	8.1	1.04	N/A	- New South Wales region - Includes governmental support for RES	Abatement data: Next Energy (2004) Baseline data: McKinsey (2008a)
		<300	8.5	1.09			
China	2030	<100	1560	10.76	4	- Costs are converted from euros[1] [TSU: reference missing]	McKinsey and Company (2009a)
Czech Republic	2030	<100	9.3	6.24	N/A	- Scenario with maximum use of renewable energy sources - Costs are converted from euros[1] [TSU: reference missing]	McKinsey and Company (2008b)
		<200	11.9	7.99			
		<300	16.6	11.14			
Germany	2020	<100	20	1.91	7	- Societal costs (governmental compensation not included)	McKinsey and Company (2007)
		<200	31	2.96			
		<300	34	3.24			
Poland	2015	<100	50	11.04	6	- Only biomass - Best case scenario - Costs are converted from euros[1] [TSU: reference missing]	Abatement data: Dornburg et al. (2007) Baseline data: EEA (2007)
		<200	55.90	12.35			

[15] Conversion rate used: 1$ = 1.28 A$

Country/Region	Year	Cost ($/t$CO_2$e)	Mitigation potential (million tonnes CO_2)	% of baseline	Discount rate (%)	Notes	Source
Switzerland	2030	<100	0.9	1.61	2.5	- Base case scenario	McKinsey and Company (2009b)
South Africa	2050	<100	83	5.19	10	- Renewable electricity to 50% scenario	Hughes et al. (2007)
Sweden	2020	<100	1.26	1.92	N/A	- Costs are converted from Swedish krones	McKinsey and Company (2008c)
United States	2030	<100	380	3.71	7		Creyts et al. (2007)
United Kingdom	2020	<100	4.38	0.61	N/A	- Costs are converted from euros[2] [TSU: reference missing]	CBI (2007)
		<200	8.76	1.21			
Global	2030	<100	6390	9.13	4	- Scenario A (Maximum growth of renewables and nuclear) - Scenario B (50% growth of renewables and nuclear)	McKinsey and Company (2009c)
		<100	4070	5.81			

One general trend can be observed based on this limited sample of studies. Abatement curve studies tend to find lower potentials for renewable energy than those focusing on energy supply. Even for the 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% of 2015 TPES in the UK (see Table 10.1 [TSU: Table 10.4.1] and the previous section) 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 renewables, as demonstrated by Table 10.3, is for Australia: 13.43% under 200 USD/t CO_2e by 2030 (in contrast with the much higher shares as a % of national TPES reported in the previous section) (data from McKinsey and Company 2008a).

A potential factor contributing to this general trend is that renewable energy 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 renewable energy sources presented by Enviros (2005) as low-cost options, such as landfill gas, sewage gas and hydropower.

Countries with the most promising abatement potentials through renewable identified in the sample of studies are Australia, China and Poland. The McKinsey and Company (2008) findings (see Figure 5) [TSU: reference to Figure unclear] in the power sector are in line with the results presented in the previous section in the sense that onshore wind seems to be the option with the largest potential with a reasonably low cost under 50 USD/t CO_2e and biomass has the second largest potential with a slightly higher cost. The steep learning curve for solar PV is also confirmed as costs from 2020 to 2030 are expected to decline to the extent that it becomes cheaper than both biomass and geothermal, although somewhat contradicting the findings of the previous chapter they envision a similarly large drop in the cost of abatement from onshore wind as well.

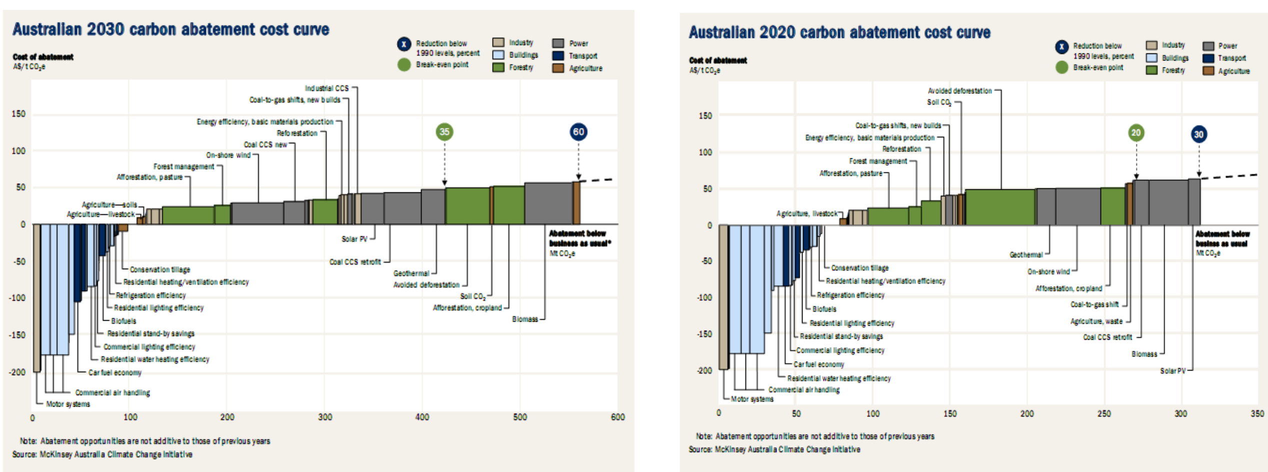


Figure 10.4.1: Carbon abatement cost curves for Australia in 2020 and 2030
Source: McKinsey and Company (2008).

In China it is again wind (both onshore and offshore) and solar PV that take the most important roles in generating renewable energy, although geothermal and small hydro is available at negative costs, but their output is not nearly as significant (McKinsey and Company 2009). According to their assumptions, both wind and solar PV remains slightly more expensive than coal or nuclear, however, the differences will largely decline (Coal: 39 USD/MWh, Nuclear: 42.9 USD/MWh, Wind: 49.4 USD/MWh, Solar PV: 57.2 USD/MWh)[16].

The role of biomass in Central Eastern Europe discussed in the previous section is reinforced by the Dornburg et al. (2007) who estimated carbon abatement potential for Poland at over 11% for biomass alone. Their cost curves are constructed in four steps in which not only do they calculate the amount of biomass and energy produced, but they also account for higher land prices and higher market prices of materials and energy carriers due to an increased production. Similarly to the biomass supply curve studies described in the previous chapter, they also use a relatively high number of scenarios (4) considering the same factors as mentioned above, in two of which they report a mitigation potential below 0 USD/t CO_2e.

10.4.4 Regional renewable energy supply curves

[TSU: No Sources to most of the figure in this section]

This section presents regional renewable electricity supply curves that were constructed based on consistent datasets reported in the literature. Unfortunately such datasets that project renewable energy generation potentials as a function of cost in a regional breakdown in a consistent framework, as well as on as a function of time, are extremely rare. For the present report two such datasources were identified, with one of them already drawing on two different sources of data.

Before detailing the datasets, however, we explain how some of the shortcomings of the cost curve method were alleviated in this exercise. First, recognizing the crucial determining role of carbon emission factors, energy pricing and fossil fuel policies in the ultimate shape of abatement cost curves, the author team of this chapter has jointly decided that it might be more misleading to produce abatement cost curves than informative, thus only renewable energy cost curves are created, avoiding these problems. Second, in order to capture the uncertainties in cost projections stemming from the various reasons detailed above, where possible (2030), two scenarios are reviewed – one that can be considered as more conservative (in this case this is the WEO 2008 (IEA 2008b) due to the typically high costs it projects for RES), and one that describes a scenario in which the world has placed a large emphasis on renewable energy deployment (Energy [R]evolution scenario, Krewitt et al. 2009a).

Another method to strengthen the usefulness of the cost curves produced for this report was to rely on realistic deployment scenarios – i.e. capturing the dynamic nature of potentials and costs in time rather than providing a static cost curve. These cost curves represent snapshot cross-sections of dynamic scenarios in a particular year, providing their details on potentials as a function of costs in that year; but dynamically developing throughout the projection period and making certain assumptions about a deployment path. As a result, the potentials they project for a certain cost category are neither technical nor an economic potentials, but can be considered as deployment potentials, since they already integrates constraints in capacity development, other local constraints such as land availability and competition, opportunities through technology learning, etc.

Unfortunately the Energy [R]evolution scenarios did not include regionally differentiated costs, and thus for their deployment potential figures a separate dataset was used for costs (Krewitt, Nienhaus et al. 2009b). While this is not an ideal solution, the main authors of the two reports have agreed that the costs correspond well to the deployable potentials in the Energy [R]evolution scenario. It is also important to note that the energy potentials are totals for the target year, i.e. include the capacities already in place today.

[16] Conversion rate used: 1.30 USD/EUR.

A major shortcoming of these curves is that they show only electricity potentials, whereas, in some regions, thermal energy and fuel potentials maybe comparable, or even significantly higher than those for electricity generation. Unfortunately, however, there is a major gap in knowledge for renewable non-electric energy potentials on a regional basis, especially as a function of cost. Finally, the real benefit of the cost curve method, i.e. to identify the really cost-effective opportunities, cannot be utilized for such aggregate datasets. Average costs for a technology for an 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.).

10.4.4.1 Africa

The differences between the two 2030 scenarios are rather extreme in Africa in the case of both types of solar power sources, PV and CSP. In the Energy [R]evolution scenario, PV and CSP have the second and third largest potentials, respectively, both of them at costs less than 100 USD/MWh. On the other hand, in the WEO 2008 scenario their role is only minor, not to mention that PV comes at the highest cost among all options. In this scenario hydro power alone has more potential than all the other renewable energy sources together with a power generation potential of over 200 TWh annually. Although neither scenario expects a large contribution from geothermal, the differences in the projected cost levels are still remarkable.

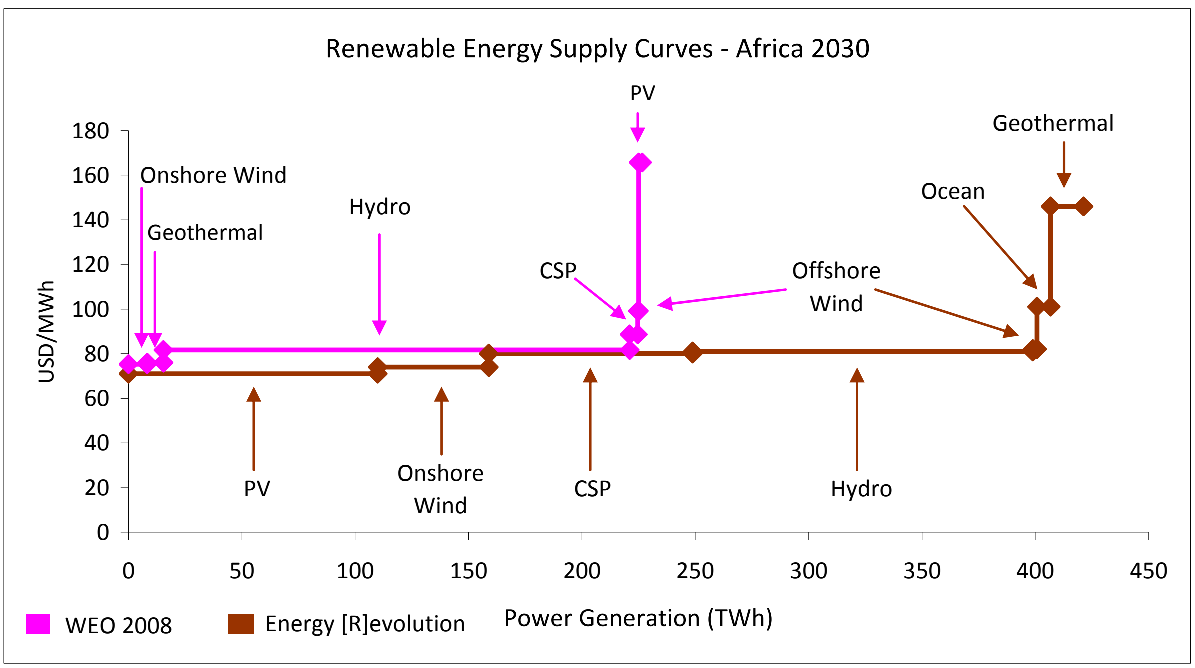


Figure 10.4.2: Renewable energy supply curves for Africa for the year 2030.

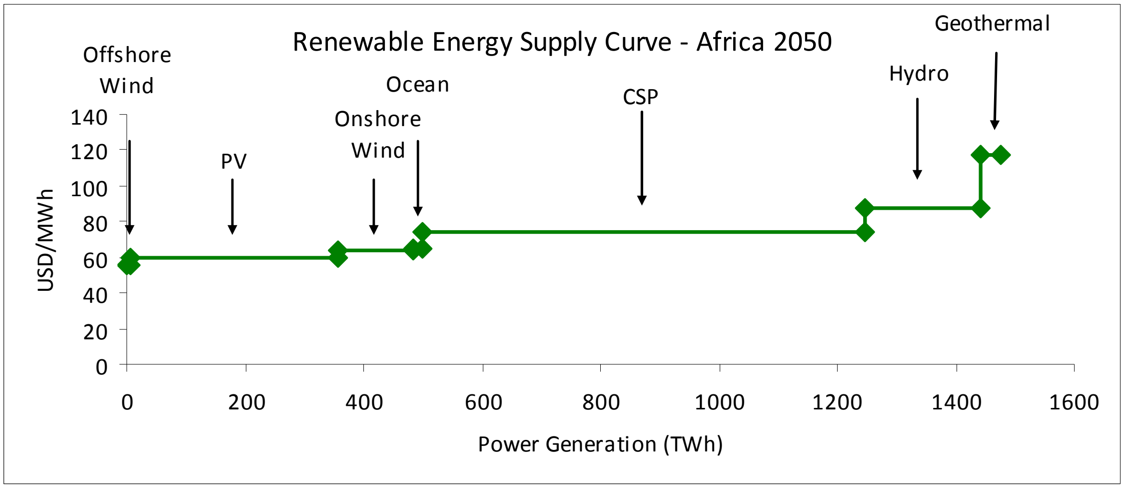


Figure 10.4.3: Renewable energy supply curve for Africa for the year 2050.

Compared to the same scenario (Energy [R]evolution) in 2030, it is evident that potentials will be significantly higher in Africa by 2050 as the total power generation can go up to 1475 TWh from 421 TWh. Shares of the individual renewable energy sources will be similar although CSP will be the one with the largest generation potential and hydro will lose some of its share.

10.4.4.2 China

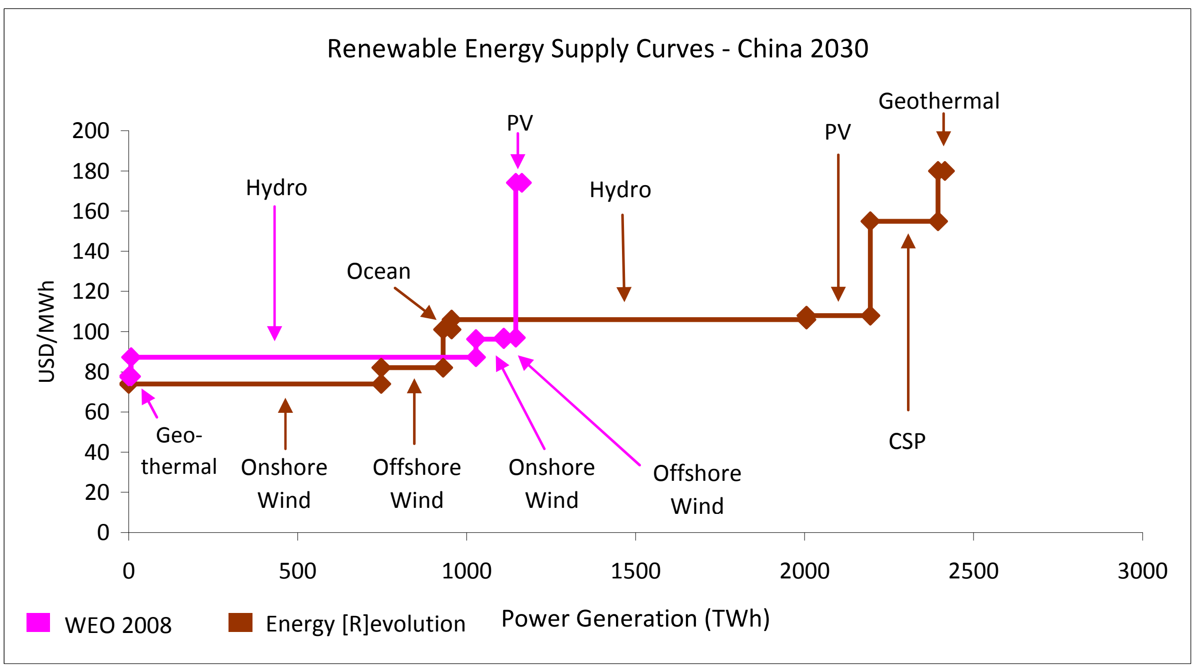


Figure 10.4.4: Renewable energy supply curves for China for the year 2030.

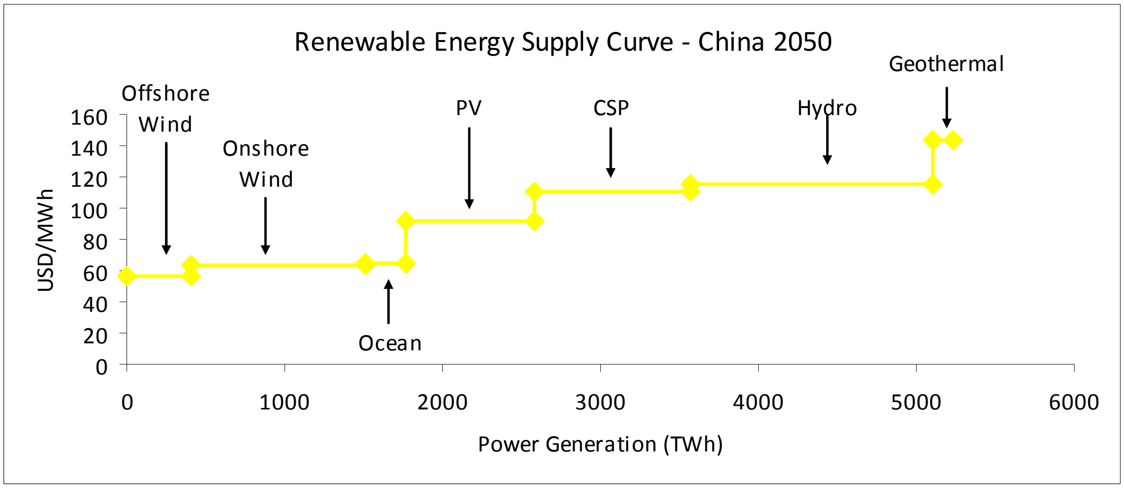


Figure 10.4.5: Renewable energy supply curve for China for the year 2050.

While hydropower in China seems to play an important role in the renewable energy mix in to both scenarios in 2030, the Energy [R]evolution scenario shows a more balanced overall portfolio. As in the case of Africa, the cost of geothermal is again at the two ends of the scale. The WEO 2008 scenario gives no projection on Concentrated Solar Power and on tidal and wave and predicts a much smaller contribution from onshore wind.

If we compare the forecasts for 2030 and 2050 it is evident that all renewable energy sources will have higher potentials. Costs will also be lower as a general trend, although the cost of hydropower is projected to increase slightly.

10.4.4.3 Europe

In the case of Europe wind energy, both onshore and offshore has a significant potential at a relatively low cost not exceeding 102 USD/MWh in either case. Hydro could also play an important role as it has the largest potential in one of the scenarios and the second largest in the other one. Geothermal, wave and tidal and CSP will most likely play a smaller role according to both scenarios, while there is an interesting difference between them in the evaluation of PV. In the Energy [R]evolution scenario it seems to be a feasible option at a cost level of 123 USD/MWh, whereas WEO 2008 predicts 280 USD/MWh making it the most expensive option by far.

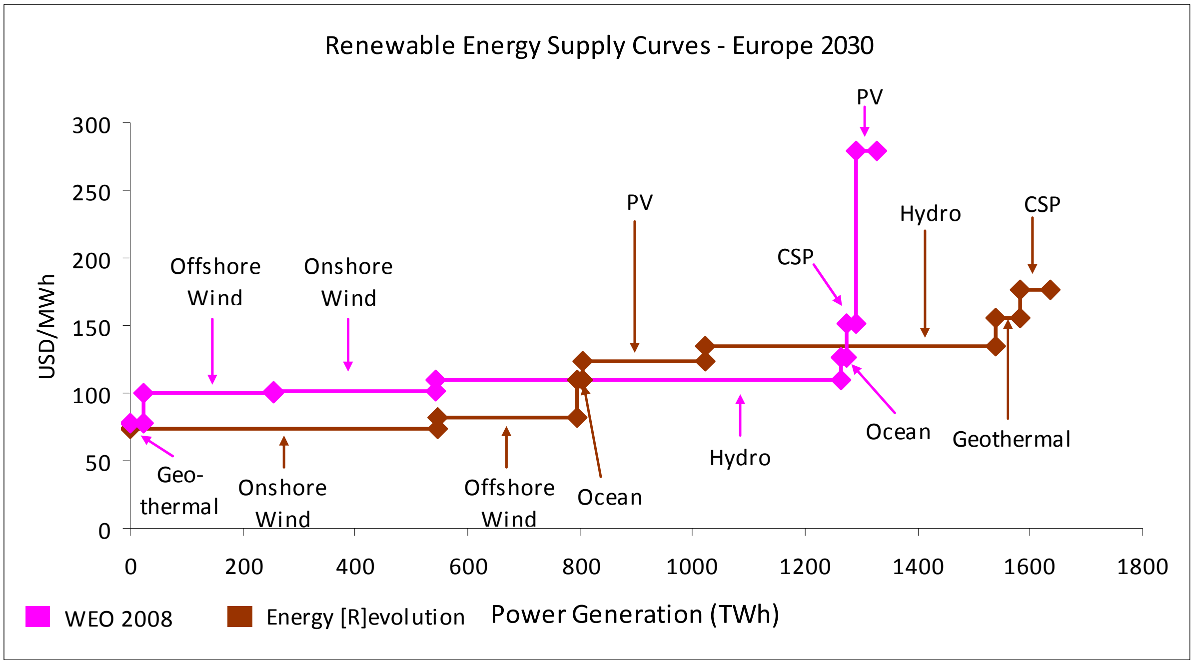


Figure 10.4.6: Renewable energy supply curves for Europe for the year 2030.

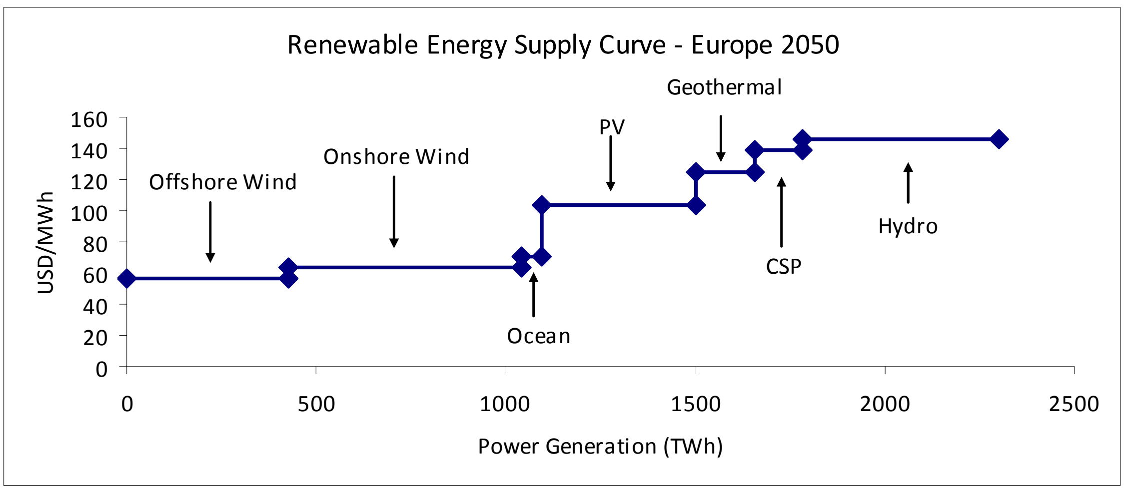


Figure 10.4.7: Renewable energy supply curve for Europe for the year 2050.

The cost level of hydropower is projected to rise also in Europe between 2030 and 2050, making it the option with the highest cost. All the other options will witness similar decreases in costs in this period along with higher power generation potentials.

10.4.4.4 India

Onshore wind is projected to be the most cost-effective option in both scenarios and India is one of the few regions where energy from offshore wind could also be an important energy source even already in 2030. In the WEO 2008 scenario, options are rather limited with only four renewable energy sources and hydro again dominating.

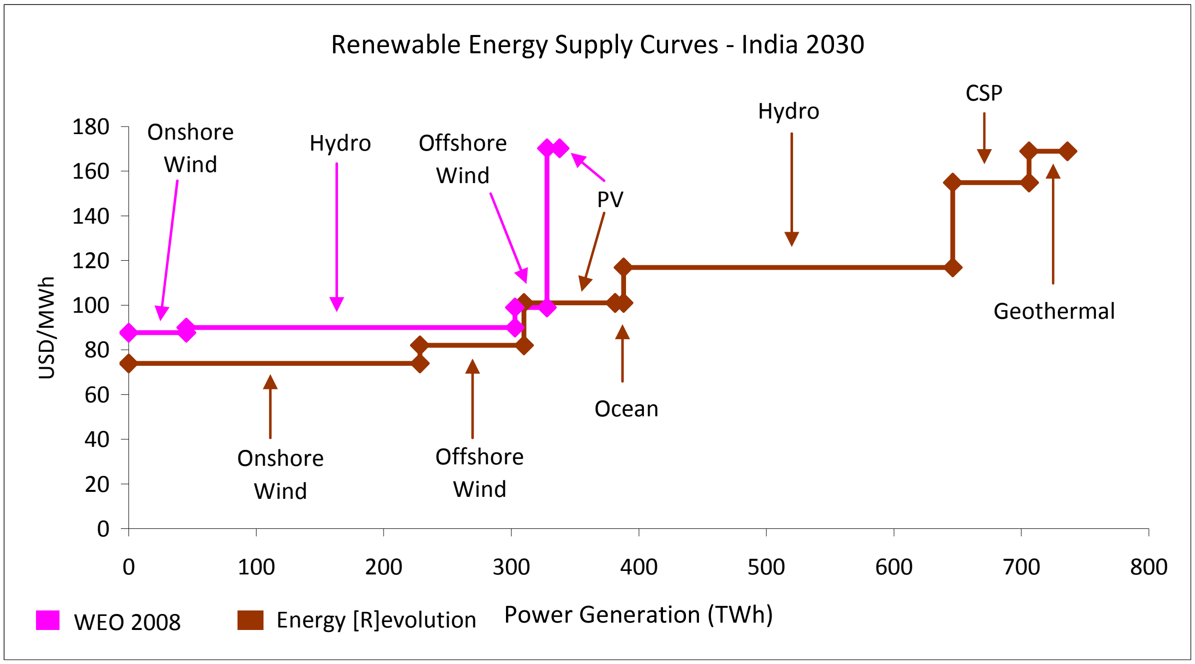


Figure 10.4.8: Renewable energy supply curves for India for the year 2030.

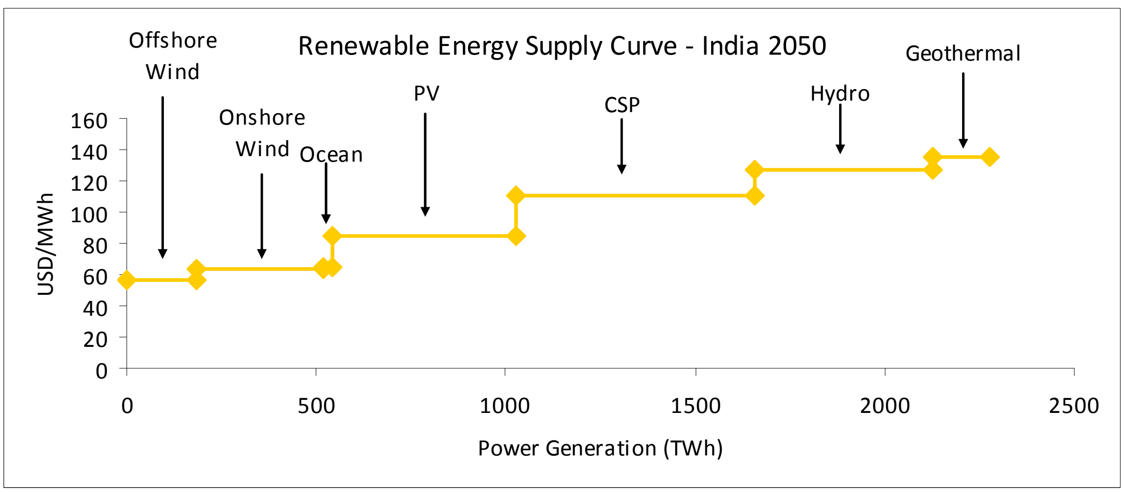


Figure 10.4.9: Renewable energy supply curve for India for the year 2050.

CSP and solar PV will see the highest increase in power generation potentials by 2050 in India and the trend of hydro losing share applies to this region as well. Offshore and onshore wind will still remain the two most cost-effective options, however there might be a different ranking between them.

10.4.4.5 Latin America

Latin America is the only region where the Energy [R]evolution scenario projects a similarly large share of hydro power than WEO 2008 showed for many other regions. The total projected power generation is comparable as well, just as the small contribution of other renewable sources except for onshore wind that is the most cost-effective option in the Energy [R]evolution scenario with a significant share.

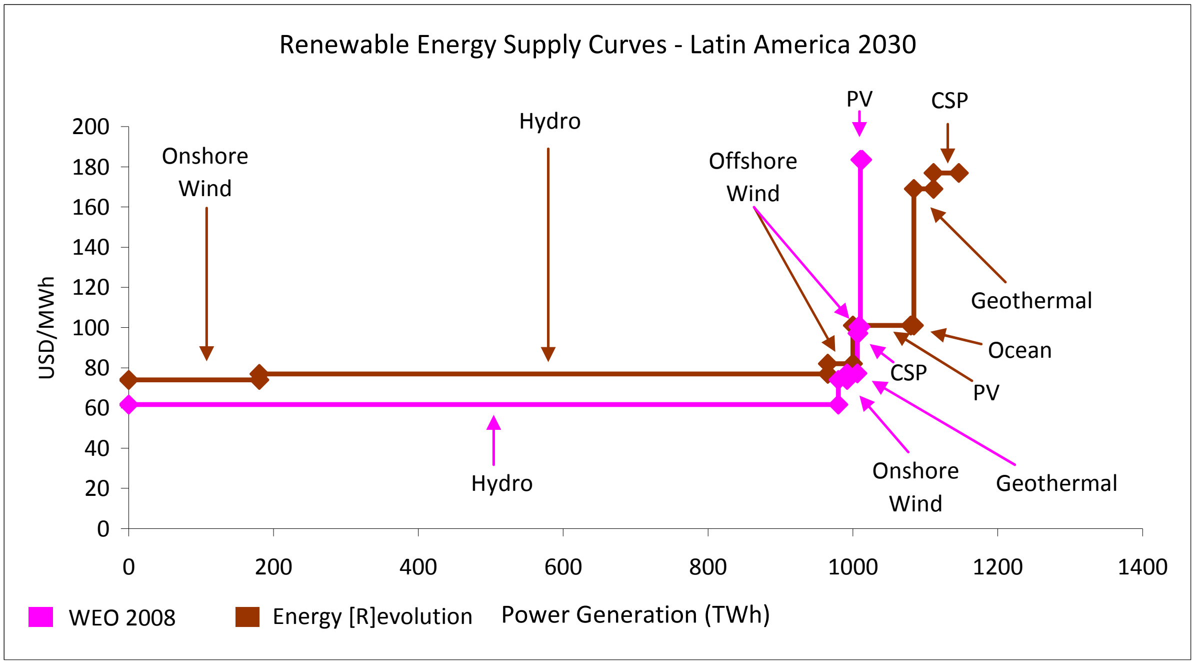


Figure 10.4.10: Renewable energy supply curves for Latin America for the year 2030.

In Latin America hydropower and onshore wind remain the two most important sources of renewable energy potentials in 2050, however all the other options will contribute at a higher level compared to 2030.

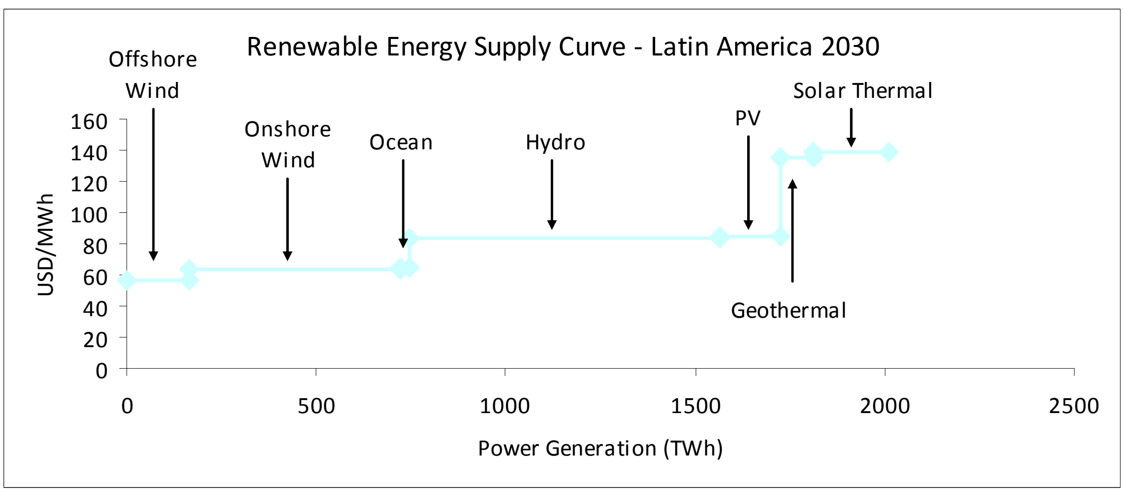


Figure 10.4.11: Renewable energy supply curve for Latin America for the year 2050.

10.4.4.6 Middle East

Whereas in other regions the role of concentrating solar power is usually marginal, it makes the largest contribution to the renewable energy mix in the Middle East according to the Energy [R]evolution scenario. Onshore wind and solar PV are also important contributors, while although offshore wind and ocean energy are in the 100 USD/MWh range as well, they will not yet be used widely in 2030 according to the forecasts. WEO 2008 projections for this region are extremely low.

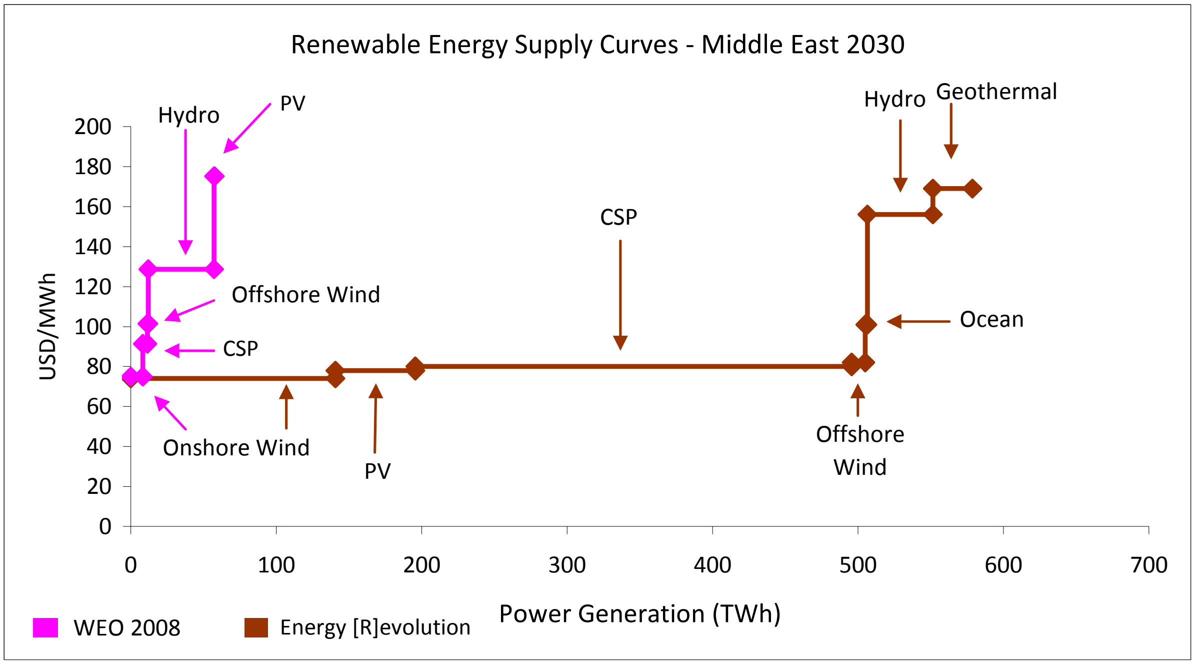


Figure 10.4.12: Renewable energy supply curves for the Middle East for the year 2030.

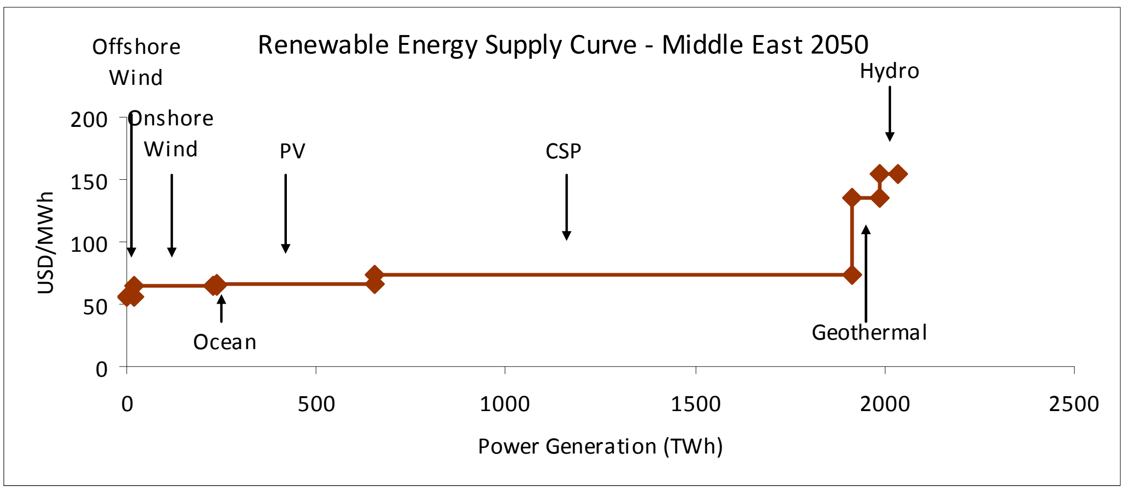


Figure 10.4.13: Renewable energy supply curve for the Middle East for the year 2050.

The graphs for 2030 and 2050 have a similar shape for the Middle East, although power generation from solar PV grows higher than from onshore wind. Hydro and geothermal stay the least attractive options, due to the geographical characteristics of the region.

10.4.4.7 North America

The difference between projected potentials by the two 2030 scenarios is almost threefold in the case of North America which is well demonstrated by the fact that according to the Energy [R]evolution scenario onshore wind alone would produce more energy than the complete renewable energy portfolio in WEO 2008. The cost of Solar PV is again well above 200 USD/MWh if using data from the World Energy Outlook, while it seems rather competitive in the Energy [R]evolution scenario.

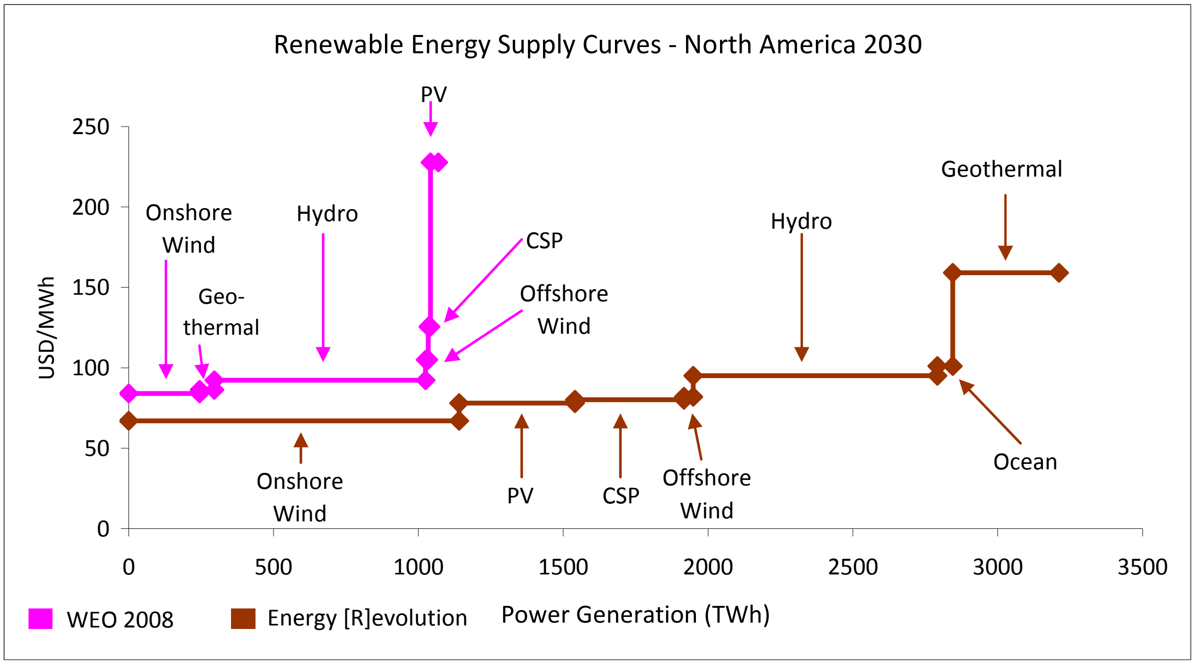


Figure 10.4.14: Renewable energy supply curves for North America for the year 2030.

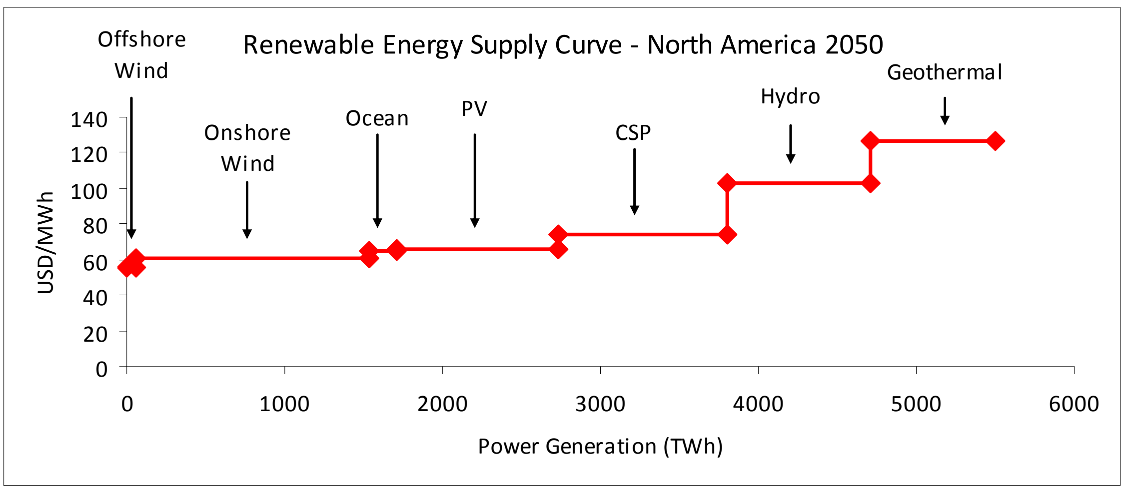
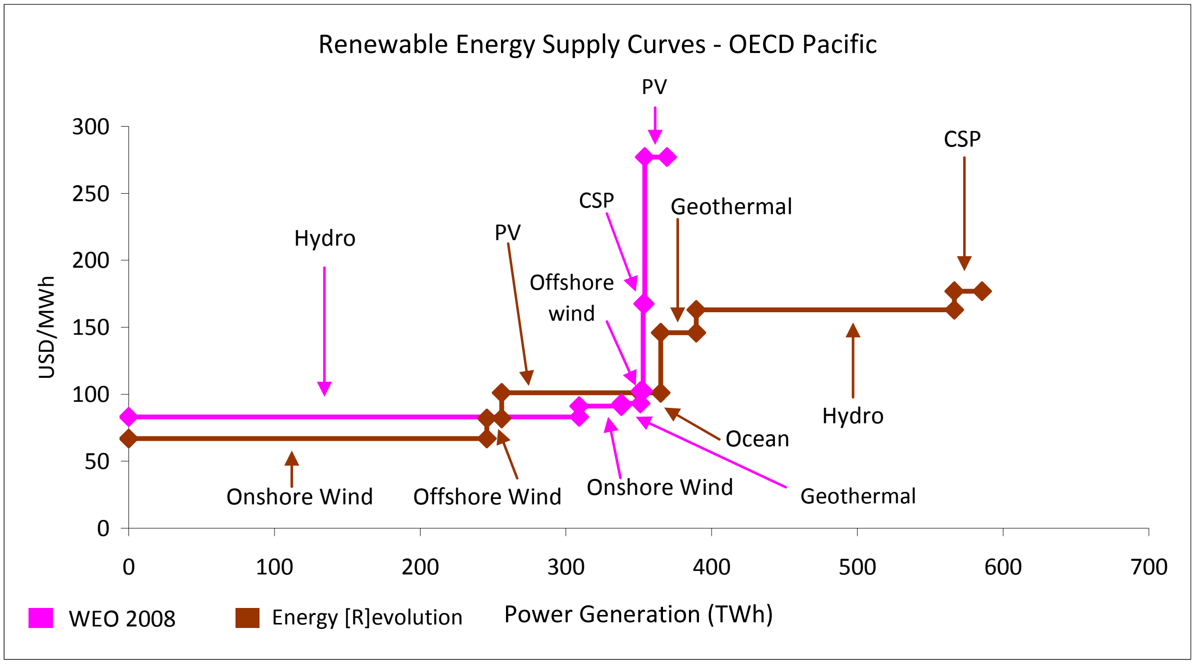


Figure 10.4.15: Renewable energy supply curve for North America for the year 2050.

Trends between 2030 and 2050 follow some of those introduced earlier for other regions: a significant increase in deployable potential but major trends remaining, with the share of hydropower decreasing and at the same time its cost going up by a little while the share of solar PV increasing.

1 *10.4.4.8 OECD Pacific*



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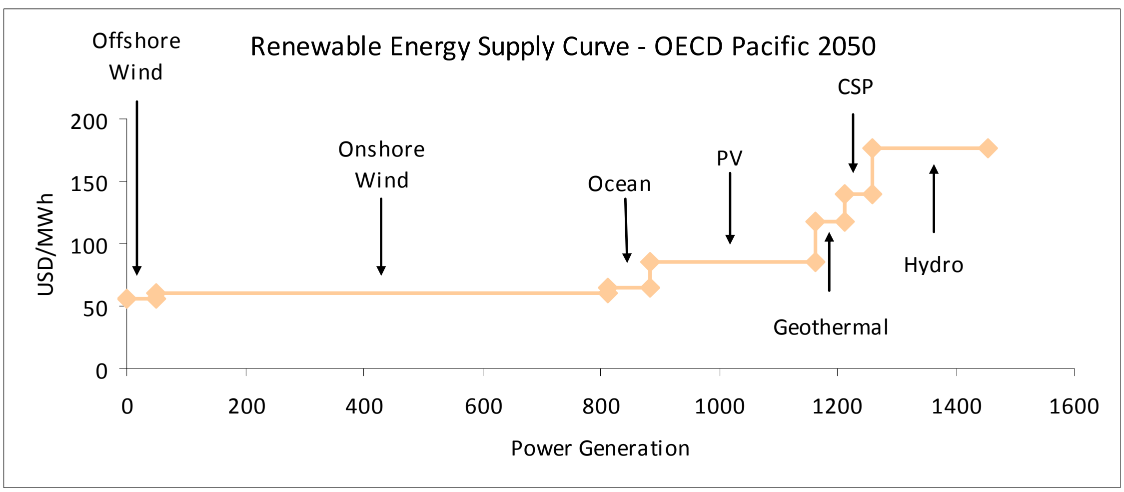
3 **Figure 10.4.16:** Renewable energy supply curves for OECD Pacific for the year 2030.



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5 **Figure 10.4.17:** Renewable energy supply curve for OECD Pacific for the year 2050.

The projections indicate that onshore wind, solar PV and hydro will be the most important renewable energy sources in the OECD Pacific region in 2030. Similarly to the Middle East, offshore wind and ocean energy can be used at relatively low costs. Until 2050, the region follows similar trends as discussed above for North America. The power generation potential from renewable energy sources will more than double during these two decades.

11 *10.4.4.9 Other Asia*

The Other Asia region in the Energy [R]evolution scenario shows a well-balanced renewable energy mix with wind and hydro being the largest contributors. All options are under 177 USD/MWh.

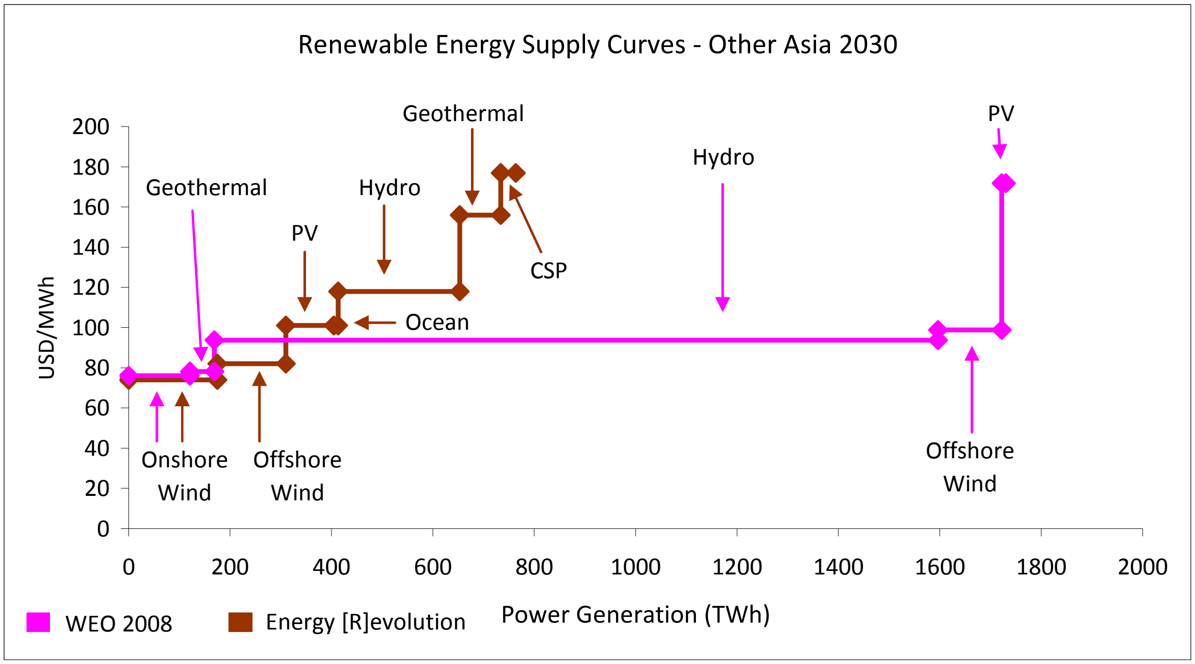


Figure 10.4.18: Renewable energy supply curves for Other Asia for the year 2030.

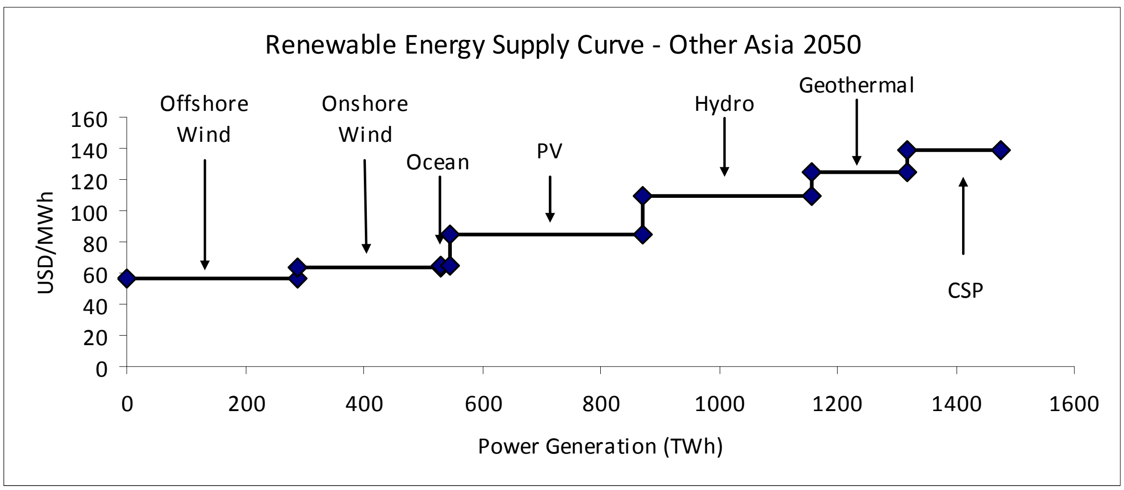


Figure 10.4.19: Renewable energy supply curve for Other Asia for the year 2050.

The Other Asia region will also follow general trends between 2030 and 2050. Offshore wind may become a more cost-effective option than onshore wind.

10.4.4.10 Other Transition Economies

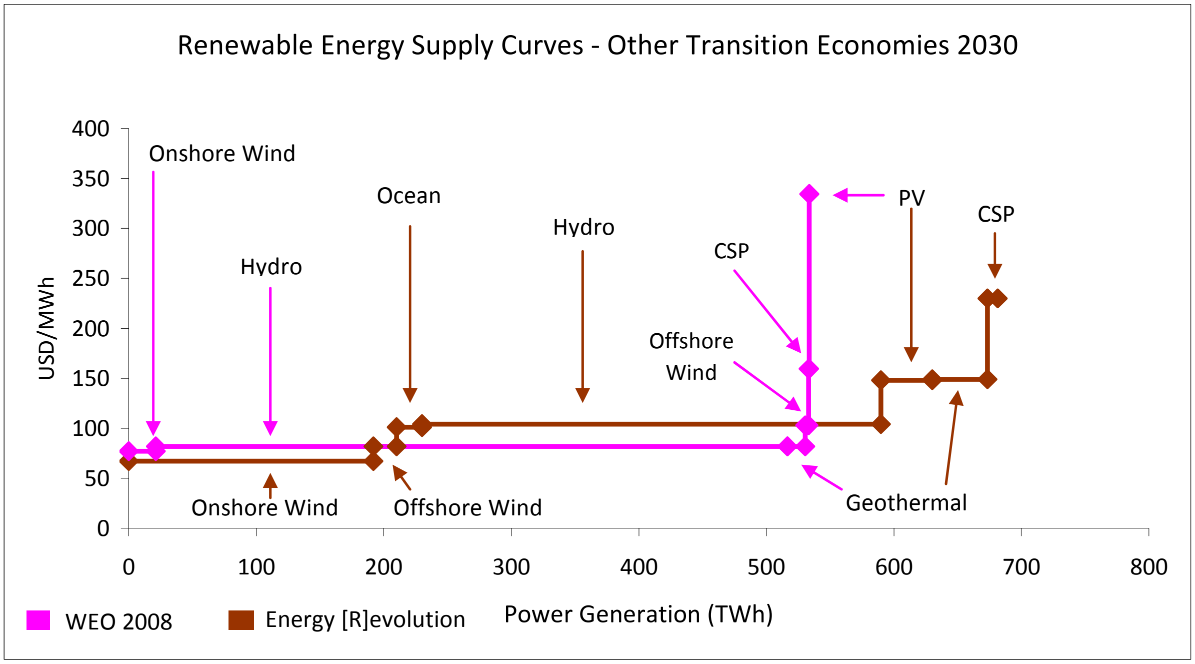


Figure 10.4.20: Renewable energy supply curves for Other Transition Economies for the year 2030.

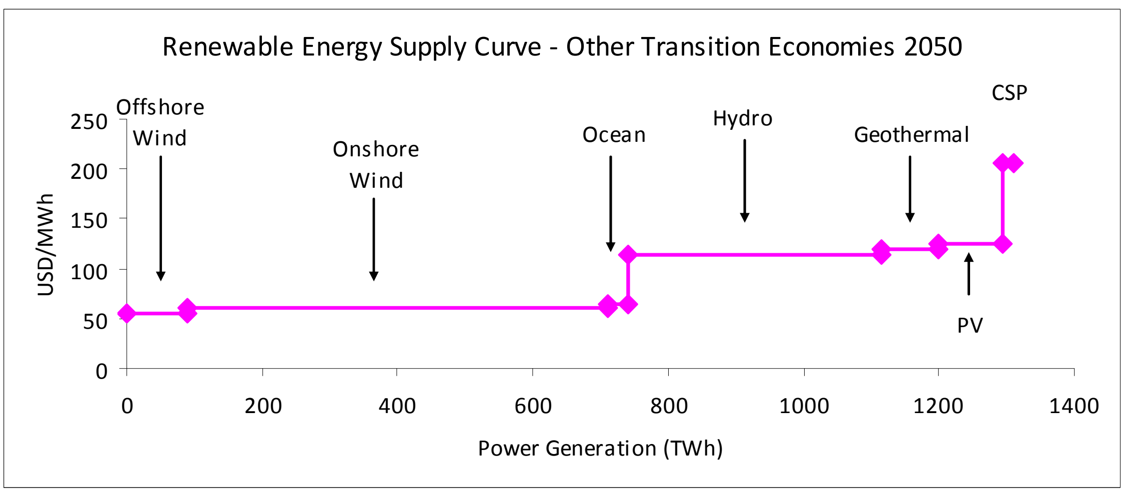


Figure 10.4.21: Renewable energy supply curve for Other Transition Economies for the year 2050.

Onshore wind and hydropower are the major contributors for 2030 in the region. By 2050, offshore wind gains in importance in the Other Transition Economies region as well, while the share of hydropower can decrease here, too.

10.4.4.11 Summary of regional and temporal renewable energy cost-curves

This section has presented the renewable energy supply curves for 10 world regions for 2030 and 2050. For 2030 the existing data are based on two different deployment paths very well documented in existing scenario analysis. The first chosen scenario (World Energy Outlook) makes more conservative cost and potential assumptions than the other (Energy [R]evolution), although in some cases the WEO curve does go below the Energy [R]evolution scenario curve for shorter sections, and even shows a significantly larger potential for Other Asia. Perhaps the largest difference between the two curves is in their projection of PV costs – over a factor of 2. While these curves have mostly regionally specific messages, a few general conclusions can be drawn.

Most typically in the presented cost curves on- and offshore wind power prove to be the most cost-effective option in many regions, both in the shorter and longer term, with the ranking of the two changing region by region. Hydropower is often close to wind in cost-effectiveness in 2030, especially in the WEO scenario, but it looses from its competitiveness by 2050 in many regions, either due to increasing specific costs, or just due to relative cost-effectiveness because the costs of other renewable energies decline. While these two technologies dominate many of the curves at reasonable costs (i.e. under USD 150/MWh) in 2030, by 2050 a more balanced portfolio of technologies appears in most regions, with many other technologies taking a large share of the available low-cost potential, including CSP, PV, and geothermal. Ocean energy is also projected to compete successfully with other technologies in regions with access to the seas, but its overall contribution to the potential remains limited everywhere. In 2050, geothermal, hydropower and CSP become the least attractive options from the perspective of costs in most regions, although CSP is projected to be among the most cost-competitive options and also supplying very large potentials in Africa and the Middle East in both the shorter and longer terms, and is very cost-competitive in North America over both periods.

With regard to temporal dynamics of potential size, the curves underline the importance of a long-term perspective and a consequent market introduction policy. Many regions see a several-fold increase in their low-cost renewable energy potential between 2030 and 2050, including an almost doubling in Latin-America, other Asia and other transition economies, over doubling in China and OECD Pacific, 2.5 time increase in Africa, over tripling in India and the Middle East.

10.4.5 Knowledge gaps

A major gap in knowledge is a consistent, dynamic dataset on renewable energy potentials by cost category and region, that breaks down renewable energy options into subtechnologies as well as preferably sites by different cost-effectiveness levels, ideally also as a function of different deployment scenarios. There is very little understanding of what renewable energy potentials are available at different cost levels in the different geographic regions, especially in non-OECD countries. Breaking the potentials down only by major renewable energy technology as is presently depicted in the cost-curves constructed from available datasets provides a misleading picture: such an approach hides much of the most attractive potentials – potentials available in good sites or attractive sub-technologies, and misleadingly may imply condemning conclusions on entire technologies when they maybe very cost-effective in certain sites or sub-technologies.

In general, a major problem is also the availability of information for non-electric renewable potentials and costs. The chapter could not construct cost-curves on thermal or fuel applications of renewable energy due to the lack of sufficient data. In general, there is often a bias in the availability of literature and data towards power applications of renewable energy technologies whereas heat and mobility applications could be equally important. Approximately 40 - 50% of global final energy demand is for cooling and heating (IEA 2007), and several forms of renewable energy can be more efficiently converted to heat or fuels than to electricity. Therefore, a better integration of thermal and fuel applications into mitigation option appraisal, including supply curves, would be important.

Another gap in the literature is the thorough, consistent documentation of the strengths and limitations of energy and abatement supply curves (esp. the latter) for climate change mitigation strategy-setting. These tools have become very popular with the increasing importance of climate targets and for the determination of target-setting and burden-sharing. However, their applicability and limitations for such purposes, as well as guidelines for robust cost-curve methodology frameworks for abatement option prioritization have not been sufficiently elaborated and documented in the scientific literature (as of Fall 2009). In particular, if it comes to GHG mitigation cost curves the missing system perspective necessary to consider the relevant interactions with the overall system behaviour in a proper way is problematic. Besides other aspects that was a reason to focus only on energy supply cost curves in this section.

10.5 Costs of commercialization and deployment

Renewable energies 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. Although some technologies are already competitive (e.g., large hydropower, combustible biomass (under favorable conditions) and larger geothermal projects (>30 MWe), 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[17] compared to energy supply from conventional sources. 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 or due to technological learning associated with increased deployment. In addition, investment needs and the associated additional cost of various strategies to increase the share of renewable energies will be discussed.

10.5.1 Introduction: review of present technology costs

In the field of renewable energy usage, the energy production costs are mainly determined by investment costs. Nevertheless, operation & maintenance costs (OMC), and – if applicable – fuel costs (in the case of biomass) might 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 $/kW installed capacity] and levelized costs [expressed in terms of $/MWh] for the generation of electricity, heat and transport fuel (see Table 1) [TSU: Table 10.5.1].

On a global scale, the values of both cost terms are highly uncertain for the various renewable energy 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 unit costs (also called levelized generation costs) are defined as 'the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent' (IEA, 2005). Levelized generation costs 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 renewable energy resource availability (e.g., due to different full load hours) and, as a consequence, are different at different locations (Heptonstall, 2007). Optimal conditions can yield lower costs, and less favourable conditions can yield substantially higher costs compared to those shown in Table 1. The costs given there are exclusive of subsidies or policy incentives. Concerning levelized costs, the actual global range might be wider than the range given in Table 1, as discount rates, investment cost, operation and maintenance costs, capacity factors and fuel prices vary. Resulting costs depend on the conventional

[17] 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.

system (see chapter 8 as well), which can limit, for instance, the feed-in capacity due to grid restrictions or a power plant with insufficient dynamic flexibility.

Table 10.5.1: Current specific investment and secondary energy generation costs. The table is based on IEA, 2008b (Table 5, p. 80 – 83).

Technology	Typical characteristics	Typical current investment costs (USD/kW)	Typical current energy production costs[1] (USD/MWh)	References
POWER GENERATION				
Hydro				
Large hydro	Plant size: 10–18 000 MW	1 000–5 500	30–120	IEA, 2008a
Small hydro	Plant size: 1–10 MW	2 500–7 000	60–140	IEA, 2008a
Wind				
Onshore wind	Turbine size: 1–3 MW Blade diameter: 60–100 meters	1 200–1 700	70–140	IEA, 2008a
Offshore wind	Turbine size: 1.5–5 MW Blade diameter: 70–125 meters	2 200–3 000	80–120	IEA, 2008a
Bioenergy[2]				
Biomass combustion for power (solid fuels)	Plant size: 10–100 MW	2 000–3 000	60–190	IEA, 2008a
Municipal solid waste (MSW) incineration	Plant size: 10–100 MW	6 500–8 500	n/a	IEA, 2007b
Biomass CHP	Plant size: 0.1–1 MW (on–site), 1–50MW (district)	3 300–4 300 (on–site), 3 100–3 700 (district)	n/a	IEA, 2008a
Biogas (including landfill gas) digestion	Plant size: <200 kW–10MW	2 300–3 900	n/a	IEA, 2008a IEA, 2007b
Biomass co–firing	Plant size: 5–100 MW (existing), > 100 MW (new plant)	120–1 200 + power station costs	20–50	IEA, 2008a
Biomass integrated gasifier combined cycle (BIGCC)	Plant size: 5–10 MW (demonstration), 30–200 MW (future)	4 300–6 200 (demonstration), 1 200–2 500 (future)	n/a	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
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
Concentrating solar power (CSP)	Plant size: 50–500 MW (trough), 10–20 MW (tower); 0.01–300 MW (future) (dish)	4 000–9 000 (trough)	130–230 (trough)[4]	IEA, 2008a
Ocean energy				
Tidal and marine currents	Plant size: Several demonstration projects up to 300 kW capacity; some large–scale projects under development	7 000–10 000	150–200	IEA, 2008a

Technology	Typical characteristics	Typical current investment costs	Typical current energy production costs[2]	References
HEATING/COOLING				
Biomass heat (excluding CHP)	Size: 5–50 kWth (residential)/ 1–5 MWth (industrial)	120/ kWth (stoves); 380–1 000/kWth (furnaces)	10–60 MWh	IEA, 2008a; REN21, 2008
Biomass heat from CHP	Plant size: 0.1–50 MW	1 500–2 000/ kWth	n/a	IEA, 2008a; IEA & RETD, 2007
Solar hot water/ heating	Size: 2–5 m^2 (household); 20–200 m^2 (medium/ multi–family); 0.5–2 MWth (large/ district heating); Types: evacuated tube, flat–plate	400–1 250/ m^2	20–200 MWh (household); 10–150 MWh (medium); 10–80 MWh (large)	IEA & RETD 2007, REN21, 2008
Geothermal heating/cooling	Plant capacity: 1–10 MW; Types: ground–source heat pumps, direct use, chillers	250–2 450/ kWth	5–20 MWh	IEA & RETD 2007, REN21, 2008
BIOFUELS (1^{ST} 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/ litre gasoline equivalent (sugar); 0.4–0.5/ 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/ litre diesel equivalent	REN21, 2008
RURAL (OFF-GRID) ENERGY				
Mini-hydro	Plant capacity: 100–1 000 kW	500–1 200 kW	50–100 MWh	REN21, 2008
Micro-hydro	Plant capacity: 1–100 kW	1 000–2 000 kW	70–200 MWh	REN21, 2008
Pico-hydro	Plant capacity: 0.1–1 kW	n/a	200–400 MWh	REN21, 2008
Biomass gasifier	Size: 20–5 000 kW	n/a	80–120 MWh	REN21, 2008
Small wind turbine	Turbine size: 3–100 kW	3 000–5 000 kW	150–250 MWh	REN21, 2008
Household wind turbine	Turbine size: 0.1–3 kW	2 000–3 500 kW	150–350 MWh	REN21, 2008
Village-scale mini-grid	System size: 10–1 000 kW	n/a	250–1000 MWh	REN21, 2008
Solar home system	System size: 20–100 W	n/a	400–600 MWh	REN21, 2008

Notes:

1. Using a 10% discount rate. Current costs relate to costs either in 2005 or 2006. Costs of off-grid hybrid power systems employing renewables depend strongly on system size, location, and associated items like diesel backup and battery storage.

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 b 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.

A comparison of levelized generation costs of renewable energy technologies with current wholesale power prices shows that, with few exceptions, renewable energies are not yet competitive with conventional sources if they both feed into the electricity grid (see Figure 1)

[TSU: Figure 10.5.1]. If the respective technologies are used in a decentral mode, their production cost must be compared with the retail consumer power price (grid parity). In this case, important niche markets 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.

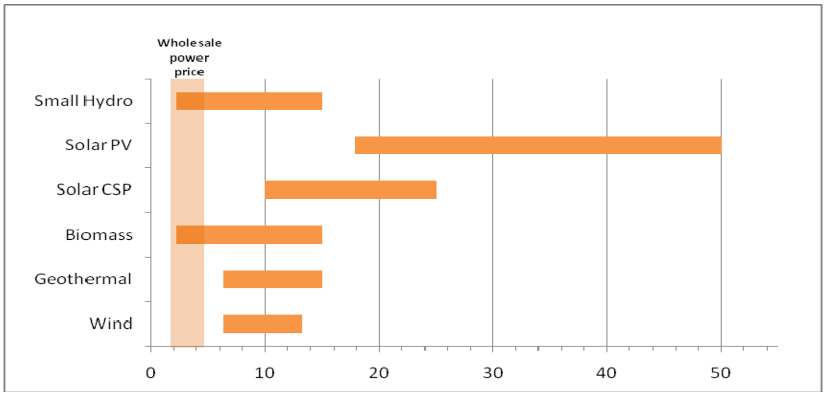


Figure 10.5.1: Cost-competitiveness of selected renewable power technologies. The figure is based on (IEA, 2007a, p. 22).

10.5.2 Prospects for cost decrease

Most technologies applied in the field of renewable energy usage are innovative technologies. Numerous technologies populate different stages of the innovation process (see Figure 2) [TSU: Figure 10.5.2]: Some technologies are still in the research and development stage, the applicability of others is investigated by demonstrations projects, and others have reached the deployment and commercialization phase (see Figure 3) [TSU: Figure 10.5.3]. 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.

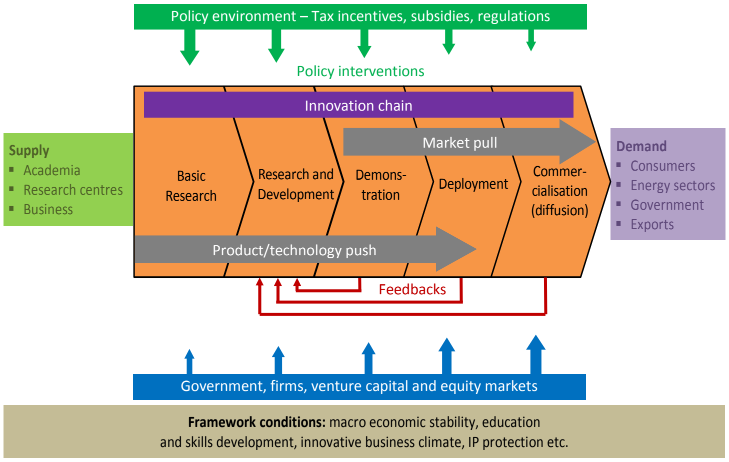


Figure 10.5.2: Schematic description of the innovation process (Source: IEA, 2008a, p. 170).

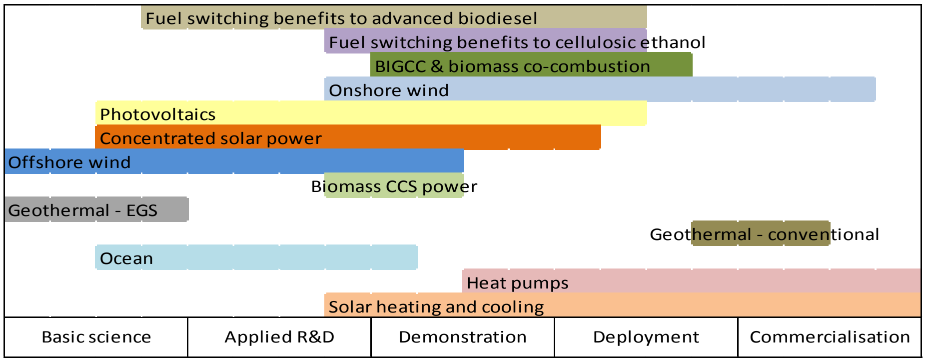


Figure 10.5.3: Relative position of various renewable energy technologies within the innovation chain. (Source: IEA, 2008a, p. 181).

According to Junginger et al. (2006, p. 4026), the list of the most important mechanisms causing cost reductions comprises:

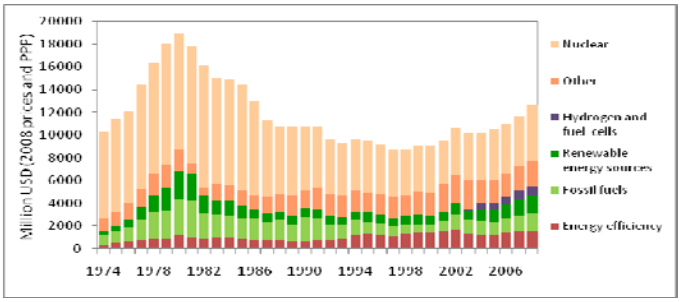
- *Learning by searching*, i.e. improvements due to Research, Development and Demonstration (RD&D) – especially, but not exclusively in the stage of invention,
- *Learning by doing* (in the strict sense), i.e. improvements of the production process (e.g., increased labour efficiency, work specialization),
- *Learning by using*, i.e. improvements triggered by user experience feedbacks occur once the technology enters (niche) markets
- *Learning by interacting*, 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.

Whereas the above list 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) distinguishes:

- *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 programmes that intend to establish a *market (or demand) pull.*

The prospective decrease of levelized costs, however, will not take place autonomously. It is not “manna from heaven”. Depending on the respective position in the innovation chain, some technologies will require for instance substantial efforts for RD&D projects funding. This is not a characteristic of renewable energies alone, but holds true for nearly every innovative energy technology. This fact is highlighted by Figures 4a and 4b [TSU: Figures 10.5.4 a) and 10.5.4 b)], which depict the historic support for renewable energy 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.



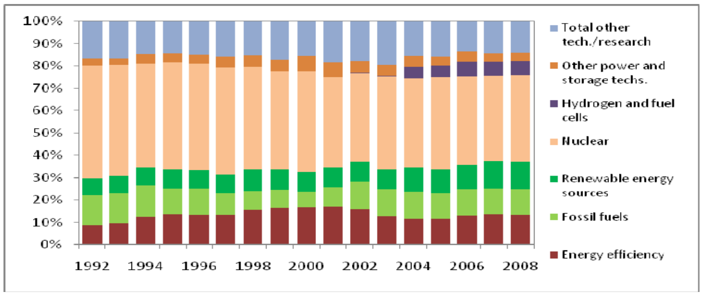


Figure 10.5.4: a) Government budgets on energy RD&D of IEA countries and b) technology shares of government energy RD&D expenditures in IEA countries (cf. IEA, 2008a, p. 172-173, updated with data from http://wds.iea.org/WDS/ReportFolders/ReportFolders.aspx, accessed 29/09/2009). [TSU: b)?]

Whereas RD&D funding is appropriate for infant technologies, market entry support and market push programmes (e.g., via feed-in tariff schemes) are the appropriate tools in the deployment and commercialization phase (Foxon et al., 2005; González, 2008). As a consequence of government aid and private industries expenditures in research and development as well as in improved production technologies and due to the growing demand on the market, many technologies applied in the field of renewable energies showed a significant cost decrease in the past (see Figure 5). This effect is called technological learning. The empirical curves describe the respective relationship of a technology's costs and experience gained expressed as cumulative capacity ever installed. They are therefore called experience (or "learning") curves (see Figure 5) [TSU: Figure 10.5.5]. For a doubling of their cumulative 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 the *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 ration of 80%). Sometimes, energy supply costs (e.g. electricity generation costs) and the cumulative energy 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 5c) [TSU: Figure 10.5.5 c)]. If the learning rate is time-independent, the empirical experience curve can be fitted by a power law. Plotting costs versus cumulative installed capacity in a figure with double logarithmic scales shows the experience curve as a straight line (see Figure 5) [TSU: Figure 10.5.5] in this case. 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. 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).

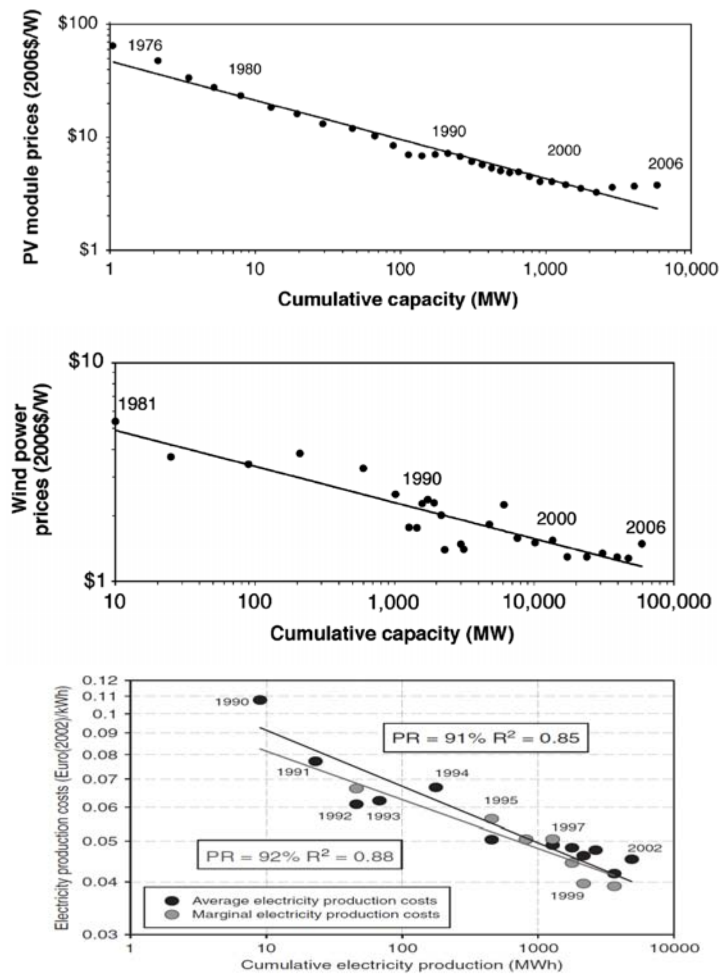


Figure 10.5.5: Illustrative learning curves for a) photovoltaic modules, b) wind turbines and c) Swedish bio-fuelled combined-heat and power plants. Source: Nemet, 2009, Junginger et al. 2006.

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 recently observed for photovoltaic modules and wind energy converters (see Figure 5.a and 5.b) [TSU: Figure 10.5.5 a) and 10.5.5 b)], therefore does not 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 maximized by further cost reduction efforts, the incentive to achieve actual reductions is not diminished even in the high price phases recently observed. According to some researchers (Junginger et al., 2005, referring to the Boston Consulting Group), 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 or completely removed. Short term deviations that can be explained by supply bottlenecks and/or high demand therefore should not immediately lead to a corresponding decrease of the learning rates used by energy models, integrated assessment models or macro-economic models.

Table 10.5.2: Observed learning rates for various electricity supply technologies (extended and updated version of the table given in IEA, 2008a, p. 205).

Technology	Source	Country / region	Period	Learning rate (%)	Performance measure
Nuclear					
	Kouvaritakis, et al., 2000	OECD	1975-1993	5.8	Electricity production cost (USD/kWh)
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, 2006	Global	1994-2001	13	Investment costs (USD/kW)
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	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 & Finland	1975-2003	15	Prices for primary forest fuel (EUR/GJ)
Combined heat and power (CHP)					
	Junginger, 2005	Sweden	1990-2002	9	Electricity production cost (USD/kWh)
CO_2 capture and storage (CCS)					
	Rubin, et al., 2006	Global	n/a	3-5	Electricity production cost (USD/kWh)

Sources: Enermodal, 1999; McDonald and Schrattenholzer, 2001; Williams, 2002; Goldemberg,2004; Junginger, 2005, 2005a, 2005b, 2006; Rubin, 2006; Isles, 2006; Jamasb, 2006; Kruck, 2007; van Sark, 2007; Nemet, 2009.

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2 ### *10.5.3 Deployment cost curves and learning investments*

According to the definition used by the IEA (IEA, 2008a, p 208), “deployment costs represent the total costs of cumulative production needed for a new technology to become competitive with the current, incumbent technology.” As Figure 6 shows, these costs are equal to the integral below the learning curve (blue line), calculated up to the break-even point. 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, 2008a, the cost difference could be extended to take into account variable costs as well. Because of fuel costs, the latter is evident for conventional technologies, but this contribution should also be taken into account if the renewable energy 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 (see Figure 6; the figure depicts the different unit costs associated with carbon prices that are expected for two differing illustrative climate protection strategies.)

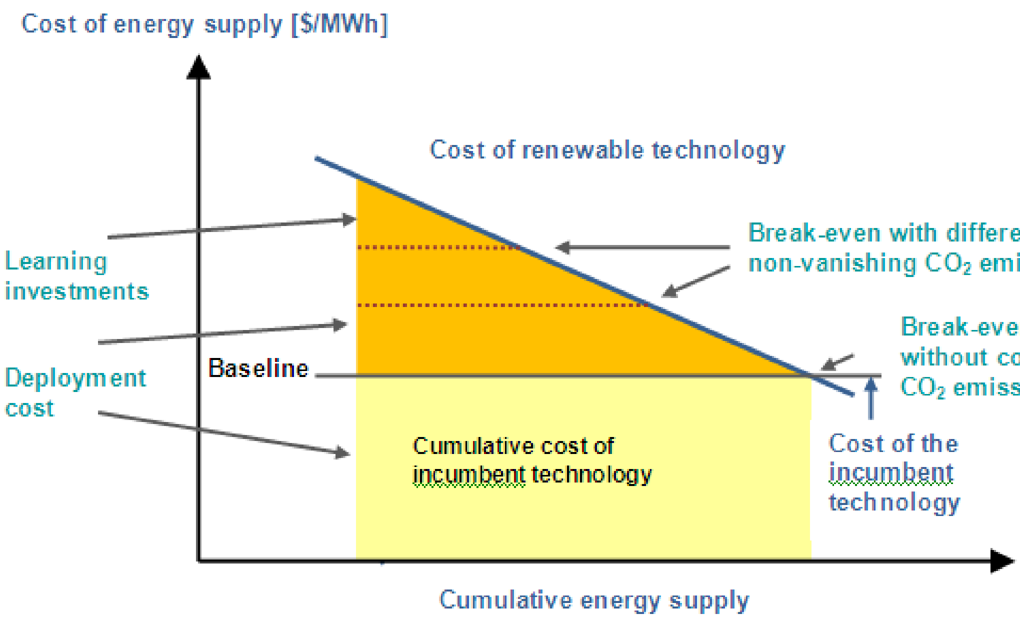


Figure 10.5.6: Schematic representation of learning curves, deployment costs and learning investments (modified version of the diagram depicted in IEA, 2008a, 204).

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, 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.

10.5.4 Time dependent expenditures

If available at all, cost discussions in the literature mostly focus on investment needs. Unfortunately, as already mentioned before, many 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). Although some assessment of the kind discussed here have taken place at a national level, a comprehensive global investigation is highly recommended.

In the following, deployment cost estimates are shown for different emission mitigation scenarios discussed in Chapter 10.3. As discussed before, deployment costs indicate how much money will be spent in the sector of renewable energies once these scenarios materialize. The given numbers therefore are important for investors who are interested in the expected market volume. Data on the energy delivered by the corresponding scenarios can be found in Chapter 10.3.

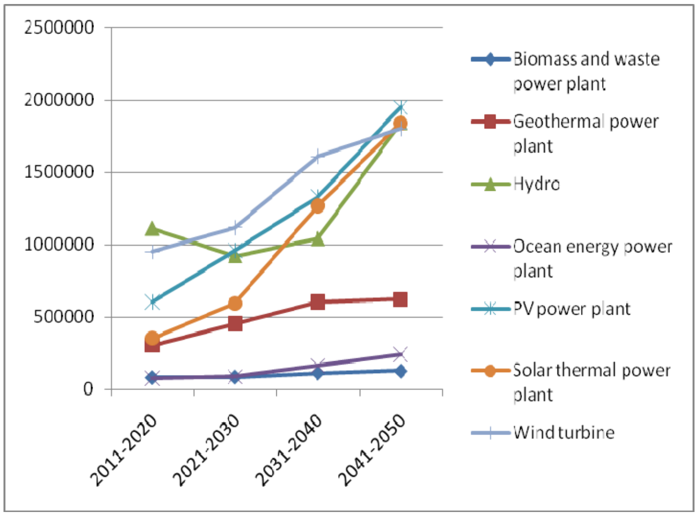


Figure 10.5.7: Illustrative global decadal investment needs (in Mio US $$_{2005}$) in order to achieve ambitious climate protection goals. Source: Greenpeace, 2007. AUTHOR COMMENT: [Editorial note: In the second order draft, this diagram will be replaced by common assessment of various top-down studies discussed in Chapter 10.3. The corresponding deployment cost ranges will be depicted similar to Fig.8 [TSU: Figure 8 not found]of Chapter 10.3 that shows the total primary energy supply for different renewable energy sources.]

Figure 7 depicts the decadal investment needs associated with renewable energy deployment strategies that are compatible with a goal to constrain global mean temperature change to less than 2°C compared to the preindustrial level. In order to achieve this goal, worldwide greenhouse emissions are reduced by 50% below 1990 levels by 2050.

Investing in renewable energies does not only reduce the investment needs for conventional technologies. In addition, fossil fuel costs (and OMC) [TSU: Operation and Maintenance Costs] will be reduced as well. A comprehensive approach therefore would have to take into account avoided fuel costs as well, especially as these costs are expected to increase significantly in the future. As a consequence, deployment costs do not indicate the mitigation burden societies face if these scenarios are realized. In calculating this burden, saved variable costs (e.g., fossil fuel costs and related OMC) must be considered as well. As the saved variable costs are dependent on the development of fossil fuel prices, the overall net cost balance could be positive from a mid or long term perspective.

Although a few scenarios considered in Chapter 10.3 provide technology specific data on the total primary energy supply (see Figure 8 in Chapter 10.3) [TSU: Figure 10.3.8 not found] and the associated (investment) needs (Figure 7, this chapter) [TSU: Figure 10.5.7], 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.

Although this information would be extremely useful in order to carry out a fair assessment of learning investments and (net) deployment costs, up to now, it is not standard to calculate the associated avoided fuel cost “wedges”. Future scenario exercises therefore should focus on delivering the respective data. Albeit some assumptions concerning the mixture of the avoided fossil fuels must be made, the calculation of “carbon dioxide emission reductions wedges” nowadays is standard; an observation which proves that the associated problems (e.g., concerning the contribution of energy efficiency measures) can be solved.

Due to the lack of global data, illustrative results of a German study (Nitsch, 2008) will be discussed in the following. The purpose is to emphasize that the upfront investment in renewable energies should be compared with fossil fuel costs that can be avoided in the long-term.

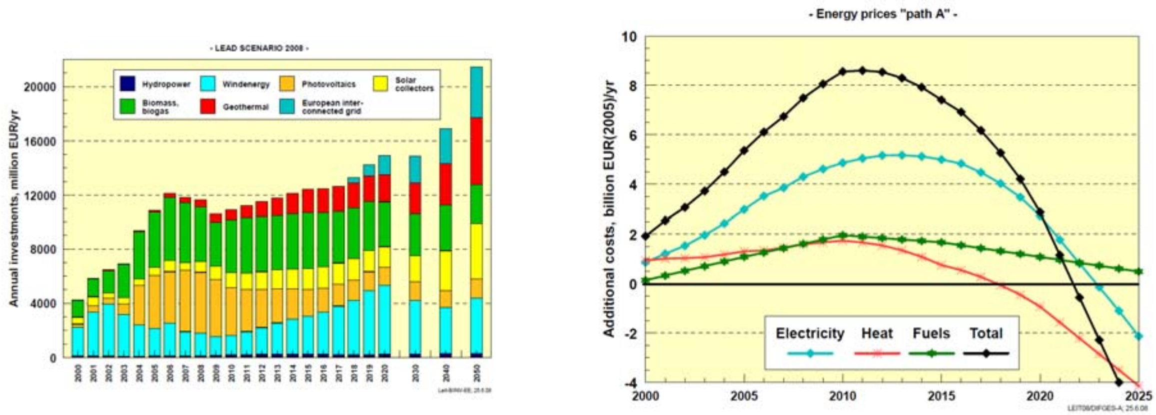


Figure 10.5.8: a) Annual investment volume for renewable installations for electricity and heat supply (including investments for local district heat networks) according to the Lead Scenario 2008. b) Additional costs of renewable energy expansion in all sectors according to the Lead Scenario 2008 (Nitsch, 2008, p. 26 and 28).

The lead study describes the cost evolution which is shown in Figure 8 [TSU: Figure 10.5.8] as follows: “The annual additional costs of the entire expansion of renewable energies amounted to 6.7 billion €$_{2005}$/yr in 2007. Of these, 57% were incurred for electricity supply. On price path A, they rise further to 8.5 billion €$_{2005}$/yr in 2010 (of which 4.8 billion €$_{2005}$/yr for the electricity sector, 1.7 billion €$_{2005}$/yr for the heat sector and 2 billion €$_{2005}$/yr for the fuels sector) and then drop sharply. No additional costs arise any longer around 2020. Renewable energies then meet almost 20% of total final energy demand and already avoid 200 million t CO_2/yr. Over the period from 2021 to 2030 renewables, which continue to expand, already save the national economy 6 billion €$_{2005}$/yr, a sum which otherwise would have to be expended for the additional fossil energy requirement. In the period from 2031 to 2040 these savings grow further to 27 billion €$_{2005}$/yr.” (Nitsch, 2008, p. 27-28).

10.5.5 Market support and RDD&D [TSU: RD&D]

In the beginning, 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. 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. In the context of mitigation scenarios relevant factors are the selected atmospheric concentration ceiling for greenhouse gases (in particular the related policies) and the deployed discount rate. Unfortunately only innovative integrated assessment models – which model technological learning in an endogenous way – are capable of assessing the overall mitigation burden associated with a cost optimal application of renewable energies within the context of ambitious climate protection strategies (Edenhofer et al., 2006). That is why only limited results are available so far.

The results obtained from these modelling exercises indicate that – 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. Being obtained by models that seek to maximize global welfare, the respective investment paths are optimal from a perspective that takes into account the dynamic efficiency of the transition path. Unfortunately caused by other decision factors that's not necessarily be undertaken by private investors. Two market failures are mainly responsible for this imperfect performance of liberalized markets: As long as external environmental effects are not completely internalized, the usage of fossil fuel is cheaper than justified. The incentive for investments in climate-friendly technologies therefore is reduced. Independent of any environmental aspects, several private sector innovation market failures distort private sector investments in technological progress (Jaffe et al., 2005). The main problem here 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. An optimal strategy therefore has to combine two complementary approaches which address the two market failures mentioned above (environmental pollution and the market failures associated with the innovation and diffusion of new technologies). Together these market failures provide a strong rationale for a portfolio of public policies that foster emissions reduction (e.g. by emission trading or carbon taxes) as well as the development and adoption of environmentally beneficial technologies (e.g., by economic incentives like feed-in tariffs, Jaffe et al., 2005).

Typical instruments to foster the diffusion of renewable energy technologies are, for instance, feed in tariffs. With a view to the considerable financial support renewable electricity supply systems are gaining via feed-in tariffs or other instruments all over the world, the question has been raised whether this support is still justified if emission trading schemes are acting in parallel (cf., German Monopolies Commission, 2009). In order to clarify the relationship between emission trading (or other schemes that led to an internalization of carbon costs) and technology specific support schemes for renewable energies (e.g., feed-in tariffs or quota systems), Figure 9 [TSU: Figure 10.5.9] should be considered.

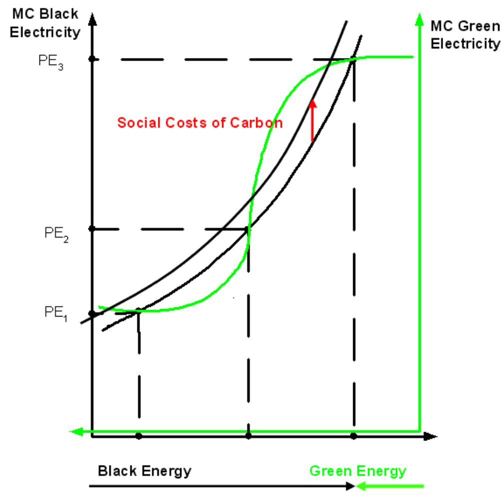


Figure 10.5.9: Equilibrium solutions for innovative technologies showing learning effects (Source Bruckner and Edenhofer, 2009).

The black curve depicts the cost of electricity produced from fossil-fuels. The respective supply curve shows the classical behaviour: marginal costs rise with increasing output. Cheap supply options are limited; we therefore have to mine more expensive commodities in case higher supply shares are requested. Small contributions from renewable energies can be found at the right hand side of the figure; the market shares for renewable electricity therefore increase from the right to the left. As long as technological learning is not taken into account, supply curves for power from renewable sources would exhibit a behaviour which is similar to that for conventional electricity. If technological learning in the field of renewable energies is taken into account, the supply curve changes significantly. Due to learning effects, an increasing market share (and a corresponding larger experience) initially causes a gradual decrease of marginal cost. As good sites are limited and system dependent additional integration costs become more and more important for higher market penetration levels, the marginal cost might exhibit a minimum for a specific market share and an increasing trend beyond (e.g., to the left of) that value. As a consequence, the supply curve for electricity from renewable energy sources could be S-shaped – as depicted in Figure 9 [TSU: Figure 10.5.9].

At the intersection points the absolute values of the marginal costs for "black" and the "green" energy are equal (note that marginal costs are nothing other than the derivative of total costs with respect to the market share). Speaking in mathematical terms, total costs exhibit a relative (or local) minimum at the intersection points (PE1 and PE3).

To the right of the intersection point PE3, marginal costs of renewable energies are smaller than those for electricity from conventional sources. Within the corresponding niche markets renewable energies are competitive and total costs can be decreased by increasing the share of renewable energies. Within market economies, this improvement potential would be exploited up to the point where equal marginal costs are achieved. As long as subsidies are not taken into account, private investors would have no incentive to increase the share of renewable energies beyond that point (i.e., towards the left-hand side).

The internalisation of the external costs of fossil fuel usage, e.g. via an emission trading scheme (or via carbon taxes) would increase the marginal cost of electricity from fossil fuels (the related shift is indicated by the red arrow in Figure 9). The intersection point PE3 would shift to a new equilibrium value exhibiting a higher market share of renewable energies. Unfortunately, the respective increase will be small. The introduction of an emission trading scheme could therefore improve the competitiveness of renewable energies, but it does not necessarily trigger a transition to point PE1, which corresponds to another local cost minimum – which might be the absolute optimum in case that sufficiently ambitious climate protection goals are prescribed. Without accompanying measures an inter-temporal market failure has to be assumed in this case. The true social optimum (PE1) would not be adopted. The cost of climate protection would be higher than necessary.

In order to achieve the absolute cost minimum PE1, additional instruments (e.g. feed-in tariff systems or quota systems) therefore are necessary that are capable to increase the market share of renewable electricity up to PE2. Beyond this point, renewable electricity is cheaper than electricity from conventional sources. As a result, autonomous market forces would increase the share of renewables until PE1 is achieved. In the short term, the additional instruments will lead to an increase of the total costs, but in the long run the upfront investment costs could be more than compensated by the cost reduction induced by technological learning.

Obviously, the static sketch shown in Figure 9 is not able to prove *quantitatively* that upfront investment costs of a specific technology are really compensated by the expected avoided fuel costs. Whether this is the case depends, inter alia, on the selected climate protection goal, the assumed learning capability, the long-term resource potential and the performance of competing mitigation technologies. Integrated assessment models – which model technological learning in an endogenous way – are able to determine emissions mitigation technology portfolios that are cost effective form a long-term dynamic point of view. These models therefore might help to identify those innovative technologies which deserve an additional, technology specific support in the context of a prescribe climate protection goal (Edenhofer et al., 2006).

10.5.6 Knowledge gaps

Experience curves nowadays are used to inform decisions that involve billions of public funding. Although the notion that learning leads to cost reductions is well supported by many empirical studies, the application (and extrapolation) of learning curves in order to guide policy is not generally accepted (Nemet, 2009). In addition, 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 is reached.

Small variations in the assumed learning rates can have a significant influence on the results of models that are using learning curves. Empirical studies therefore should strive to provide error bars for the derived learning rates (van Sark et al, 2008).

10.6 Social, environmental costs and benefits

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 renewable energy 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 (ExternEE 2004, NEEDS 2008), although other definitions have also been used in the past (e.g. Hohmeyer 1988). Figure 10.6.1 below shows a possible representation of the different definitions of costs and benefits.

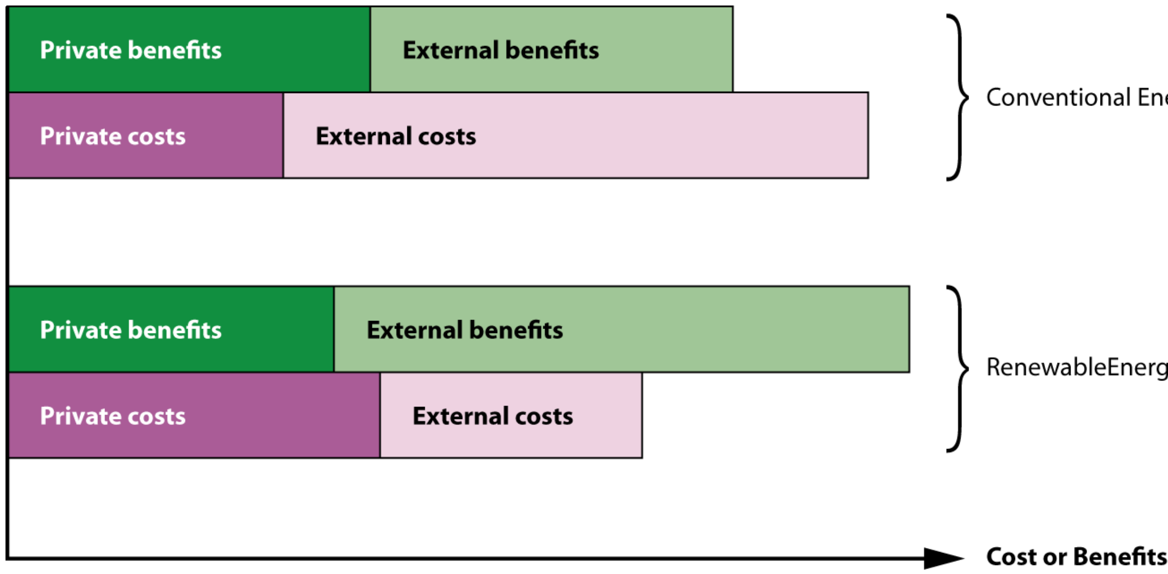


Figure 10.6.1: Simple representation of cost and benefits in the context of conventional and renewable energy sources. [TSU: No Source]

In conventional non-renewable energy production the 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 renewable energy forms on the other hand can often be unprofitable for the energy producer. If the external costs (including environmental costs) are taken into account, the production of renewable energy can, however, as a whole be more profitable from a social point of view than conventional energy production (e.g. 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 greenhouse gases, acidifying emissions and particulate emissions. These types of emissions can often but not always (e.g. biomass) be lowered if renewable energy is used to replace fossil fuels (e.g. Weisser 2007)[18]. Increasing the share of renewable energy often contributes positively to access to energy[19], energy security and the trade balance and it limits the negative effects from fluctuating prices of fossil-based energy (Chen et al. 2007; Bolinger et al. 2006, Berry & Jaccard 2001). Further, increasing renewable energy 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 renewable energy have their own private and external costs and benefits, depending on the energy source and the technology utilised (e.g. NEEDS 2009a).

Costs and benefits can be addressed in cost-benefit analyses to support decision-making. However, the value of renewable energy 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

[18] One has to keep in mind that in particular biomass applications can also cause particulate emissions.
[19] 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.

of an increased use of renewable energy are to a large part attributable to the reduced use of non-renewable energy 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 (Weitzmann 2007; Dietz & 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. (Grubb & Newberry 2007; Söderholm & Sundqvist 2003; Krewitt 2002).

The production and use of energy can be considered from the viewpoint of sustainable development. [TSU: see chapter 9] Sustainable development is often divided into three aspects, namely environmental, economic and social sustainability. Renewable energy 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, Krausmann et al. 2008, Rathmann et al. 2010) although other references indicate that both food and fuel demand can be met in many cases at some reasonable level (Sparovek et al. 2008). 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 (Fargione et al. 2008; Searchinger et al. 2008, Adler et al. 2007).

When the response to climate change is considered, renewable energy can be linked to the changing climate in regard to both climate change mitigation and adaptation (IPCC 2007b). On the other hand, climate change can have a great impact on renewable energy 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-off into rivers (Figure 10.6.2) (Bates at al. 2008; Kirkinen et al. 2005; Lucena et al. 2009a, 2009b, 2010; Venäläinen et al. 2004).

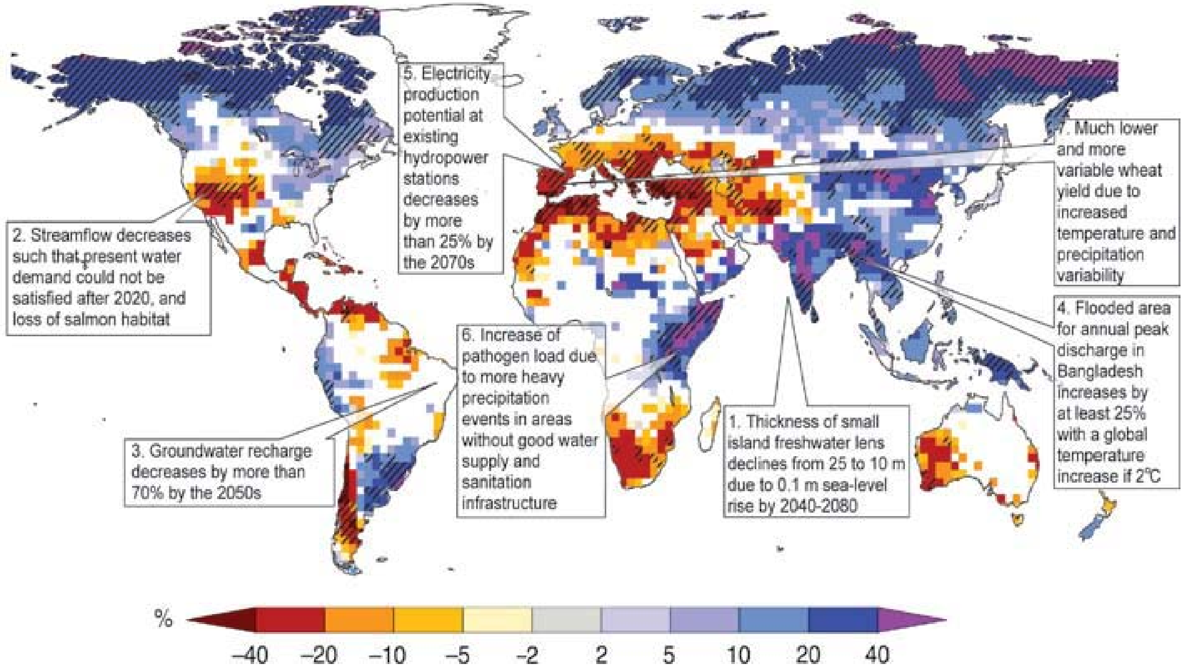


Figure 10.6.2: Illustrative map of future climate change impacts related to freshwater which threaten the sustainable development of the affected regions. Ensemble mean change in annual runoff (%) between present (1980–1999) and 2090–2099 for the SRES A1B emissions scenario. Areas with blue (red) colours indicate the increase (decrease) of annual runoff. (Bates et al. 2008.)

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. Renewable energy 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 Section 10.6 is to make a synthesis and discuss external costs and benefits of increased renewable energy 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 renewable energy 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 et al. 2008).

Although replacing fossil-fuel-based energy with renewable energy can reduce greenhouse gas emissions and also to some extent other environmental impacts and social costs caused by them, renewable energy 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 everything important. In the case of non-combustible energy sources, the life-cycle approach is also very important when considering the total impact (WEC 2004; Kirkinen et al. 2008, NEEDS 2009a).

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 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. (Söderholm & Sundqvist 2003)

10.6.2.1 Climate change

Carbon dioxide is the most important anthropogenic greenhouse gas. The growth of its concentration in the atmosphere causes the greatest share of radiative forcing (NOAA 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 Grubb & Newbery (2007), Anthoff (2007) and Watkiss & 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. Beside the question about discount rate which is quite relevant considering the long term impacts of greenhouse gas emissions there is considerable uncertainty in areas such as climate sensitivity, damages due to climate change, valuation of damages and equity weighting (Watkiss & Downing 2008).

A German study dealing with external costs (Krewitt & Schlomann 2006) uses the values of 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 & 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 £35/tC (about 10€/tCO_2). 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. 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 & Newbery 2007).

Renewable energy sources have usually quite low greenhouse gas emissions per produced energy unit (WEC 2004; Krewitt & Schlomann 2006; IPCC 2007b), 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 biofuels produced under unfavourable conditions (Soimakallio et al. 2009b; Hill et al. 2006). Land use change for increasing biofuel production can release carbon from soil and vegetation and in practice increase net emissions for decades or even longer time spans (Edwards et al. 2008; Fargione et al. 2008; Searchinger et al. 2008). 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). Often case specific studies are needed in order to achieve realistic estimates concerning the greenhouse gas emissions of certain renewable energy technology applications.

Increasing the use of renewable energy sources often displaces fossil energy sources which have relatively high greenhouse gas emissions and external costs (Koljonen et al. 2008a). 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 renewable energy 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 (e.g. Krewitt 2002; Torfs et al. 2007; Amann et al. 2008). 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 &Schlomann 2006). 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. 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 (e.g. Torfs et al. 2007).

The specific costs per tonne of emissions have been assessed in reference (Krewitt & Schlomann 2006) to be for SO2 about 3000€/t, for NOx about 3000€/t, for Non-Methane VOC about 200€/t and for particulates PM_{10} about 12000€/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 renewable energy 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 renewable energy. 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 renewable energies cooling water demand is relevant in particular for biomass combustion plants. However, the unit size of bioenergy 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 to some extent 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, DDP 2007)

10.6.2.4 Impacts on land use, soil, ecosystems and biodiversity

Some large hydropower projects need considerable water reservoirs, which can have a clear impact on land use on a local to regional scale, although in the case of small hydropower plants the impacts are usually small. The reservoirs can cover settlements, agricultural land and land used for other livelihoods (Fearnside 1999, 2005).

The use of bioenergy can be increased by utilising residues from agriculture and forestry as well as by increasing the efficiency of land use and using set-aside lands. A large increase in bioenergy use, however, requires an increase in the land area designated to energy crops, resulting 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; Krausmann et al. 2008; Rathmann et al. 2010, Searchinger et al. 2008; Sparovek et al. 2008).

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 renewable energy 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 & 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 (UNPD 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. (IEA 2008a)

The depletion of the limited energy reserves of fossil fuels (WEC 2007; VTT 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 renewable energy (Berry & Jaccard 2001; Koljonen et al. 2008b; BIWARE 2005; VTT 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 renewable energy resources, and reducing overall demand through energy conservation. Renewables, as part of a cleaner energy mix, are growing in importance. Renewables 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 renewable energy creates jobs in R&D and manufacturing (Monni et al. 2002; BMU 2006a, b). 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 & Jaccard 2001; Bergmann et al. 2006; Koljonen et al. 2008b). Moreover there is not only a possible employment effect due to the production process of renewable energies, but a general possibility that access to energy and in particular renewable energy 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, e.g. in hydropower, 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).

Use of local energy sources improves access to energy (Berry & Jaccard 2001, BIWARE 2005, Sahay 2009), enhances energy security and reduces the impact of energy price volatility in international markets (Koljonen et al. 2008b). Access to energy is especially important in many developing countries where hundreds of millions of people live without modern energy services.

The biggest impacts of renewable energies 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 renewable energy 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. (Möller 2006). Biomass plantations might not be as visible from far away as wind mills are, but they require a huge amount of land and are often in the form of monocultures, leading to corresponding negative impacts on biodiversity.

10.6.3 Regional considerations of social costs and benefits

Most of the studies covered in this section consider North America (Gallagher et al. 2003; Roth & Ambs 2004; Kennedy 2005; Chen et al. 2007; NRC, in press) and Europe (Groscurth et al. 2000, Bergmann et al. 2006, Krewitt & Schlomann 2006, NEEDS 2009a), 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. (2008) 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. Amann et al. (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.

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 et al. 2008; Bollen et al. 2007).

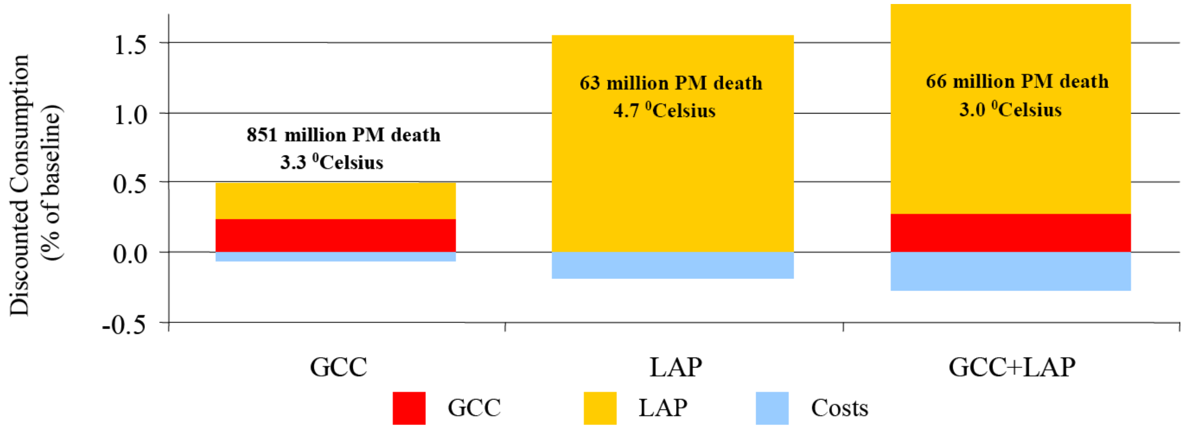


Figure 10.6.3: Changes in costs, benefits and global welfare for three scenarios (GCC, LAP, GCC+LAP), expressed as percentage consumption change in comparison to the baseline (Bollen et al. 2007). In the scenario GCC the social costs of Global Climate Change (GCC) have been internalised, in the scenario 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. (2007) have made global cost-benefit studies using the MERGE model (Manne & Richels 2004). 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 10.6.3), 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 et al. (2008) have reached quite similar conclusions in a case study for China. According to the study, the reduction of greenhouse gas 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.

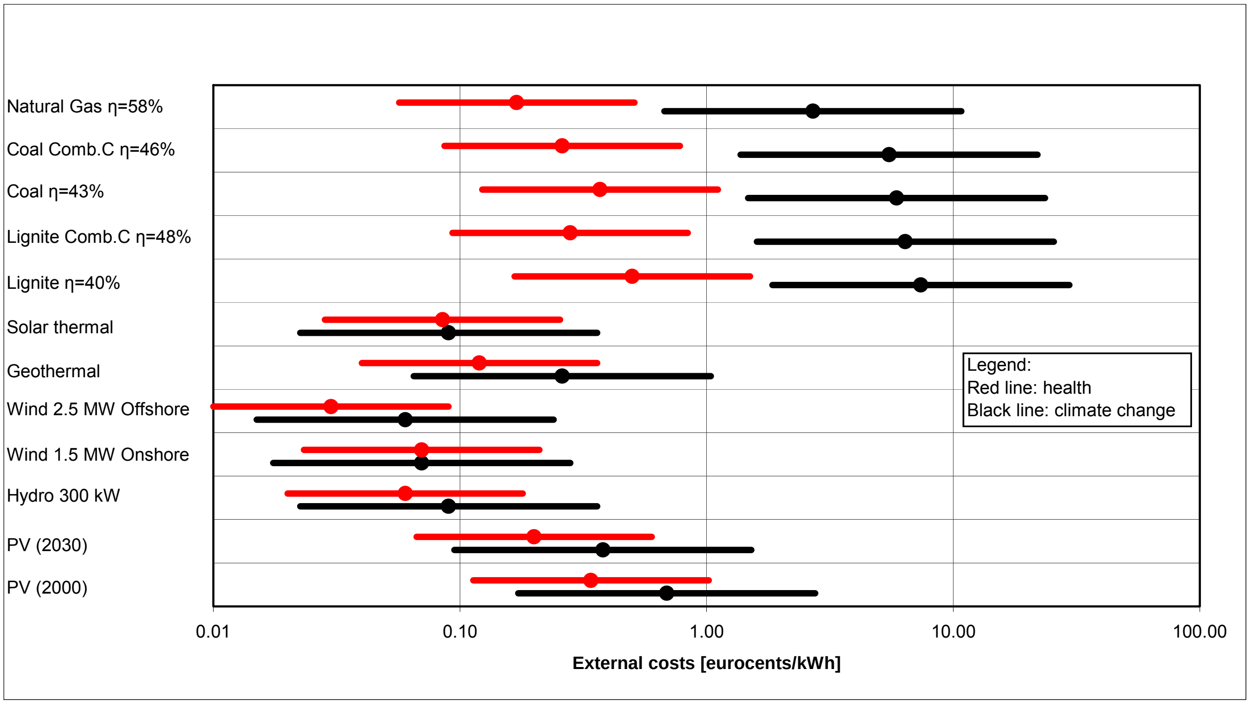
10.6.5 Summary of social and environmental costs and benefits by energy sources

To calculate the net impact in terms of social costs of an extension of renewable energies 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 (NEEDS 2009a; Krewitt & Schlomann 2006; Roth & Ambs 2004; Pingoud et al. 1999). The other thing (b) is to consider the renewable energy technologies as parts of the total energy system and society, when the impacts of a possible increase in the use of the renewable energy technologies can be assessed as causing decreases in the use and external costs of other energy sources. (Koljonen et al. 2008a; Kennedy 2005; Loulou et al. 2005).

Table 10.6.1: External costs (eurocents/kWh) due to electricity production based on renewable energy sources and fossil energy. Valuation of climate change is based on an SCC value of 70 €/tCO_2. (Krewitt & 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	0.69	0.38	0.09	0.07	0.06	0.26	0.09	7.4	6.4	5.9	5.5	2.7
Health	0.34	0.20	0.06	0.07	0.03	0.12	0.085	0.50	0.28	0.37	0.26	0.17
Ecosystems	green	green	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow
Material damages	0.009	0.006	0.001	0.001	0.001	0.003	0.002	0.015	0.008	0.013	0.01	0.005
Agricultural losses	0.005	0.003	0.001	0.002	0.0004	0.002	0.001	0.010	0.004	0.009	0.005	0.004
Large accidents	green	green	green	green	green	green	green	green	green	green	green	green
Proliferation	green	green	green	green	green	green	green	green	green	green	green	green
Energy security	green	green	green	green	green	green	green	green	green	green	green	yellow
Geopolitical effects	green	green	green	green	green	green	green	green	green	green	green	yellow
	~1.0	~0.59	~0.15	~0.15	~0.09	~0.39	~0.18	>7.9	>6.4	>6.3	>5.7	>2.9

● "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 10.6.4: Illustration of external costs due to electricity production based on renewable energy and fossil energy. Note the logarithmic scale of the figure! The black lines in dicate 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 70 €/tCO_2 and its lower limit of 15 and upper limit of 280 €/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)

An assessment of external costs is presented in Table 10.6.1 (Krewitt & Schlomannn 2006) and in Figure 10.6.4. 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. If a lower value of social costs of carbon of 15 €/tCO_2 is used in Table 10.6.1 instead of 70 €/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 10.6-4 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 (NRC, in press) 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.

Results of an other study in Figure 10.6.5 show somewhat lower external costs for different technologies (NEEDS 2009a,b) 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. 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.

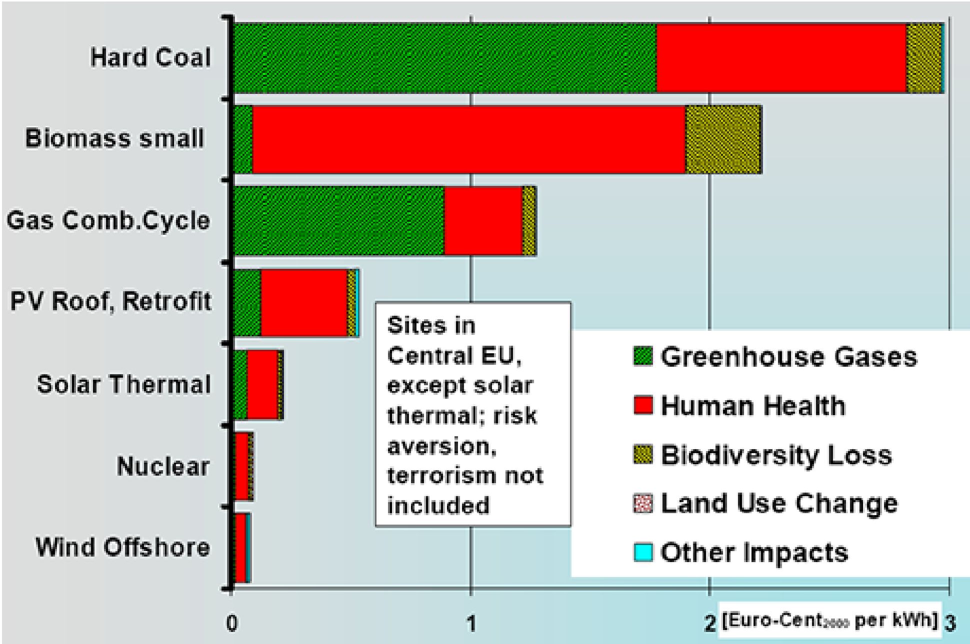


Figure 10.6.5: Quantifiable external costs for some electricity generating technologies. Estimation of external impacts and their valuation include considerable uncertainties and variability (NEEDS 2009a,b).

As only costs of individual technologies are shown in Table 10.6.1 and Figures 10.6.4 and 10.6.5, benefits can be derived when assuming that one technology replaces another one. Renewable energy 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. For example, in some cases biomass use can cause relatively high greenhouse gas emissions (Fargione et al. 2008) and particulate emissions (NEEDS 2009a).

When the share of renewable energy 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. This change can be roughly estimated in respect to climate change with the use of SCC. When renewable energy replaces fossil energy the carbon dioxide emissions from the total energy system decrease and so too do the total external costs (social benefits increase).

Increased usage of renewable energy is usually synergistic with sustainable development. In most cases the environmental damages and costs decrease when fossil fuels are replaced by renewable energy. Also the social benefits from the supply of renewable energy usually increase. In some cases, however, there can be trade-offs between renewable energy expansion and some aspects of sustainable development. Therefore, it is important to carry out Environmental Impacts Assessment (EIA) studies on renewable energy projects in consideration in order to be sure that sufficient requirements for the implementation of the projects are met.

10.6.6 Knowledge gaps

There are considerable uncertainties in the assessment and valuation of external impacts of energy sources.

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INTERGOVERNMENTAL PANEL ON climate change

Chapter 11

Policy, Financing and Implementation

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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 11 has been allocated a total of 85 pages in the SRREN. The actual chapter length (excluding references & cover page) is 108 pages: a total of 23 pages over target.

Expert reviewers are kindly asked to indicate where the Chapter could be shortened in terms of text and/or figures and tables.

Reviewers are also asked to note that a number of references in the text are not yet reflected in the reference list. At times in the text reference titles appear as full names (e.g. International Energy Agency) and others as acronyms (IEA) – this will be made consistent in consecutive drafts.

In addition, all monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to USD for the base year 2005.

Chapter 11: Policy, Financing and Implementation

CONTENTS

EXECUTIVE SUMMARY

Government policies are required for a substantial increase in deployment of renewable energy. Market signals alone - 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. 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 of RE into the existing energy system. After more than 30 years of policy experience, there is now a clear understanding of what does work and what does not. Some policies has proven efficient and effective, others have 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, none have proven themselves superior thus far.

Instrument design is key for effective and efficient policies. 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 systems long-term nature, the necessary investments in renewable energy plants, in manufacturing facilities, in infrastructure for integration and R&D rely on stable and predictable policies and frameworks. Clear, long-term, consistent signals and robust 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. Market deployment is a crucial element of any successful policy since only then can results from R&D be transferred into practice, 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 renewable energy. 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 increase the rate of deployment needed is a systemic and evolutionary process. Thus, coordination among policies and the sub-components of the enabling environment, whether economics, technology, law, institutional, social and cultural , is essential.

The global dimension of climate change and the need for sustainable economic development call for a global partnership on deploying renewable energy that recognizes diversity of countries, regions and business models. Deployment of renewable energy provides opportunities for international cooperation. New finance mechanisms and creative policies on all levels are needed to stimulate the technology transfer, investment and deployment of renewable energy. 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. With higher shares of renewable energy, 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. Today's energy system was designed primarily for fossil 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 RE to become the standard energy provider in a low carbon energy economy. This implies important changes in societal activities, practices, institutions and social norms, and government policy can and must play a role in driving this transformation.

11.1 Introduction

Capturing the potential of the globe's renewable energy (RE) resources depends on a wide spectrum of factors. The previous chapters have explained the state of technological understanding and described the required issues of integration. This chapter sets out the issues surrounding the policies, financing and implementation of renewable energy.

As noted in previous chapters, RE capacity and production of electricity, heat and fuels have increased rapidly in recent years, although most technologies are growing from a small base. RE policy trends, toward an increasing number of policy mechanisms in place in a growing number of countries, have played an important role in advancing renewables. This rapid growth has occurred mostly in a limited number of countries that have enacted strong policies to promote the development and use of RE technologies. Wherever there has been significant installation of capacity, production of RE, and investment in manufacturing and capacity to date, there have been policies to promote RE.

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, best practice policy design suited to a country's characteristics and needs, and other enabling factors. This chapter examines the policy options that are available for rapidly increasing the uptake of RE (See Table 1). It looks at which policies have been most effective and efficient to date and why, and other factors (the enabling environment) that can help to overcome the many barriers to RE and increase the effectiveness of policies.

However, the rate of installation has to increase rapidly in order to mitigate 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 have experienced limited implementation and limited policy support despite its enormous potential ((IEA, 2007; Seyboth, Beurskens *et al.*, 2008)).

11.1.1 The Importance of Tailored Policies and an Enabling Environment

There is now clear evidence of success, and the chapter highlights several case studies throughout in boxes. Although there are very limited examples of countries that have come to rely primarily on RE without supportive policies (such as Iceland with geothermal and hydropower), in most cases targeted policies are required to advance RE technology development and use, and they have played a critical role in each of the cases highlighted in this chapter.

Further, while each of these country and community case studies has seen success to date, not all policies enacted to advance RE have worked effectively and/or efficiently. The IEA (2008) 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 policies is not enough. Some countries (e.g., Germany) with relative low RE resources have achieved high levels of implementation, while some high resource countries (e.g. the UK) have not, despite the existence of government policies to advance RE.

Overall, policy is more important than resource potential in determining success (Meyer, 2003; test, 2009), and policy design and implementation are critical to this success (International

Energy Agency (IEA), 2003). 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, and robust, 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 combines economic, technological, social and cultural, institutional and financial dimensions, including both the public and private sectors. Coordination with policies related to other key and inter-linked sectors—including agriculture, transportation, construction, technological development, and infrastructure—is also important.

11.1.2 Innovation and Structural Shift

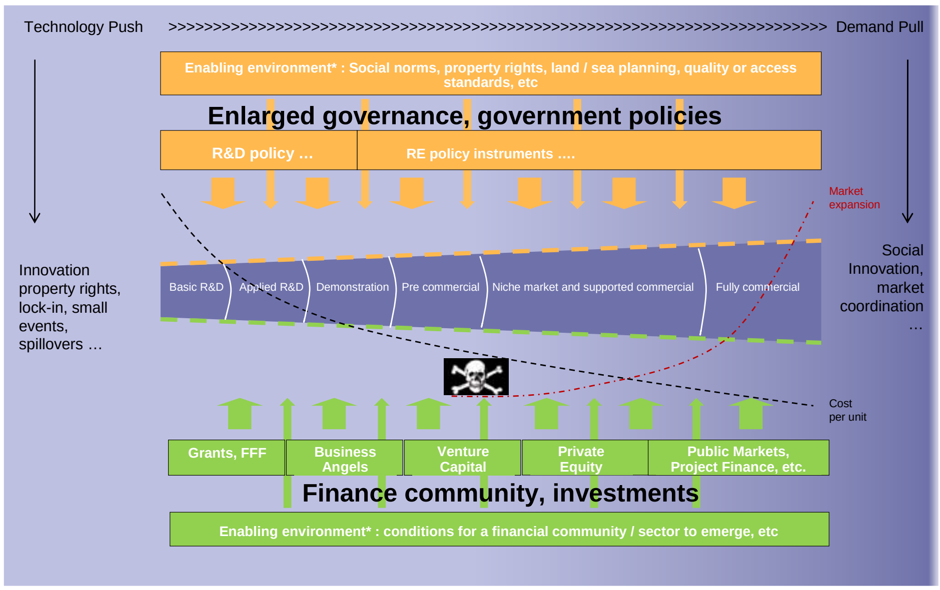
Finally, achieving a sustainable energy system, one in which RE becomes the standard energy provider in a low-carbon energy economy, will require a structural shift to a more integrated energy service approach that takes advantage of synergies between RE and energy efficiency.

To enable this shift, a combination of innovative 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 therefore a central component for the successful fulfilment of RE policies. 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 scale of innovations can be incremental (building on and improving existing technologies or practices), radical (entirely new technologies or practices), or structural (economy-wide technological shifts) (Fagerberg, 2005). Thus, while innovation is seen as important for encouraging economic, and sustainable, growth and as a means of developing competitive advantage for industry, it is increasingly understood that innovation will be necessary for addressing both adaptation and mitigation of climate change (Stern, 2006; Department for Innovation Universities & Skills (DIUS), 2008; van den Bergh and Bruinsma, 2008).

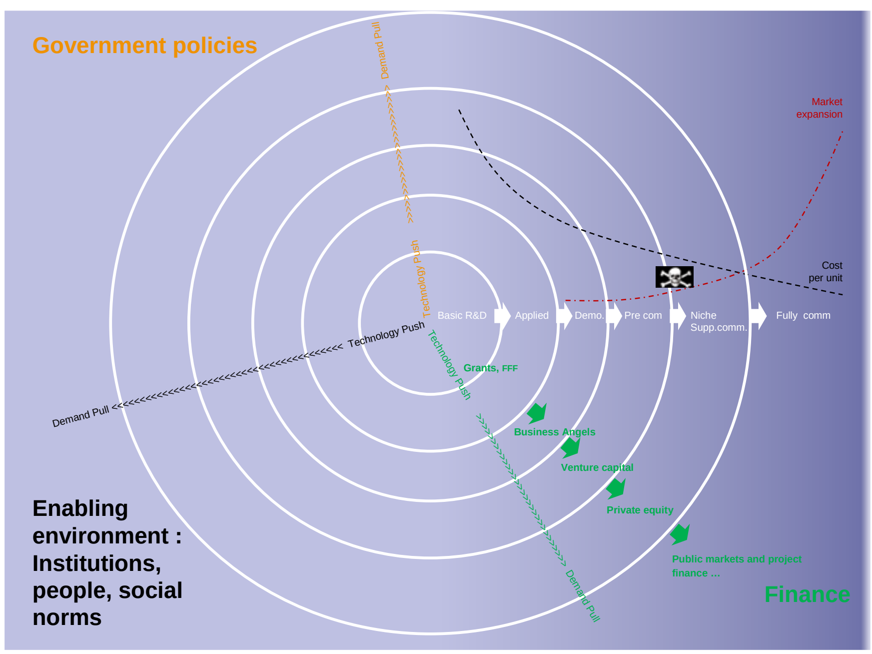
To a greater or lesser degree, the private sector is likely to pursue innovative technologies or practices in order to gain competitive advantage (Freeman and Soete, 2000). However, government also has a role to play in encouraging the development and deployment of successful innovations in the context of climate change. In other words, if they want to encourage environmentally desirable innovations, governments must use public policy in order to create supportive environments in which innovations can develop and mature (Alic, Mowery *et al.*, 2003; Foxon and Pearson, 2008). Implementation of well-designed RE policies and the creation of an enabling environment conducive to successful policy implementation would inherently be conducive to innovation (Mitchell, 2008).

Figure 1 shows that innovation is a process over time, with different phases. These include basic R&D at the front end of technology development, with a move through a number of phases to being fully commercial at the other end. However, a linear progression fails to capture the complexities of the innovation process. Figure 2 attempts to illuminate the difficulties of taking an idea or a product to full commercialization. Innovation is as much a 'demand pull' process as it is a 'technology push' process. The transition from one stage of technological development to another is not automatic; and many products and ideas fail. This has long been understood within the technology, firm and market sphere (Dixit and Pindyck, 1994; Freeman and Soete, 2000; Moore, 2002).



The innovation chain and the technology "valley of death"

Figure 1: Interaction of innovation processes between different scale levels



The innovation chain and the technology "valley of death"

Figure 2: The enabling environment of RE technologies

Government is able to encourage innovation through its R&D policies and its renewable policy instruments, but the success of an idea or technology is also linked to private investment in it. The financial community has different products and sectors to match the differing requirements of the stages in technology development. These products will be all the more successful within an environment of favourable social innovation and acceptance. Thus, Figure 2 also illuminates the importance role of individuals and society in the transformation. This is the case in both developed and developing countries.

11.1.3 Fundamental Principles of RE Development and Deployment

This chapter comes to a number of fundamental principles about RE deployment:

- Targeted RE policies are required to overcome numerous barriers that limit uptake and investment in private R&D and infrastructure and to accelerate RE deployment. Market signals alone—even when incorporating carbon pricing—have been insufficient 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. Good practice exists and it is important to learn from it.
- To be as effective as possible, policies must be well-designed and –implemented, taking into account the state of the technology, available RE resources, and responding to local political, economic, social and cultural needs and conditions.
- Well-designed policies are more likely to emerge, and they will be more effective in rapidly scaling up RE, in an enabling environment. An enabling environment combines technological, social, institutional and financial dimensions, and recognizes that technological change and deployment come through a systemic and evolutionary (rather than linear) process.
- The global dimension of climate change and the need for sustainable economic development call for new international partnerships on deploying RE that recognizes the diversity of countries, regions and business models. RE deployment can contribute to sustainable development, and new finance mechanisms are required to stimulate technology transfer, investment and RE deployment.
- A structural shift is required if RE is to become the standard energy provider in a low-carbon economy. Political will and effective policies for RE deployment will be required, in concert with improvements in energy efficiency, and important changes in societal activities, practices, institutions and social norms will be needed.

11.1.4 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 barriers to deployment of RE technologies. 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.

Table 1: List of RE Policy Mechanisms and Definitions (Metz, Davidson et al., 2007; Pachauri and Reisinger, 2007; REN21, 2007)

Policy	Definition
Biofuels blending mandates	Mandates for blending biofuels of total transportation fuel in per cent or million liters; Ethanol (E) and Biodiesel (B)
Capital subsidies, grants or rebates	One-time payments by the government or utility to cover a percentage of the capital cost of an investment
Feed-in tariff (FIT)	A policy that sets a fixed guaranteed price at which power producers can sell RE power into the electric power network. Some policies provide a fixed tariff; others provide fixed premiums added to market- or cost-related tariffs.
Energy production payments/ production tax credits	Provide investor or owner of qualifying property with an annual tax credit (against income) based on the amount of electricity generated by that facility
Green power purchasing	Voluntary purchases of renewable electricity by customers, directly from utility companies, from a third-party renewable energy generator, or through the trading of renewable energy certificates (RECs).
Hot water/ heating policies	Mandates and programmes for solar hot water/heating and other forms of renewable hot water/heating in new construction
Investment tax credit	Allows investments in RE to be fully or partially deducted from tax obligations or income
Net metering	Allows a two-way flow of electricity between the electricity distribution grid and customers with their own generation. The customer pays only for the net electricity used
Production tax credit	Provides the investor or owner of qualifying property with an annual income tax credit based on the amount of electricity generated by that facility
Public competitive bidding	Tendering system for contracts to construct and operate a particular project, or a fixed quantity of RE capacity in a country or state.
Public investment loans or financing	Provides preference to RE in government procurement, infrastructure projects and use of public benefits, funds, loans, etc.
Renewables obligation	See Renewable portfolio standard
Renewable portfolio standard (RPS)	Also called renewables obligations or quota policies. A standard requiring that a minimum percentage of generation sold or capacity installed be provided by RE. Obligated utilities are required to ensure the target is met.
Sales tax, energy tax, excise tax or VAT reduction	Reduction in taxes applicable to the purchase (or production) of renewable energy or technologies
Subsidy	Direct payment from the government or tax reduction to a private party for implementing a practice the government wishes to encourage.
Tender scheme	See Public competitive bidding
Tradable renewable energy certificates (RECs)	Each certificate represents the certified generation of one unit of RE (typically one megawatt-hour). Certificates provide a tool for trading and meeting renewable energy obligations among consumers and/or producers, and also a means for voluntary green power purchases.

1 **Table 2:** Policy Mechanisms by Category and End-Use Sector

			END-USE SECTOR	
	Policy Mechanism	**Electricity**	**Heating/Cooling**	**Transportation**
Regulatory	Feed-in tariff	X	X	
	Quota/RPS	X		
	Tendering/Bidding	X		
	Mandate - installation, capacity or blending	X	X	X
	Green power purchasing	X		
	Tradable green certificates	X	X	
	Priority access to distribution/transmission network and market	X	X	?
	Low-carbon standards?			
Fiscal	Accelerated depreciation	X	X	X
	Reduction in sales, VAT, energy or other taxes	X	X	X
	Energy production payments	X	X	
	Production tax credits	X	X	X
	Capital/investment grants, subsidies or rebates	X	X	X
	Investment tax credits	X	X	X
Govt Finance	Low-/no-interest loans	X	X	X
	Loan guarantees	X	X	X
	Capital grants	X	X	X
Other	Government procurement	X	X	X

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 or heating requirements and feed-in tariffs; fiscal policies including tax incentives and rebates; and financing mechanisms. A range of mechanisms is provided and defined in Table 11.1, while Table 11.2 summarizes what types of policies have been applied to RE in each of the three end-use sectors of electricity, heating and cooling, and transportation.

The number of RE policies, and the number of countries with RE policies, is increasing rapidly around the globe. They are also spreading from focusing almost entirely on electricity to covering the heating/cooling and transportation sectors as well. These trends are matched by increasing success in the development of RE technologies and their manufacture and implementation (See Chapter 1), as well as by a rapid increase in annual investment in RE and a diversification of financing institutions. This section describes the trends in RE policies; in R&D; and in financing and investment.

11.2.1 Trends in RE Policies

Growth in RE capacity and energy production have increased rapidly over the past several years (International Energy Agency (IEA), 2008a), with several technologies experiencing average annual growth rates in the double digits.(REN21, 2009a; United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2009) Although renewable technologies still account for a relatively small share of total global energy use, in 2008 alone the world added an estimated 65 gigawatts (GW) of new renewable electric capacity, accounting for 41 percent of total capacity additions that year.(United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2009) Several factors are driving this rapid growth in RE markets, but government policies have played a crucial role in accelerating the deployment of RE technologies (Sawin, 2001; Meyer, 2003; Sawin, 2004b; Rickerson, Sawin *et al.*, 2007; REN21, 2009a).

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, and municipal levels (REN21, 2005; REN21, 2009a). Initially, most policies adopted were in developed countries, but more recently a growing number of developing countries have enacted policy frameworks to promote RE (Wiser and Pickle, 2000; Martinot, Chaurey *et al.*, 2002). In 2005, an estimated 45 countries—including 10 developing countries—had policy targets for RE (REN21, 2005); by early 2009, the number of countries with policy targets had increased to at least 73 (REN21, 2009a). (See Figure 3) Many of these policies and targets have been strengthened over time and several countries have more than one policy in place.

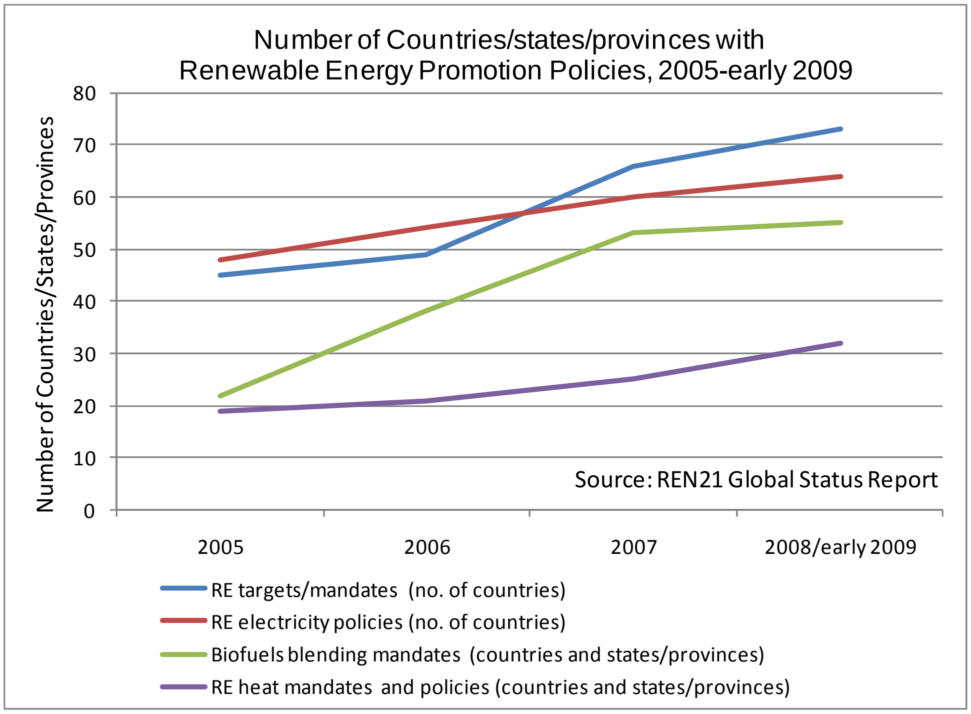


Figure 3: Number of Countries, states and provinces with RE Promotion Policies, 2005-early 2009 (REN21, 2005)[1]

Most of these targets and promotion policies have focused on electricity generation from renewable sources, with at least 64 countries adopting some sort of policy to promote renewable power generation by early 2009 (REN21, 2009a). Of these, the most common electricity policy to date has been the feed-in tariff (FIT); by early 2009, feed-in tariffs had been enacted in at least 45 countries (including much of Europe) and 18 states, provinces or territories (Mendonça, 2007; Rickerson, Sawin *et al.*, 2007; Rickerson, Bennhold *et al.*, 2008; REN21, 2009a). Renewable Portfolio Standards (RPS) or quotas are also widely used and, by early 2009, had been enacted by an estimated 9 countries at the national level and by at least 40 states or provinces (REN21, 2009a). As seen in Figure 4, RE's share of new global electricity generation has risen in line with the increase in FIT and RPS policies. The 40 GW of additional capacity in 2008, shown in Figure 4 below, represents 23 percent of the additional total global generation increase (UNEP and NEF, 2009). Many additional forms of policy support are used to promote renewable electricity, including direct capital 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).

[1] 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; and GSR 2009 Update, pp. 17-20. Note that all numbers are minimum estimates. Not all national renewable energy targets are legally binding. Overall renewable energy 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 renewable electricity promotion policies is average of 2005 and 2007 data from REN21.

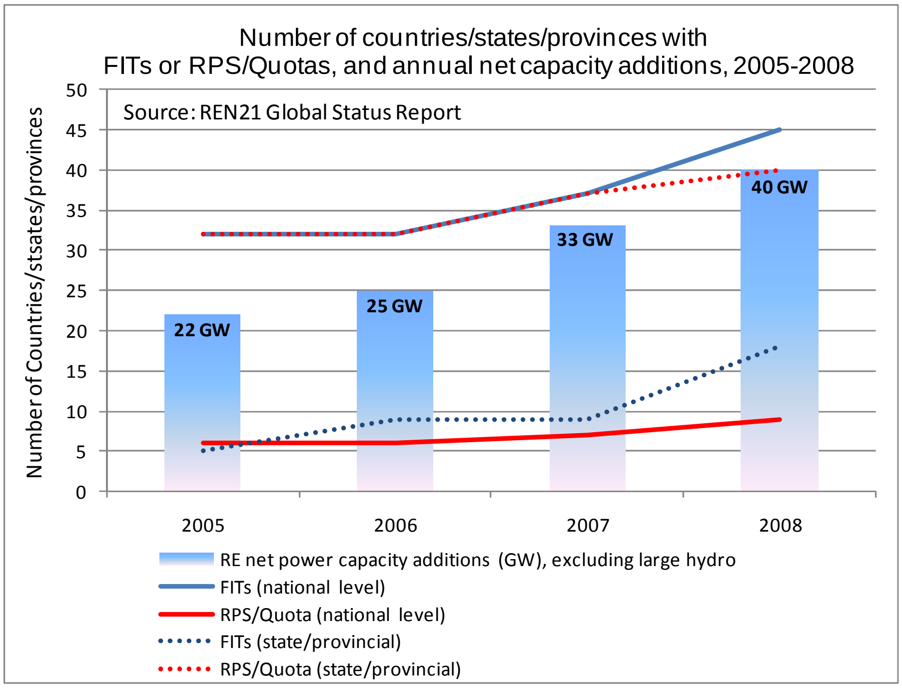


Figure 4: Number of countries/states/provinces with feed-in tariffs or RPS/Quotas, and annual net electric capacity additions (excluding large hydropower), 2005-2008. (REN21, 2005; REN21, 2009a; United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2009)

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, 2009a; Rickerson, Halfpenny *et al.*, 2009). For example, in the 12 countries analysed for the 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 (International Energy Agency (IEA), 2007). According to REN21, the number of countries, states and provinces with RE (mostly solar) heat mandates increased from an estimated 19 in 2005 to more than 30 in 2008 (REN21, 2005; REN21, 2007; REN21, 2009a). By early 2009, all European Union countries had adopted biofuels targets (most of these mandated) and several other countries and states had targets or blending mandates (REN21, 2009a).

Many countries or regions have established targets for multiple end-use sectors, or for shares of final energy consumption. Perhaps the best example is the European Union, which in 2008 confirmed its commitment to a binding target for renewable sources to provide 20 percent of final energy by 2020; member states have all established individual targets as well (REN21, 2009b).

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, 2009a). 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 percent sustainable energy systems (Droege, 2009; Sawin and Moomaw, 2009).

And, as mentioned in Section 11.1, several countries are also demonstrating that transformation can happen quickly even on a national scale. Germany, for example, had relatively little renewable electricity capacity in the early 1990s, but had become a world leader within a decade. In 2000, just over 6.3 percent of Germany's electricity came from renewable sources; by the end of 2008, the share had exceeded 15 percent thanks primarily to the German FIT (German Federal Ministry for the Environment, 2009). China was barely in the wind business in 2004 but ranked second after the United States for new installations in 2008, doubling its cumulative wind capacity for the fourth year in a row (Global wind Energy Council (GWEC), 2008; Global Wind Energy Council (GWEC), 2009b; Global Wind Energy Council (GWEC), 2009a; Global Wind Energy Council (GWEC), undated). Decentralized RE capacity, in terms of number of households with electricity access, has also been increasing rapidly (REF).

According to REN21, as of early 2009, 6 countries—China, the United States, Germany, Spain, India and Japan—represented roughly 70 percent of the world market for wind, solar and other renewable power (excluding large hydropower) generating technologies; the top four countries account for more than 61 percent of the world market for these technologies (REN21, 2009a). A handful of countries lead in the production and use of biofuels, while China alone has installed about 70 percent of total global solar heating capacity and represented 75 percent of the world market in 2008 (REN21, 2009a).

11.2.2 Research and Development Trends

11.2.2.1 Government spending on R&D

Figures collected by the International Energy Agency (International Energy Agency (IEA), 2008b)are a good guide to RE R&D spending in OECD countries up till the middle of this decade. (IEA, 2008) 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), 2008a), 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 (Jawaharlal Nehru National Solar Mission (JNNSM), 2009)and Singapore (Solar Energy Research Institute of Singapore (SERIS), 2009). But there are important exceptions to the rule. The European country whose government spends most on R&D into photovoltaic technology, Germany (EC, 2009), does so with a view to growing a competitive export industry (IEA, 2008).

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, solar energy for heating and cooling. Ocean energy has been the Cinderella of R&D funding throughout, barely receiving more R&D support than hydropower, despite the latter's greater technical maturity, demonstrated by its vastly greater presence on the market. 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 spending patterns the years since climate change began to hit the headlines routinely. Spending on wind, solar PV and concentrating solar thermal power and bioenergy averaged 431 M EUR_{2005}[TSU: Needs to be presented in 2005 US$]annually in the EU Member States over the 2002-2006 period, compared to 182 M EUR_{2005}[TSU: Also needs to be presented in 2005 US$]in the US and 77 M EUR_{2005}[TSU: Needs to be presented in 2005 US$]in Japan during the same years (EC, 2009). The International Energy Agency (IEA, 2008) notes that averaging figures over this period hides some steep increases in spending, which have occurred in UK, France, Hungary and China. Roughly speaking, the sum of Chinese spending on solar and wind R&D, which stood between 37 and 42 M USD_{2005} in 2006, approximated to that of Spain.

In Europe, the large majority of public R&D money is paid out by national governments to research teams in their country rather than entrusted to a central body empowered to fund projects across the whole region. Only 12-17 percent of public funds for RE R&D and handled by bodies other than national governments, and they are administered by the European Commission. The Commission downplays the extent to which it is valid to consider Europe as a single, unified bloc in RE R&D funding, saying that "pan-European cooperation is limited and synergies between Member States in the development of new energy technologies have so far not been fully exploited," but the EC has plans to change that (EC, 2009 and SETP, 2007).

The European Commission (EC, 2009) reports how country-level spending on nuclear energy has evolved in Europe since 1985 (it now accounts for 40 percent of all such spending on energy, down from three quarters in the mid 1980s), and provides a snapshot of how nuclear energy, fossil energy and RE spending compared against each other in 2007 (35 percent, 8 percent and 22 percent 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, 2008). The dominance of nuclear energy spending is apparent.

11.2.2.2 Private sector spending on renewables 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 the nations of the European Union (LISBON, 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 rates of 0.6 percent and 0.3 percent, respectively, which the Commission rationalizes by saying these industries are "supplier dominated".

11.2.3 Financing trends and implications for future growth

In response to the increasingly supportive policy environment, the RE sector has seen rapidly increasing levels of financing in the past few years, with $116 billion of new financial investment in 2008, up from 15.5 billion USD_{2005} in**,** as shown in Figure 5[2].

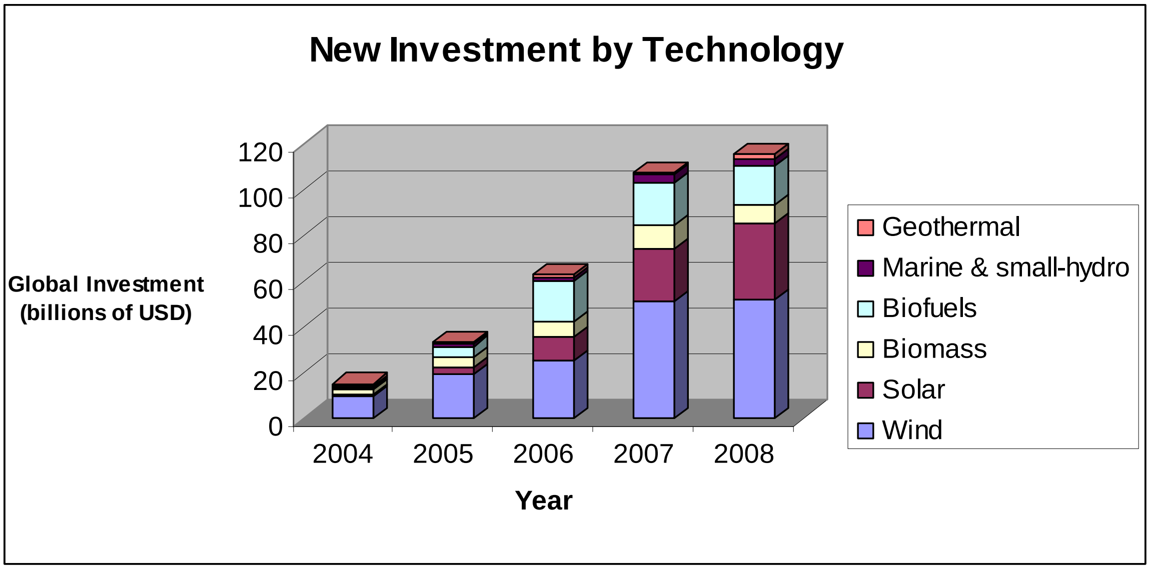


Figure 5: Global Investment in RE, 2004 – 2008, source: (United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2009)

Financing has been increasing into the five areas of i) R&D (which is covered in the previous subsection); ii) technology development and commercialization; iii) equipment manufacturing and sales; iv) project construction; and v) the refinancing and sale of companies. The trends in financing going into these areas represent successive steps in the innovation process (see Figure 11.1 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 mid- to long-term expectations for the sector – investments are being made that will only begin to pay off several years down the road.
- 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, since increasing refinancing activity over time indicates that larger more conventional investors are entering the sector, buying up successful early investments from first movers.

[2] 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.

Each of these trends is discussed in the following sub-sections. Table 3 provides information about the variety of financing types, arranged by phase of technology development.

11.2.3.1 Financing technology development and commercialization – Venture Capital Investment

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).

Table 3: Table of Financing Types Arranged by Phase of Technology Development

Table of Financing Types arranged by Phase of Technology Development	
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 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 (i.e. projects/corporate finance, bonds), 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 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. 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.
Refinancing and Sale of Companies	Mergers & Acquisitions involve the sale and refinancing of existing companies and projects by new corporate buyers.

Energies accounting for only 1-3 % 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 $204 million in 2002 to $3.456 billion in 2008[3][TSU: Needs to be presented in 2005 US$], representing a compound annual growth

[3] 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.

rate of 60%. This capital has mostly been used to finance the commercialisation of new technologies that have been developed through R&D programmes in government, academia and industry. This growth trend in innovation investments 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 (United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2009).

11.2.3.2 Financing equipment manufacturing facilities – Equity Investment

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. Private and public equity investment in RE has grown from $0.168 billion in 2002 to $18.07 billion in 2008 [TSU: Needs to be presented in 2005 US$], representing a compound annual growth rate of 118 percent (United Nations Environment Programme (UNEP) and New Energy Finance Limited (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 the first 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 (United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2009).

11.2.3.3 Financing Project Construction – Asset Investment

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 to $97 billion in 2008[TSU: Needs to be presented in 2005 US$], representing a compound annual growth rate of 59% (United Nations Environment Programme (UNEP) and New Energy Finance Limited (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 (United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2008). The financial markets have also started to value RE companies more highly than conventional energy companies, based on expectations of future market growth [Authors: Reference missing]. This is borne out by the trend started in 2007 for European utilities to spin out their RE divisions and finance them as free-standing corporate entities. The largest financial transaction globally in the RE sector in 2007 was the $7.2 billion[TSU: Needs to be presented in 2005 US$] initial public offering for Iberdrola Energias Renovables, a spin-out from the Spanish utility Iberdrola. If Iberdrola had chosen to raise capital through a share offering from the parent company, investors would have valued the business at about one-third of the value it was given as a separate listing. By listing separately three times as much money was raised, essentially based on the expectation that this business would be worth three times as much in future due to expected higher growth of the renewables sector as compared to the slower growth of conventional electricity companies.(United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2008).

11.2.3.4 Refinancing and the Sale of Companies – Mergers and Acquisitions

In 2008, $64 billion[TSU: Needs to be presented in 2005 US$] worth of mergers and acquisitions (M&A) took place involving the refinancing and sale of RE companies and projects, up from $6 billion[TSU: Needs to be presented in 2005 US$] in 2002 or 48 percent compound annual growth (United Nations Environment Programme (UNEP) and New Energy Finance Limited (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

The above-mentioned financing trends are being 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. The glossary explains definitions (see Chapter 1 and Annex 1), but broadly this chapter is differentiating drivers—as 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), from opportunities (which, for example, lead a country to invest in RE with the explicit goal of developing a new domestic or export industry, irrespective of the drivers), and from the benefits of promoting RE, which are generally the flip side of the drivers or opportunities (for example, reduced emissions, improved health, more jobs, better skills and so on). The distinctions among these factors are necessarily close and overlapping.

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, 2004).

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.

11.3.1 Climate change mitigation

RE is a major tool for climate change mitigation, its potential being the focus of this report. The degree to which RE mitigates climate change depends on many factors, addressed in the various sections of this chapter and report.

As a result, RE is an integral aspect of government strategies for reducing carbon dioxide (and other) emissions in many countries, including all member states of the European Union (e.g. (European Parliament and of the Council, 2009); BMU, 2006). Several U.S. states, including California (CEC and CPUC, 2008) and Washington (CTED, 2009), and numerous U.S. cities, from Chicago (Parzen, 2009) to Miami (Miami, 2008), have adopted RE targets and policies to advance their strategies for addressing climate change.

Developing countries are also enacting RE policies in order to address climate change, among other goals. In June 2008, in launching India's National Action Plan on Climate Change, Prime Minister Dr. Manmohan Singh said that: "Our vision is to make India's economic development energy-efficient. Over a period of time, we must pioneer a graduated shift from economic activity based on fossil fuels to one based on non-fossil fuels and from reliance on non-renewable and depleting sources of energy to renewable sources of energy (GOI, 2009)." 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 [Authors: Reference missing].

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 modern energy services, including lighting 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 also reduces 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 they can be constructed to any size 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. 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 [Authors: Reference missing].

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 China [Authors: Reference missing], Bolivia (REN21, 2009a), Tonga, Bangladesh (Urmee, Harries et al., 2009), India (Hiremath, Kumar et al., 2009), Nepal (MEST, 2006b), Pakistan (Government of Pakistan, 2006a) (Government of Pakistan, 2006), 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. 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 (Boardman, 2009). Examples of these programmes include the Weatherization Assistance Program in the United States [Authors: Reference missing] and the Carbon Emission Reduction Target in the UK (DECC, 2009).

11.3.3 Energy security

The definition of energy security, or energy insecurity, tends to alter from person to person, company to company, and country to country [Authors: Reference missing]. Energy security issues encompass

- the technical underpinnings of the energy infrastructure so that it seemlessly transports and delivers energy without failure or threat of failure;
- concerns that incentives within markets and economic regulation will not encourage sufficient investment in the energy system to ensure enough infrastructure (whether generation facilities, ports, storage and so on) to meet energy demand;
- concerns that a physical resource (i.e. oil or natural gas) will not be delivered as contracted, thereby limiting energy use and raising prices;
- concerns that the price of a physical resource, such as oil or gas, may rise to such an extent that it becomes unaffordable to increasing numbers of people, thus causing social unrest or difficulty;
- concerns that supply chains will not be able to deliver the technologies, parts and skills to enable deployment or operation of technologies, including RE;
- and concerns that the international relationships and foreign policies between countries may exacerbate concerns of resource access, including energy.

The addition of RE technologies to the broad energy mix alters these concerns 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 et al, 2006). Some U.S. states rely on solar power, wind and other distributed generators for public safety and emergency preparedness purposes (Sawin et al, 2006).

RE can diversify energy supply portfolios. 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 (Lee, Mogi *et al.*, 2009); (Katinas, Markevicius *et al.*, 2008); (Chien and Hu, 2008); (Lipp, 2007). 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). For small non-oil producing economies, RE combined with reductions in total energy demand and/or improvements in the efficiency of its use, offers the best opportunity for reducing dependence on imported fuels [Authors: Reference missing].

Even countries that are rich in fossil fuel reserves are recognizing that their fuel production could peak and begin to decline in coming years [Authors: Reference missing]. 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; Department of Trade and Industry (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 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. 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 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 current 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). The Obama Administration in the United States is promoting RE to create jobs [Authors: Reference missing].

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 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).

It is clear that 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 so on (e.g. (Sastresa, Usón *et al.*, 2009).

Rural development is often tied with the deployment of RE in developing countries. The SNV/Biogas program and AEPC in Nepal links the deployment of RE with its socio-economic development program. Slurry, 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 rope-ways (?). In much of the world, the development and availability of ICT devices and equipment have prompted companies and communities to develop electricity supply, and the easiest way is often through RE (REF). Biogas systems in Shaanxi 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[TSU: Needs to be presented in 2005 US$] (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). Rizhao in China saw the number of tourists increase by 48 and 30 percent in 2004 and 2005, respectively, after enacting policies to increase use of RE and improve the local environment (Bai, 2007).

11.3.5 Non-Climate Change Environmental Benefits

The benefits of sustainable RE 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 [Authors: Reference missing]; 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); and South Africa (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 a harmful impacts on biodiversity of plant and animal species (Intergovernmental Panel on Climate Change (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).

11.4 Barriers to RE Implementation

IPCC-WGIII (2007; AR4 Glossary) defines an RE barrier as “any obstacle to developing and deploying a RE potential that can be overcome or attenuated by a policy, programme or measure” (Intergovernmental Panel on Climate Change (IPCC), 2007b). Barriers to RE deployment range from intrinsically natural properties of particular RE sources (for example intermittency and diffuse incidence of solar radiation) to artificial, unintentional or intentionally constructed, impediments (for example badly oriented, shadowed roof surfaces; a tilted (ie not having an equal playing field) power grid access conditions against independent generators). RETD (2006: 32) adopts the IPCC approach (Renewable Energy Technology Development (RETD), 2006): “only barriers that may be overcome by human actions are examined” with omission of “intrinsically non-competitive attributes and lack of natural resources in some regions of the world .” IPCC-WGIII (2007: 810) completes its barrier definition with: “Barrier removal includes correcting market failures directly or reducing the transactions costs in the public and private sectors by, for example, improving institutional capacity, reducing risk and uncertainty, facilitating market transactions, and enforcing regulatory policies.”

Barriers to RE deployment were introduced in Chapter 1, and Section 11.6 sets out what we have called an ‘enabling environment’ which is conducive to RE deployment through the removal of hurdles or barriers to development. This section focuses on the specific literature on barriers to RE supplies[4] that is developing (Moskovitz, 1992; Nogee, Clemmer *et al.*, 1999; Jacobsson and

[4] RE supplies are resulting from combining RE resources that are tremendously large (Moomaw, 2008) with operational energy technologies for harvesting the available resources (Twidell and Weir, 2006). “Supplies” as flows of energy (power; light) or accumulation of stocks (biofuels; reservoirs) emphasizes actual effectiveness in delivering energy or energy services.

Johnson, 2000; Painuly, 2001; Beck and Martinot, 2004; Margolis and Zuboy, 2006; Renewable Energy Technology Development (RETD), 2006; Stern, 2006; Willis, Wilder *et al.*, 2009). It broadly corresponds to the nine areas below:

- There is no 'level playing field' for RE technologies, meaning that RE has to compete against other sources which have preferential treatment, whether in markets or network rules,
- RE have to exist in regulations which maintain status, including avoiding stranded assets in existing infrastructure
- The incentives for Governments and private companies to support RE development are insufficient
- Financing is either scarce or unreasonably costly for RE technologies
- Technology standards are lacking for (some) RE technologies and fuels
- Import tariffs and technical barriers impede trade in renewables
- Permits for new RE plants are difficult to obtain
- Energy markets are not prepared for RE
- RE skills and awareness is insufficient

This short section does not discuss these barriers one by one; this is left to Section 11.6. Rather this section places market and policy barriers and failures in context (Section 11.4.1); then it touches on policy barriers and failures (Section 11.4.2). Finally, in section 11.4.3, it discusses financing barriers.

11.4.1 Market and Policy Barriers[5] and Failures in context

The goal is to maximise deployment of the RE supplies (Verbruggen, Fischedick *et al.*, 2009), and this means maximising the potential of renewable energy supply. Barriers and failures 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, while being subjected to their own failures.

A diagram helps to clarify the links among various components in the RE potentials-barriers-policy chain. Figure 6 highlights the main components and relations in the policy cycle for deploying RE supplies. In reality governments, markets, innovations, energy systems are many times more complex and intertwined than a diagram can show (Grubler, 1998; Foxon, Gross *et al.*, 2005a; Foxon and Pearson, 2008; Mitchell, 2008).

[5] Depending on the goals pursued, the term "barriers" may refer to facts and conditions that should be maintained or strengthened to avoid the realization of perverse goals: for example, public opposition against nuclear power risks and weapons proliferation is a barrier for the nuclear renaissance (IEA, 2006: 134; GIGATON Throwdown, 2009: 97).

The rest of this section explains Figure 6 in more detail. However, this figure does not explicitly mention the barriers concerned with the means of accessing finance. This is discussed in greater detail in Section 11.4.4, which examines three areas: the availability of capital; financing for large scale projects; and financing for small-scale projects.

Figure 11.4: Barriers and Failures in Realizing Renewable Energy Supplies

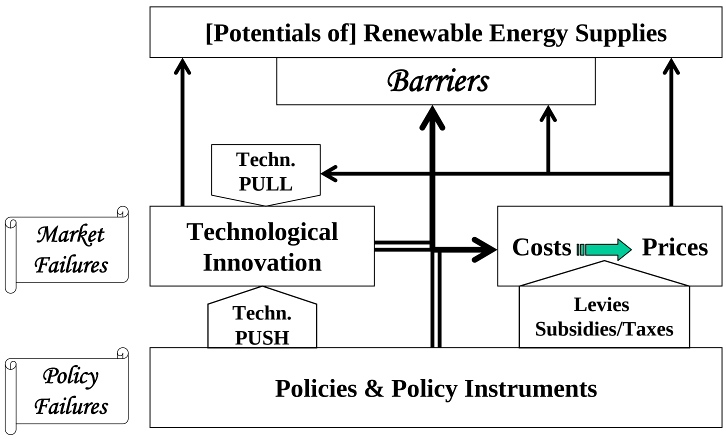


Figure 6: Barriers and Failures in Realizing RE Supplies

11.4.1.1 Market Failures

The economic literature discusses a number of important market failures (Bator, 1958; Arrow, 1974; Williamson, 1985). The bliss equilibrium of Arrow-Debreu competitive markets (Debreu, 1959; Becker, 1971) remains an ideal for some or a "gigantic once-for-all-higgle-haggle" for others (Meade, 1971).

- In practice it is not workable to organize complete "futures" and "contingent" markets to extend static market equilibriums for appropriately covering time and uncertainty (Arrow, 1974).
- Williamson (1985) criticizes that the role of institutions is suppressed in favour of the view that firms are production functions, consumers are utility functions, the allocation of activity between alternative modes of organization is taken as given, and optimizing is ubiquitous.
- The existence (predominance) of monopoly or monopsony powers in actual markets, limiting competition among suppliers or demanders, free entry and exit. Natural monopolies occur when in relation to the size of the market costs are sub-additive (Baumol, Panzar *et al.*, 1982), as in interconnected network industries (in particular electric grids). Monopoly and oligopoly power is also factual by deliberate concentration, control and collusion

- The existence of public goods and/or the absence of strictly defined and enforced property rights (Bromley, 1986). Two major cases are widely discussed and accepted as being market failures:
    - Underinvestment in invention and innovation because initiators cannot benefit from exclusive property rights on their efforts (Margolis and Kammen, 1999; Foxon and Pearson, 2008)
    - Un-priced environmental impacts and risks because economic agents are freed from internalizing in an exclusive way the full costs of their actions (Coase, 1960; Baumol and Oates, 1988; Beck, 1995).

Apart from the economics doctrine that delivers Pareto optima for whatever distribution of wealth and income, other social sciences point to the disturbing impacts of skewed distributions (Pen, 1971; Rawls, 1971; Thurow, 1971; World Commission on Environment and Development (WCED), 1987; United Nations Development Programme (UNDP), 2007). For example, poor regions of the world with abundant RE sources lack financing capacity for rolling out the apt technologies, in particular Africa (Painuly and Fenhann, 2002).

All the above standard market failures are present in actual energy markets where RE supplies compete against incumbent fossil fuels and nuclear power (International Energy Agency (IEA), 2009b). Energy markets are dominated by incumbent monopolies or oligopolies (Glachant and Finon, 2003; Thomas, 2003). Innovation of the energy systems is disrupted and retarded (Jacobsson and Johnson, 2000; Unruh, 2000; Mitchell, 2008). Major externalities and risks from fossil fuels and nuclear power are only partly priced, while non-sustainable energy supply and use often get significant subsidies (International Energy Agency (IEA), 2008b). Unequal distribution of governance, wealth and technology across and within countries blocks global progress in climate change mitigation (United Nations Development Programme (UNDP), 2007).

Failures endanger the performance of markets as efficient allocation institutions, for example monopolies exclude or limit market entry and competition, and externalities misplace incentives. Failures require repairs by market supervising authorities as governments or their appointed regulators (Kahn, 1970).

11.4.1.2 Market Barriers

Market barriers cause shortfalls to the competitive ideal. Generic market barriers stated in economics are agents pursuing satisfaction rather than optimization in production and consumption behaviour (Leibenstein, 1966), bounded rationality, principal-agent conflicts, moral hazard, and free-riding (Laffont and Martimort, 2002). Most market barriers are interwoven with institutional, social and cultural barriers. Frequently observed barriers in energy supply and use are the following (Nogee, Clemmer *et al.*, 1999; Jacobsson and Johnson, 2000; Unruh, 2000; Painuly, 2001; Fuchs and Arentsen, 2002; Global Network on Energy for Sustainable Development (GNESD), 2002; Neuhoff, 2005; International Energy Agency (IEA), 2006a; Margolis and Zuboy, 2006; Global Network on Energy for Sustainable Development (GNESD), 2007):

- **Factors favoring incumbents**: Educational assets, R&D spending, information processing and dissemination unduly support incumbent technologies and firms as distinct from potential ones failing to react quickly enough to the emergence of new generic technologies. Sequentially causing: inadequate workforce skills and training to develop, construct, repair and maintain RE installations; lacking testing and certification standards, equipment and centres; technological inertia and lockout; insufficient data and knowledge on emerging options; low awareness and slow acceptance by authorities, companies and the public.

- **Asymmetry in information and political influence**: Information asymmetry in access to data and knowledge, available staff, linked in networks, lobbying power, organizational strength, etc., across market parties, for example: incumbent centralized energy suppliers versus independent decentralized suppliers; energy suppliers versus end-users; industrialized versus developing countries; donors versus beneficiaries.
- **Split incentives and failure to internalize costs**: Cost accounting practices, tariffs for energy use with fixed and variable terms not reflecting real costs and often stimulating higher energy intensity, split incentives across market parties (building owners and tenants; owners of water rights and riverside villages; officials living in the capital and rural populations), practices of rewarding consultancy services, risk premiums imposed on new options.
- **Incumbents and sunk costs**: Incumbent interests with monopoly power stick to established technologies and practices. Their efforts to hinder new options depends on the extent of sunk investments that may strand, on disparity between existing and challenger solutions (carbon capture and storage is preferred above RE; within RE biomass is often preferred above wind and solar), on controllability of new developments via centralized capital markets. Their success rate is dependent on the strength and independency of public authorities.

11.4.2 Policies to address market failures and barriers

Section 11.5 addresses policies for RE development. This section endeavours to explain the role of different policies in relation to market failures and barriers. Governments set up institutions, policies and instruments to care for the public good. Among others this requires good designs of markets with levelled playing fields within social and environmental boundaries, ordered by transparent and enforced rules (Kahn, 1970). Stern (2006) labels climate change “the greatest and widest-ranging market failure ever seen” and recommends policies composed of “three essential elements: carbon pricing, technology policy, and removal of barriers to behavioural change”.

Public authorities must price externalities by levies (Baumol and Oates, 1988). In practice, the transformation of private and social costs in prices to be paid by end-users is mingled with subsidies, taxes and monopoly rents (Verbruggen et al., 2009). A non-sustainable energy (NSE) policy is placing significant externalities and risks on the environment and on future generations (IPCC, 2007), while RE deployment itself has relatively few externalities and risks.

Resetting the balance of the end-use energy prices between NSE and RE is a key route for developing RE market and economic potentials, directly and indirectly. Market failures and barriers will be redressed or reduced. In particular a more attractive pricing balance of RE in energy markets will pull technological innovation towards RE options (Fri, 2003; Reichman, Rai *et al.*, 2008).

‘Pulling’ RE innovations via various policies, such as a FIT or quota, is complemented by ‘pushing’ such innovations through deliberate public R&D policies (ref.), in helping to overcome underinvestment in public knowledge on social goods like RE. Technological innovation has direct impact on achieving the RE potentials (for example improved technology allows the concentration of diffuse energy flows or the better management of power grids). Indirectly, the impact of lower costs of RE technologies will contribute to re-establishing the price balance between NSE and RE, further boosting the deployment of RE and strengthening technological pull forces. “Although continued research is needed to pin down the precise magnitudes, it seems clear that economic motivations—operating directly through higher energy prices and indirectly through falling costs of technological alternatives due to innovation—are effective in promoting the expanded market penetration and use of more energy-efficient, GHG-reducing technologies” (Jaffe, Newell *et al.*, 1999). In combination with targeted policy initiatives, innovation directly reduces or removes barriers to RE deployment, for example: enhanced awareness of the values of RE, attracting researchers, improving skills and capacities; attracting venture capital, raising understanding; establishing new entrants, prime movers and organisational power which counter incumbent interests.

11.4.3 Policy barriers and failures

Governments and policies maintain a crucial position in addressing market failures and barriers that impede RE deployment. However, deployment of RE may be obstructed by policy failures as well as the aforementioned market failures. For example, governments may pick and adhere to technological options conflicting with a sustainable development of society [Authors: Reference missing], subsidize NSE (International Energy Agency (IEA), 2008a), be slow and reluctant in levying externalities and risks of NSE [Authors: Reference missing], be weak in addressing monopoly power and enforcing transparent equitable market conditions, fall short in redistributing opportunities and wealth over constituencies. Resistance to governments’ role can be due to ideology; different interests; but also to observed wide-spread policy and political shortcomings and failures.

The last decade has shown the importance of the role of institutions and regulations in transforming pervasive societal activities like energy supply and use [Authors: Reference missing]. “This new focus on regimes recognizes that firms and technologies are embedded within wider social and economic systems (Rip and Kemp, 1998). Some of the reasons cleaner technology is not diffusing rapidly through firms relate to overarching structures of markets, patterns of final consumer demand, institutional and regulatory systems and inadequate infrastructures for change” (Smith et al., 2005: 1491).

We look at policy barriers in terms of design, creation and execution. Policy design starts at the identification, recognition, and formulation of the core problems. Standard policy thinking still accepts a narrow correlation between economic growth and commercialized energy consumption (fossil fuels, grid electricity), with little attention for ambient energy supplies and for small-scale on-site extraction (Twiddell and Weir, 2006) (Global Network on Energy for Sustainable Development (GNESD), 2002). Neoclassical growth mantras are not yet balanced by institutional, evolutionary, and ecological thinking (Williamson, 1985; Gowdy and Erickson, 2005; van den Bergh and Kallis, 2009). Renewable energy is gaining acceptance as an important part of future energy supplies, but its positioning needs further clarification regarding complementary energy efficiency pathways, regarding other low-carbon energy supply options (fossil fuels with CCS, nuclear power), and regarding infrastructures in secondary energy converters (electricity, hydrogen) (International Energy Agency (IEA), 2006b; Gigaton Throwdown, 2009).

Despite many authoritative authors arguing for the necessity of "urgent and drastic" change in energy systems (Hennicke, 2004; Stern, 2006; Intergovernmental Panel on Climate Change (IPCC), 2007a), policy makers may continue follow advice by architects and beneficiaries of the foregoing energy paradigm (Mitchell, 2008). Cost-benefit analyses remain bounded by temporal, spatial and value myopia (Sawin and Moomaw, 2009). This practice delays the transition to renewable energy and may make it many times more costly than necessary (Stern, 2006; Stern, 2009). As a corollary, government choices and plans for urgent and drastic turnover to an increasingly efficient and predominantly based RE system are vacillating. Clear goal setting also implies boosting sustainable innovation regimes and operational dialoguing with stakeholders and global constituencies.

Policies and policy instruments can be ex-ante and ex-post evaluated on criteria, generally assembled under the headings of effectiveness, efficiency and equity (Verbruggen and Lauber, 2009). Performance is contingent on the goals (objectives, targets) adopted. A first and major policy failure may be setting the wrong or too weak goals. The latter case may be particularly valid in climate change mitigation policies, where understanding is developing and spreading that only the full transition from NSE to RE systems will suffice if realized swiftly (ref.). Temporally and spatially short-sighted policies do not advance such transitions, but may become a barrier in itself. 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.

Policy execution requires solid administrative capacity. It is observed for RE deployment that public administrations are inadequately capacitated, and that coordination in countries and between international and national financial institutions is ineffective [Authors: Reference missing].

The transition in knowledge basis from NSE to RE options follows natural decay patterns of NSE expertise, moreover resisted by incumbent influence in assigning R&D money to second-best low-carbon options (International Energy Agency (IEA), 2008a). In educational curricula, energy is often taught as purely technical. RE deployment needs more disciplines than mechanical engineering (Twiddell and Weir, 2006), but today's academic metrics do not necessarily promote multi- and interdisciplinary research and teaching. RE specialized research centres are few, as are diffusion and training centres and networks. Collection and verification of site-specific data on natural resources availability (micro climate, land use, topography, water flows, etc.) is available in state-of-the-art countries moving clearly to the RE transition. There, analysis and modelling, standards and certification, monitoring and control services, access to reliable data, and replication of best practices are supporting RE deployment. CDM RE projects can take off when host countries have implemented long term regulations to encourage RE projects, as did China and India but not the most deprived countries (Willis, Wilder *et al.*, 2009).

Energy sector regulatory institutions play a decisive role in designing and imposing on incumbents, transparent and RE transition oriented rules and terms of grid access and of integrating distributed electric power. Regulation can enforce fair tariffs for delivering surplus power and for acquiring back-up and complementary power (also named balancing power) by independent RE generators (chapter 8), or can be responsible for allowing barriers (SDC, 2007). Regulators often are responsible for RE support systems (section 11.5). Many countries have no, or under-staffed , regulatory offices. In other countries, governance relations between political authorities and regulators are blurred or problematic. Also capture of regulators by incumbent energy corporations is a documented phenomenon [Authors: Reference missing].

11.4.4 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. It looks first at the availability of capital; then moves on to financing for large scale projects; and lastly examines financing of small scale projects.

Private and public sources contribute to RE financing. When risks to investors are significant, public investment, or significant subsidies, or public-private partnerships (or other types of mixed financing / ownership) may be needed. This is discussed in the next section.

Most RE projects have, what is known as ‘upfront' requirements (with an exception for biomass). This means that financing is relatively more important than for competing NSE projects. The availability of finance depends on general economic conditions, on the state of development of the capital markets in various countries, on the rating of the investor, on the type and characteristics of the RE project, etc. Even CDM envisioned for technology transfer does not address the point "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 participant in the project" (Willis, Wilder *et al.*, 2009).

Developing nations with the largest potential for distributed, small-scale RE projects face the most and the highest financing hurdles due to "affordability for users and entrenched attitudes in some financial institutions. Affordability is a compound problem of low income, high upfront investment cost to obtain RE technologies, and no adequate financing mechanisms" (Global Network on Energy for Sustainable Development (GNESD), 2002). In developing and undeveloped economies, RE deployment will grow if users are able to pay for their energy services. But there are not that many financial schemes and income generating activities that allow people to pay for investment and maintenance of RE options.

The "chequered history" of donor sponsored failing RE projects causes financial institutions to perceive a lack of reliability and long-term viability of RE technologies (GNESD, 2002). This implies a strong call for robust quality control on all future RE investments especially in developing countries. However, donors providing capital continue to add strict preconceived conditions on the technology to be applied and how projects are to be managed, usually not matching the needs and priorities of recipient communities. The latter often prefer local mechanical and thermal power supplies above expensive grid power (Painuly and Fenhann, 2002). Access to funding by international institutions is difficult, even to GEF funds earmarked for RE. It continues that significant shares of the funds are spent on studies and reports, leaving too little money for actual equipment and installations on the ground and strengthening local capacity. “The transaction costs of developing smaller scale RE projects such as CDM projects (including the costs of external auditors, registration fees, consultants’ fees and legal fees for the negotiation of CER purchase agreements and power purchase agreements) may be prohibitively high compared to the volume of CERs expected to be generated” (Willis, Wilder *et al.*, 2009). Project appraisal studies often fail to incorporate important local aspects and values, also due to limited local stakeholder involvement (Jacobs, 1997; Lovins, Datta *et al.*, 2002; van de Kerkhof, Cuppen *et al.*, 2009).

In various countries, a stimulating RE policy contributed to easing of financing bottlenecks for large-scale RE projects (for example wind parks onshore and off-shore). During the 2008 financial crisis maverick developers were threatened by bankruptcy (for example Econcern, NL,…). Banks are said to lack the technical analysis capacity needed for assessing expected performance and risk of innovative RE projects (Lisbon Council, October 22, 2009).

Smaller-scale and independently owned distributed installations face more restrictive financing offers. Institutional creativity by co-operative ownership, micro-financing, energy service suppliers, and the like is still limited to niche experiments, and community-owned projects face several barriers (Walker, 2008a).

As observed for energy efficiency and other distributed small-scale mitigation options, RE investments are also facing the “pay-back gap”: 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 (Verbruggen, 2003). The pay-back gap is often hidden in the addition of high risk premiums to the time discount rates applied in project appraisal and cost-benefit studies.

11.5 Experience with and Assessment of Policy Options

Policies are necessary to overcome the large number and variety of economic, technical, institutional, social and other barriers outlined in Section 11.4. This section focuses on the range of policy options available for developing and promoting RE, including government RD&D, and regulatory, fiscal and financial instruments summarized in Tables 11.1 and 11.2. The innovation required to stimulate the take-up of new technologies encompasses government policies from basic RD&D through to those that move niche technologies to being fully commercial. This is inter-linked with various policies and investments within the private finance community which match these government policies. In addition, technologies are ‘pulled’ by social innovations and market co-ordination. And all of this occurs within the enabling environment, discussed in Section 11.6.

To the extent that literature is available, the section provides analysis of policy design and what makes various policies most effective. It covers only those specifically targeting RE advancement; a full discussion of other policies required to create an enabling environment and to drive innovation for RE is provided in the next section.

This section begins with an overview of RD&D policies and their significance for RE technology development in 11.5.1. The next three subsections examine policies to promote deployment of RE electricity (11.5.2), heating and cooling (11.5.3), and transportation (11.5.4), respectively.

Subsection 11.5.5 then looks at cross-cutting issues including government procurement and financing. The section concludes with 11.5.6 and a brief overview of lessons learned to date.

11.5.1 Policies for Technology Development

This section explores the importance of different polices for RE development that broadly fit within the overall classification of RD&D. Besides the creation of markets that stimulate private sector investment, and support for R&D, direct government intervention is needed in several areas to help technologies move through several hurdles from the innovation phase to commercial development. This section covers expenditure in Basic R&D, Applied R&D, Demonstration and Pre-Commercial as shown in Figure 1.

Table 4 below explains the stages of technological development; the type of RD&D policies or mechanisms that suit them. Gone are the days when R&D was seen as a primarily linear task which was the responsibility of governments alone. Now it is recognized that all sections of society, whether governments, private companies or individuals, play an important role in technology development. Government's primary role is to create an environment conducive to innovation and to fill gaps in a technology's development while stimulating input from other sectors where possible, as shown in Figure 7 (Smith, 2005) [TSU: Reference missing from reference list](International Energy Agency (IEA), 2008a).

11.5.1.1 Technology Development' – an integrated for the society, public and private sectors

'Technology Development' is carried out to improve an attribute of a technology. The attributes most often targeted in RE technologies are the performance as well as the cost of the delivered kWh or Btu of energy. Governments that choose to embark on a program to cut the cost of RE technology will aim to do so in a way that balances the benefits they can gain against the short-term financial burden they must put on their citizens. Among the more concrete benefits associated with technology development is the acquisition of know-how in the design and manufacture of technologies that will become increasingly important in the energy supply mix. Among the costs will be the economic costs of public support for research, development and demonstration—'technology push'—and incentives employed for achieving economies of scale in manufacturing, such as Renewable Portfolio Standards (RPS) or FITs—known as 'market pull' (discussed later in Section 11.5).

Both the process of RD&D and the enabling of economies of scale through increasing volumes of manufacture are needed for cost reduction. Table 4 outlines the technology diffusion process and shows how different mechanisms support the roll-out of a technology at different stages. Here "invention" and "innovation" phases are characterized by basic and applied research, sometimes building on a serendipitous discovery.

Table 4: Generalized illustration of the technology diffusion process (Grubler, Nakicenovic *et al.*, 1999)

Stage	Mechanisms	Cost	Commercial Market share	Learning Rate	
Invention	Seeking and stumbling upon new ideas; breakthroughs; basic research	High, but difficult to attribute to a particular idea or product	0%	Unable to express in conventional learning curve	↑ "Radical"
Innovation	Applied research, development and demonstration (RD&D) projects	High, increasingly focused on particular promising ideas and products	0%	Unable to express in conventional learning curve; high (perhaps > 50%) in learning curves modified to include RD&D (see text)	↓
Niche market commercialization	Identification of special niche applications; investments in field projects; "learning by doing"; close relationships between suppliers and users	High, but declining with standardization of production	0–5%	20–40%	↑ "Incremental"
Pervasive diffusion	Standardization and mass production; economies of scale; building of network effects.	Rapidly declining	Rapidly rising (5–50%)	10–30%	↓
Saturation	Exhaustion of improvement potentials and scale economies; arrival of more efficient competitors into market; redefinition of performance requirements	Low, sometimes declining	Maximum (up to 100%)	0% (sometimes positive due to severe competition)	↑ "Mature"
Senescence	Domination by superior competitors; inability to compete because of exhausted improvement potentials	Low, sometimes declining	Declining	0% (sometimes positive due to severe competition)	↓

At a later stage, when a technology is in the early and mid-stages of commercialization, both R&D and economies of scale through market deployment result in cost reductions, each driving the other in a "virtuous cycle" (International Energy Agency (IEA), 2003) (See Figure 7) In this virtuous cycle, investors have confidence in the technology and capital becomes easy to access, leading new companies to enter the market and to increased competition for market shares through additional R&D investment for technological improvement. It becomes possible to draw learning curves for energy technologies in this stage, which show the correlation between declining technology costs and the capacity installed (Busquin, 2003). 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).

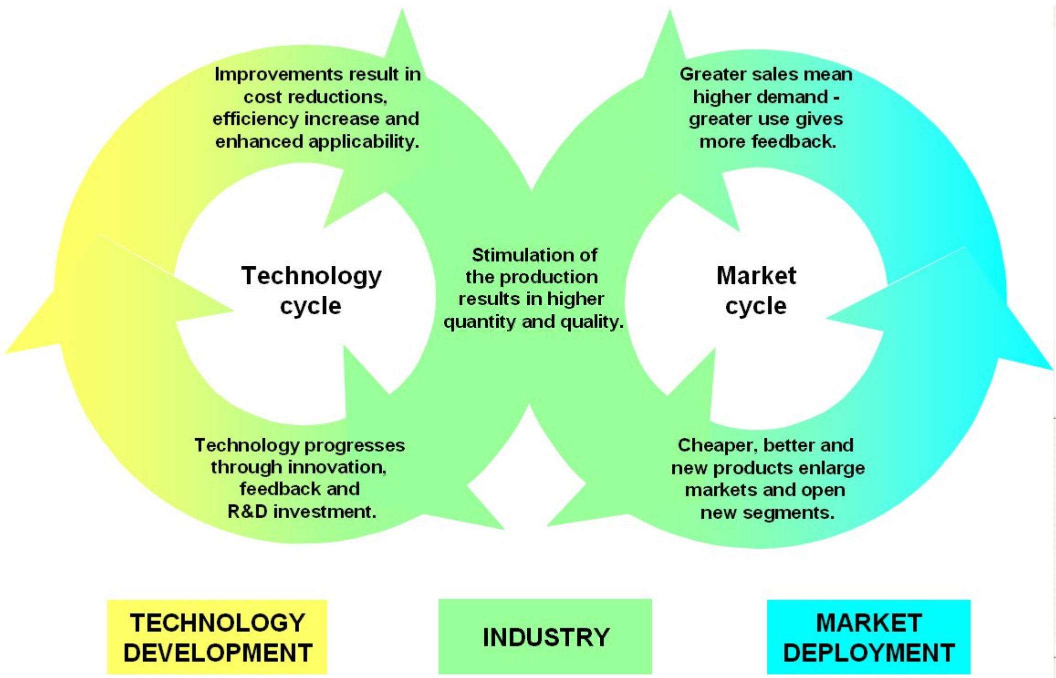


Figure 7: The mutually-reinforcing "virtuous cycle" of technology development and market deployment drives technology costs down (IEA, 2003)

To retain or increase market share, a company in the sector might choose to work on its technology to refine it, and launch an improved version. A technology sector that is in this phase can therefore take on responsibility for funding a share of its own R&D, A company is typically prepared to do this if it considers that the improved version can be launched within five years. Direct public support will still be needed for research with less certain prospects for commercialization (European Photovoltaic Technology Platform, 2009).

11.5.1.2 Policy Measures Specifically Targeting Technology Development

This section explores collaborative R, D&D, which may be all public (i.e. international centres of excellence); or may involve public private research (i.e. co-funded research; road mapping, open innovation) or stimulation (i.e. prizes). It shows that RD&D is becoming more innovative itself, as it seeks new means of tapping into potential innovators.

11.5.1.2.1 Crossing "Valleys of Death" with Public-Private Partnerships in Demonstration

As with any new technology, RE technologies are likely to traverse a period 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). This is the phase in which a technology is generating a large and negative cash-flow. In Figure 8, the maturity of the technology is on the horizontal axis, and the blocks represent measures that can help technologies to cross the valley (UNDP). The definitions of these terms are found in Table 4.

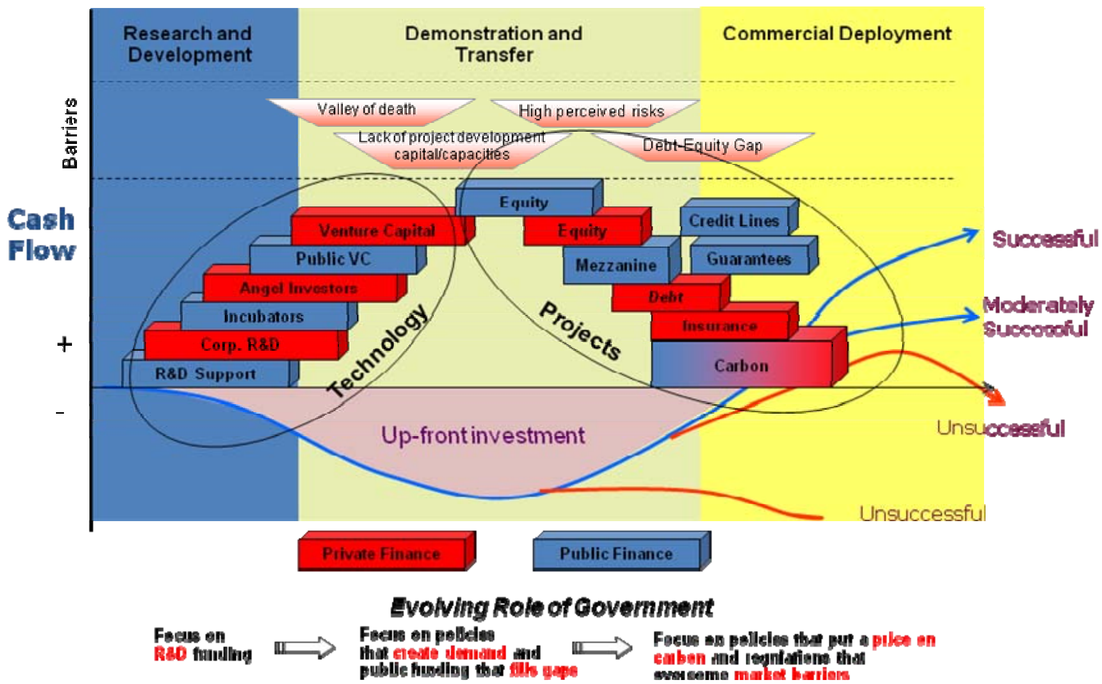


Figure 8: The Valley of Death (Kammen/UNEP/Carbon Trust)

Continued support from governments is necessary in this phase (House of Commons - Innovation, 2008). In the United States and Europe, public-private partnerships in demonstration, meaning industry-led projects to 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).

11.5.1.2.2 Government Co-funded Research

Public-private partnerships have also been developed beyond demonstration projects in order to bring incremental improvement to existing new RE technologies, such as the introduction of new material in design or changes in manufacturing processes (International Energy Agency (IEA), 2008a). In such cases, public support (e.g. grants to research or industrial consortia) is often conditional upon the research being conducted collaboratively, i.e. by a partnership of companies and not-for-profit research centres. For instance, in the EU, support to collaborative research is a policy strategy aimed at (FP7, 2006) building excellence and attractiveness, and strengthening the European industrial and technological base.

A variety of rules can govern how intellectual property is managed in these projects, with each set of rules being specific to each funding instrument. As research centres tend to be reluctant to cede the intellectual property of their discoveries, specific property right regimes, such as an exclusive licence for a fixed period, can be associated with co-funding (http://cordis.europa.eu/fp7/dc/index.cfm?fuseaction=UserSite.CapacitiesDetailsCallPage&call_id=138#infopack [Authors: need another reference]).

11.5.1.2.3 Road Mapping

Collaborative R&D 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 (International Energy Agency (IEA), 2008a). Governments can then scrutinize and adopt these plans. Road mapping has been outlined in Japan for photovoltaic technology, and in the European region (Strategic Energy Technology Plan, 2007; NEDO, 2009).

11.5.1.2.4 Internationally-Spread Publicly-Funded Research Centres

The publicly funded Fraunhofer Institute for Solar Energy Systems has long been a force in solar energy research and in technologies for efficiently using and converting energy. In 2008 it formed a partnership with the Massachusetts Institute of Technology and with the Solar Energy Research Institute of Singapore. This was followed in late 2009 with a Memorandum of Understanding creating a partnership with a science park belonging to the University of Hyderabad (Fraunhofer ISE, 2008; Solar Energy Research Institute of Singapore (SERIS), 2009; SolarIndiaOnline.com, 2009).

11.5.1.2.5 Open Innovation

'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; Jawaharlal Nehru National Solar Mission (JNNSM), 2009). Analysts have pointed to the need for financial support from governments in order to sustain the emergence of 'Open innovation' (CORNET, 2007). SMEs tend to have a short-term focus that neglects the importance of R&D, a tendency that persists in associations of SMEs which would potentially be able to contract R&D on their behalf. The offer of government money enables them to look beyond their short-term concerns and gives governments leverage in controlling the innovation strategy of a sector. (CORNET, 2007)

11.5.1.2.6 Prizes

Prizes are sometimes used to foster technology development. For example, by late 2009, ten prizes of more than $1m [TSU: Needs to be presented in 2005 US$] existed in the United States (Next Prize, 2009); a one million USD [TSU: Needs to be presented in 2005 US$] prize was on offer from the U.S. Department of Energy for storage materials for hydrogen ; and Virgin had offered $25 million[TSU: Needs to be presented in 2005 US$] for material advancement to the reduction in anthropogenic emissions (Virgin, 2009) In December 2008, the Scottish Government launched the 10 million Pound[TSU: Needs to be presented in 2005 US$] '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 Atc, 2010)

11.5.1.3 Lessons Learned from R&D

As with policies and the enabling environment, successful outcomes from R&D programmes relate not only to the total amount of funding. Carnoe 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; moreover, the Danish Government required that all those who had benefited from public money were required to provide data about reliability and output which was then published, further supporting the reliable turbines Carnoe (Carnoe REF; Sawin, 2001) –In a funding scheme for installations of innovative renewable energy technology and CCS soon to be launched as part of the European Union's revision of its Emissions Trading Scheme, proposers will be obliged to share knowledge (Directive 2009/29/EC new Article 10a(8) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0063:0087:en:PDF), specifically on reliability and performance[TSU: URLs are to be cited only in footnotes or reference list.] [Authors: Reference NEED TO WAIT FOR OFFICIAL VERSION OF CALL TEXT FOR QUOTABLE REFERENCE. CALL EXPECTED Q1 2009]

11.5.2 Policies for Deployment - Electricity

To date, far more policies have been enacted to promote RE for electricity generation of electricity 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, 2009a). A variety of support mechanisms exist for promoting renewable electricity. In developing countries, rural and off grid projects with renewables are considered in national poverty reduction strategies, energy strategies and developing plans as an adjunct to access to energy needs, a standard option of electrification (REN21, 2007).

Financial instruments compensate for the various market failures (see Section 11.4) that leave RE at a competitive disadvantage compared to conventional energy, in particular the negative externalities of fossil fuels and insecurity of energy supply. Financial instruments include investment support (capital grants, tax exemptions or reductions on the purchase of goods) and operating support (price subsidies, green certificates, tender schemes and tax exemptions or reductions on the production of electricity). Market-based instruments that provide operating support can be divided into instruments that fix a quantity of renewable electricity to be produced and those that fix a price to be paid for renewable electricity (Commission of the European Communities, 2008).

This section begins by discussing the two main types of regulatory policies that have emerged for promoting renewable electricity in developed countries and that are increasingly being adopted in developing countries. Feed-in tariffs guarantee price, while quotas or RPS (Renewable Portfolio Standards) ensure market share through government-mandated targets or quotas. It then discusses net metering and fiscal incentives for promoting renewable electricity both on- and off-grid.

11.5.2.1 Regulatory Policies

11.5.2.1.1 Feed-in Tariffs

The most prevalent national policy for promoting renewable electricity is the feed-in tariff (FIT) (REN21, 2009a), also known as Feed Laws, Standard Offer Contracts, Minimum Price Payments, Renewable Energy Payments, and Advanced Renewable Tariffs (Couture and Gagnon, 2009). FITs have driven dramatic renewable electric capacity growth in several countries—most notably Germany and Spain—over the past 15 years, and have spread rapidly across Europe and around the world (Christensen, Denton *et al.*, 2006; Mendonça, 2007; Rickerson, Sawin *et al.*, 2007; Girardet and Mendonca, 2009; REN21, 2009a).

Under feed-in laws, fixed payments, or tariffs, are paid for each kilowatt hour of renewable electricity fed into the grid, usually over a period of several years. There are several forms of FITs in operation, with the two main categories being market independent (government sets full fixed prices) and market dependent (premium price on top of the retail rate), and all have different impacts on investor certainty and payment, ratepayer payments, the speed of deployment, and transparency and complexity of the system (Couture, 2009). The costs of the FIT 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.

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). After enacting its first FIT, Germany's share of electricity from renewable almost tripled between 1991 and 2002, rising from 2.8 percent to 7.8 percent, to 15 percent by the end of 2008 (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 9 and Figure 10) Germany's system is often held up as a model, but several other countries have also experienced success with FITs. Before Spain passed a feed-in tariff in 1998 the country had little wind capacity; by the end of 2007, Spain ranked third in the world in wind installations and generated 10 percent of its electricity with the wind. Denmark, which also had a FIT in place until 2000 now generates more than 20 percent of its electricity from wind and has long been the world's wind-turbine manufacturing leader (REN21, 2009b; Sawin and Moomaw, 2009).

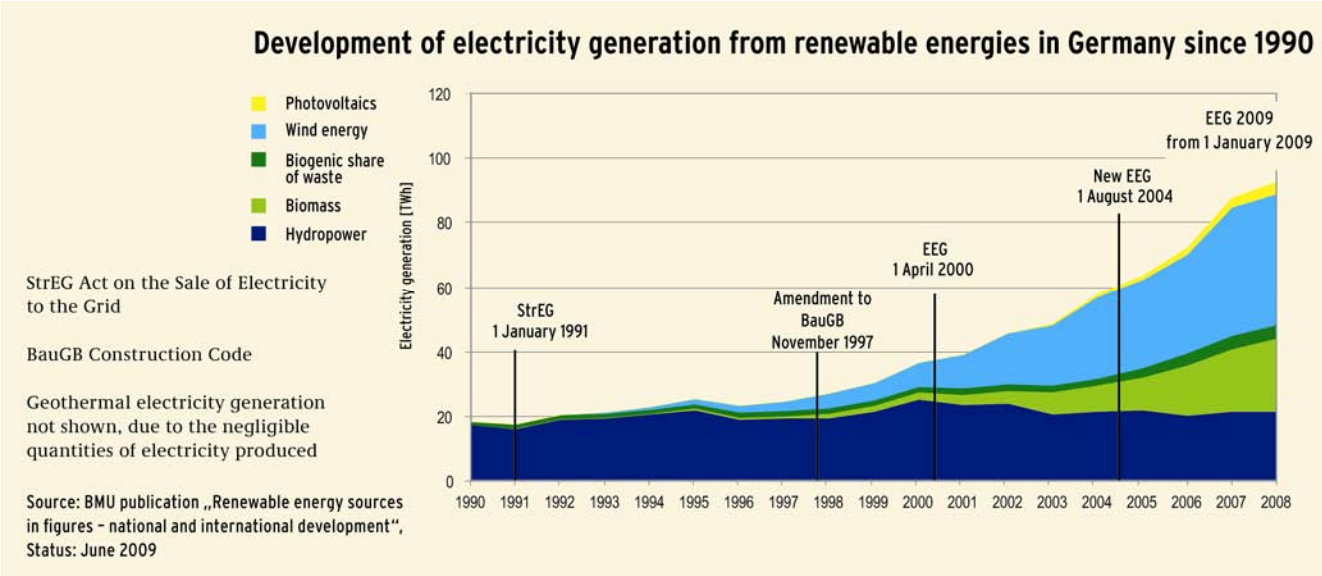


Figure 9: Development of Electricity Generation from RE in Germany, 1990-2008 (German Federal Ministry for the Environment, 2009) [TSU: Figure will need to be redrawn.]

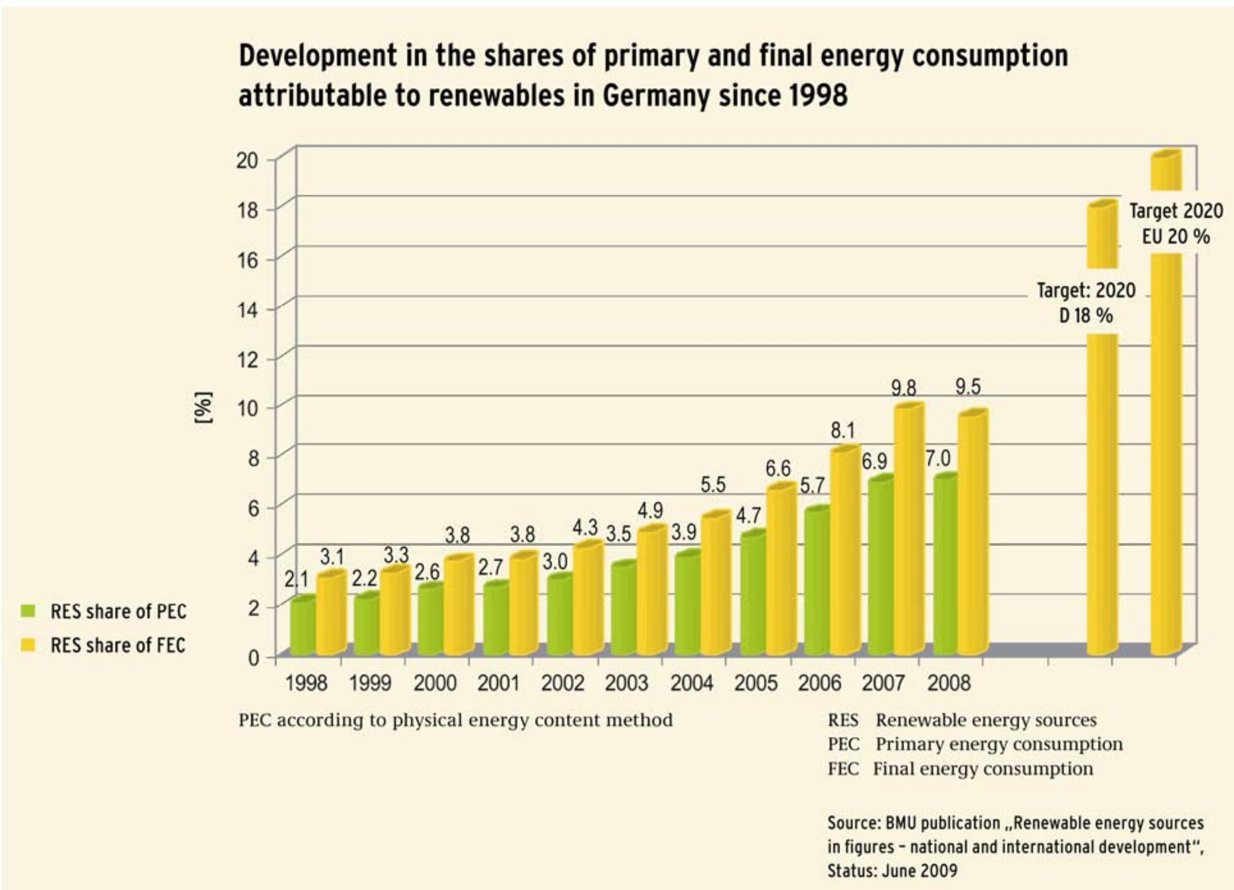


Figure 10: Development in the Shares of Primary and Final Energy Consumption Attributable to RE, Germany, 1998-2008 (German Federal Ministry for the Environment, 2009). [TSU: Figure will need to be redrawn.]

FITs can also be used to promote RE for mini-grids — small-scale electricity networks based on a local and often isolated distribution system (Mendonça and Jacobs, 2009). Van Alphen et al (2008) note that FITs are more effective than quotas for dispersed markets in small island states and for varying sizes of projects (van Alphen, Kunz *et al.*, 2008).

However, having a FIT mechanism is not necessarily enough per se to increase RE involvment. Not only do the details of the FIT matter (see bullets below) but also the enabling environment discussed in 11.6. It does come down to are not necessarily enough to increase renewable deployment (Commission of the European Communities, 2008; Fouquet and Johansson, 2008). Experiences in France, Greece and elsewhere demonstrate that high administrative barriers can hamper development even under relatively stable policy environments (Commission of the European Communities, 2008; International Energy Agency (IEA), 2008a; Lüthi and Wüstenhagen, 2009). Two studies by Lüthi and Wüstenhagen (2009a and 2009b), that focus specifically on solar PV experiences in several European countries, found that above a certain level of return, risk-related factors play a greater role in influencing investment decisions than do return-related factors. This perhaps explains why even under similar FIT policies, countries experience different outcomes in terms of capacity installations. Beyond a certain rate of return, the level of market diffusion will be highly sensitive to factors such as long administrative processes, the existence of a market cap, numerous unexpected policy changes (Lüthi and Wüstenhagen, 2009), and problems associated with grid access (Lüthi and Wüstenhagen, 2009).

Other studies of FITs have also found that development can be forestalled by lack of grid connection regulations or problems accessing the grid, onerous building approval procedures and capacity limits, lack of standards, high taxation on renewable technologies, and low tariffs or short guaranteed payment periods (Sawin, 2004b; Papadopoulos and Karteris, 2009). If tariffs are set too high, they can encourage significant development and dramatically increase electricity prices; if they are not high enough, little development will occur (Wiser and Pickle, 2000).

Success with the FITs is dependent upon the specifics of the law, and other policies enacted in parallel (Sawin, 2004b; Fouquet, Grotz *et al.*, 2005). 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 purchase
- Establish tariffs based on cost of generation and differentiated by technology type and project size; can also help to differentiate by location/resource time of day
- Ensure regular adjustment of tariffs, with incremental adjustments built into law, to reflect changes in technologies and the marketplace
- Provide tariffs for all potential developers, 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.

11.5.2.1.2 Quota Obligations and Renewable Portfolio Standards (RPS)

After feed-in tariffs, 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, such laws had been enacted 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, 2009b).

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 borne by electricity consumers. With the most common form of quota system, investors and generators comply with the quota by installing capacity, purchasing renewable electricity through a bidding process, paying a penalty or buying-out their obligation (under some systems), or, in many cases, buying “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 utilities and customers to trade, sell, or buy credits to meet obligations—provided there is sufficient liquidity in the marketplace. They can add value to renewable installations by creating a paper market separate from electricity sales, and can allow for trading and expanding RE markets between states or countries (Sawin, 2004b).

Under tendering systems, another type of quota system, potential project developers bid to a public authority for contracts to fulfil their government mandate. Projects that are considered viable and that compete successfully on price terms against other bidders are offered contracts to receive a guaranteed price per unit of electricity generated. The government often covers the difference between the market reference price and the winning bid, and contracts are generally awarded for a period of several years (Sawin, 2004b).

There are significant variations from one scheme to the next, even among various U.S. state policies (Wiser, Namovicz et al., 2007). Some state policies, such as that in Texas, have stimulated RE development at seemingly low cost, while others have not. 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). However, 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
- Set different bands by technology type
- Provide long-term targets, of at least 10 years (van der Linden, Uyterlinde et al., 2005)
- Require long-term contracts to reduce uncertainty for project developers
- 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)

11.5.2.1.3 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, 2009b). 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. The key to success in countries like Germany, Spain and Denmark has been high investment security coupled with low administrative and regulatory barriers (International Energy Agency (IEA), 2008a). This section reviews existing literature regarding effectiveness and efficiency, risk minimisation, impacts on costs and prices, technological diversity and innovation, and participation and equity.

11.5.2.1.3.1 Effectiveness and Efficiency

Because quota systems, particularly those with tradable certificate markets, do not regulate technology choice or price, many policy makers and analysts have considered them to be more competitive and market-oriented than FITs (Lipp, 2007). However, 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), 2008a; 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 (Ragwitz, Held et al., 2005; Stern, 2006; de Jager and Rathmann, 2008). Although they have not succeeded in every country that has enacted them, those countries with the most significant growth and the strongest domestic industries have had FITs (Sawin, 2004a). The IPCC Fourth Assessment Report (2007) concluded that FITs have been more effective than quotas at deploying renewables and increasing production efficiency (Intergovernmental Panel on Climate Change (IPCC), 2007b). However, some feed-in tariff systems have not been as successful as non technology-specific quota systems at developing low-cost options, such as sewage gas and certain types of biomass (International Energy Agency (IEA), 2008a).

Quotas can act as a cap on capacity installations because the value of tradable certificates drops off once the quota is achieved (Sawin, 2004b; Fouquet and Johansson, 2008). 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). In contrast, many countries with FITs—including Germany and Spain—have regularly surpassed national targets (Menanteau, Finon et al., 2003; Meyer, 2003), and some analysts consider them the most effective policy mechanism for meeting national renewable electricity targets (Ragwitz, Held et al., 2005). As a result of its success with the FIT tariff, the German government has increased its electricity target to 30 percent from renewables by 2020 (REN21, 2009b). The German government estimates that renewables avoided 100 million tons of carbon dioxide emissions in 2006, with 44 percent of this attributable to the nation’s FIT (German Federal Ministry for the Environment, 2007).

11.5.2.1.3.2 Risk Minimisation

An important factor of effectiveness and efficiency of is the policy’s accompanying investor risk. The Stern Review on the Economics of Climate Change (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.” (Intergovernmental Panel on Climate Change (IPCC), 2007b).

The higher risk under quota systems comes in a number of forms, including price risk (fluctuating power and certificate prices), volume risk (no purchase guarantee), and balancing risk; all three risks increase the cost of capital (Mitchell, Bauknecht *et al.*, 2006). While quota and tendering systems theoretically make optimum use of market forces, they have a stop-and-go nature not conducive to stable conditions. In addition to private investment-related risks, there is also the risk that low-bid projects may not be implemented (European Commission, 2005). The first wind power tender program launched in the mid-1990s in France is a case in point. It succeeded in achieving only a few MW of capacity installations because projects selected were based on bids that were too low to find investors (Nadaï, 2007).

Relatively high investment risks mean that quotas tend to favour large companies experienced in power trading, and particularly incumbent utilities (Sawin, 2004b; Mitchell, Bauknecht *et al.*, 2006; New Energy Finance Limited (NEF), 2007; Jacobsson, Bergek *et al.*, 2009). Because large players can control the price of certificates, there is a risk of gaming, particularly where penalty money is recycled back to certificate holders, as is the case in the UK (Mitchell, Bauknecht *et al.*, 2006; Agnolucci, 2007); this creates greater investment risk for smaller players (Fouquet and Johansson, 2008).

However, 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). Others have concluded that more challenging targets and better enforcement in the United Kingdom and elsewhere could improve the results of TGC systems (Mitchell and Connor, 2004; Mitchell, Bauknecht *et al.*, 2006; Fouquet and Johansson, 2008), and that quota systems in many states and countries are still quite new and thus in a transitional phase (Wiser, Namovicz *et al.*, 2007; Commission of the European Communities, 2008). The IPCC (2007) points out that quotas with TGCs delivered under long-term agreements can be effective with high compliance rates (Intergovernmental Panel on Climate Change (IPCC), 2007b).

11.5.2.1.3.3 Impacts on Costs and Prices

Quotas are generally credited with dramatically reducing the cost and price of RE through competition, and doing so more effectively than FITs, though there is some debate about the actual causes of price reductions seen to date under some quota systems (Wiser and Pickle, 2000; Espey, 2001; Sawin, 2004b; Rickerson, Sawin et al., 2007; Butler and Neuhoff, 2008; Klein, Pfluger et al., 2008). They promote least-cost projects: the cheapest resources are used first, which in theory brings down costs early on (Sawin, 2004b). According to Kildegaard (2008), "By separating the renewable attribute from the energy itself, and subsequently allowing different eligible technologies to compete in the supply of certificates, TGC markets promise to create a robust competition that minimizes the social cost [marginal cost of production] of any given level of renewable production." (Kildegaard, 2008).

In the United States, there is little evidence of a sizable impact on electricity costs associated with quotas, but cost impacts have varied from state to state and significant REC price fluctuations are possible, impeding development (Wiser, Namovicz et al., 2007). Further, Toke (2007) notes that success of the U.S. quota in states like Texas, and their ability to achieve targets cost-effectively, is greatly due to the federal production tax credit (Toke, 2007).

Most evidence shows that, at least in Europe, the higher risk present under many quota systems relative to FITs calls for higher expected returns, resulting in excess profits (Fouquet, Grotz et al., 2005; New Energy Finance Limited (NEF), 2007; Jacobsson, Bergek et al., 2009; Verbruggen and Lauber, 2009). Excessive profits are distinguished in this study from acceptable profits where higher risks are real and so required returns are higher.

Such profits primarily benefit incumbent actors and relatively mature, low-cost technologies, and can be costly for consumers (Jacobsson, Bergek *et al.*, 2009). The UK's RO scheme was intended to bring about a significant reduction in RE costs although this has not occurred (Mitchell and Connor, 2004; Jacobsson, Bergek *et al.*, 2009). Instead, several studies have shown that the UK and other European quota systems have generated renewable electricity—from wind, biogas and small-scale hydropower—at higher cost than the FIT (European Commission, 2005; Toke, 2007). A European Commission (2005) study found that, despite better wind resources in the United Kingdom, wind development there has been more costly than in any other European country (European Commission, 2005). In 2008, the German FIT premium for onshore wind ranged from 5.3-8.4 euro cents/kWh[TSU: Also needs to be presented in 2005 US$/kWh]; in contrast, in the UK, where there was a quota system, the premium was higher, with wind power at 12-14 euro cents/kWh[TSU: Also needs to be presented in 2005 US$/kWh] (Fouquet and Johansson, 2008). The IEA (2008) found that in 2005 the average remuneration levels in countries with FITs were lower than those with quotas with TGCs, due most likely to high non-economic barriers in these countries as well as intrinsic problems with design of existing tradable certificate programs (International Energy Agency (IEA), 2008a).

A 2008 analysis found that market competition (number of players) was stronger among wind turbine producers and constructors under the German FIT than under either quota scheme used in the United Kingdom (Butler and Neuhoff, 2008). FITs encourage competition among manufacturers rather than investors (Held, Ragwitz et al., 2007). They have been found to encourage development of domestic manufacturing industries, which leads to a large number of companies which creates competition (Sawin, 2004b). FITs shift competition from electricity price to equipment price, which some analysts have argued is more appropriate competition for capital-intensive RE technologies (Wagner, 1999; Hvelplund, 2001). Higher investor security (under fixed price models, in particular) enables investors to obtain capital at a lower cost, which also helps to reduce the costs of RE deployment (Couture and Gagnon, 2009). Verbruggen and Lauber (2009) demonstrate that well-designed FITs provide dynamic incentives to reduce long-run marginal costs of a variety of RE technologies because investment money is assigned to investors accordingly; more efficient producers obtain greater rents by lowering costs, and rates are regularly adjusted to avoid excessive rents. Van Alphen et al (2008) found that, in small island states with dispersed markets, FITs are also more cost-effective than tradable RE credits or tendering systems.

11.5.2.1.3.4 Technological Diversity

Quota systems have been found to benefit the most mature, least-cost technologies (Espey, 2001; Sawin, 2004b; Jacobsson, Bergek et al., 2009). As a result, on their own they cannot create markets for less mature technologies to help drive them down their “learning curves” (Sawin, 2004b). Under quota systems 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, 2008). Solar-specific RPS designs, under which utilities must purchase a certain number of solar RECs to meet their mandated quotas, are becoming more common in the United States.(Wiser and Barbose, 2008) However, without a floor price, many small companies have found it difficult to estimate a revenue stream and to obtain financing for projects, and some states have thus far fallen short of their targets (Lacey, 2009).

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). While most of the new renewable electric capacity in Germany has been wind, other renewable technologies—including biomass and solar (both small-scale distributed and centralized)—have also experienced significant growth. By the end of 2008, Germany accounted for 42 percent of the world’s grid-connected PV capacity (REN21, 2009a). Verbruggen and Lauber (2009) argue that success of the German FIT is due primarily to the careful categorizing of sources and technologies (Verbruggen and Lauber, 2009). Spain has also become a world leader in solar PV installations through its FIT (REN21, 2009a).

11.5.2.1.3.5 Technological Innovation

Quota systems involve high risks and low rewards for equipment industry and project developers, slowing innovation (Sawin, 2004b). As Unruh notes, incumbents are rarely the source of radical innovations (Unruh, 2000). Jacobsson et al (2009) found that profits attained under quotas with TGC systems are captured by incumbents, investing in the most mature technologies, rather than acquired as a reward for entrepreneurship and innovation (Jacobsson, Bergek et al., 2009). According to Lauber (2008), the high internal rate of return and windfall profits associated with quotas "divert resources from innovators to incumbents while the extra risk leads to emphasis on cheapest, short-term solutions; this discourages innovations with longer time horizons" (Lauber, 2008).

Innovation is also discouraged in cases where quotas create on–off cycles (due to bidding rounds), deterring continuous market development and making it difficult to establish a strong domestic industry as investment in production facilities will take place only with a short-term perspective. This in turn limits potential domestic job growth and economic development benefits associated with RE (Martinot and Reiche, 2000; Wagner, 2000). In contrast, FITs have been found to be the most successful mechanism for creating new jobs and strong domestic manufacturing industries (Menanteau, Finon *et al.*, 2003; Lewis and Wiser, 2005).

Under FITs, the combination of a guaranteed market and long-term minimum payments has reduced investment risks, making it easier to obtain financing and more profitable to invest in renewable technologies. By creating demand for renewable electricity and technologies, well-designed FITs have attracted private investment for R&D and manufacturing capacity, spread the costs of technology advancement and diffusion relatively evenly across populations, and enabled the production scale-ups and the installation, operation, and maintenance experience needed to bring down the costs of renewable technologies and generation (Sawin, 2004a).

Except in the case of Spain, where the premium option attracts mostly incumbent power generators, FITs have been more successful at bringing new players into the market (Verbruggen and Lauber, 2009). Stenzel and Frenzel review renewable energy generators in the UK, Spain, Germany and Sweden. They showed that in the UK, 85 percent of renewable energy generation is owned by the ex-monopoly companies etc etc. However, in Spain where an ex State company is the main renewable energy developer, 50 percent of the market share is made up of small, new entrant companies (REF).

Bürer and Wüstenhagen (2009) found that, because FITs effectively reduce risk, venture capital and private equity investors perceive FITs to be the most effective policy to stimulate investment in RE technologies. They surveyed 60 European and North American cleantech investors who rated FITs higher than any other of 12 policy options provided, while quota mechanisms ranked among the least preferred market-pull options, followed only by the Kyoto trading mechanisms (Bürer and Wüstenhagen, 2009).

11.5.2.1.3.6 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) Further, 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). 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). The most important benefits associated with community ownership are that "it increases public acceptance of wind generation, represents an additional source of capital to build the industry, and increases the potential for distributed generation benefits."(Barry and Chapman, 2009).

Many analysts argue that quota systems primarily benefit incumbent actors, which enables them to continue controlling the market and introducing RE at their own pace (Girardet and Mendonca, 2009; Jacobsson, Bergek *et al.*, 2009; Verbruggen and Lauber, 2009). In contrast, 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 broad public support for renewables (Damborg and Krohn, 1998; Sawin, 2001; Sawin, 2004b; Hvelplund, 2006; Mendonça, Lacey *et al.*, 2009). Mendonça (2007) compared the UK RO to the German FIT and found that the UK system has low public acceptance, while public acceptance in Germany is high (Mendonça, 2007).

Alongside the debate about FITs versus quotas, in which the assumption is that the two policies are contradictory, are several other schools of thought. Some experts propose that FITs might be most appropriate for smaller-scale projects and emerging technologies, while quota systems might be best used to promote near-market renewable technologies that are well-established and compete favourably with conventional energy (Sawin, 2004b; Midttun and Gautesen, 2007; Rickerson, Bennhold *et al.*, 2008). In other words, it is argued, which policy mechanism is most appropriate depends on the level of maturity of the technology in question. Yet others argue that institutional settings (Dinica, 2008), are more important than the policy instrument.

The European Commission (2008) and others find that the clear distinctions between the two mechanisms have faded somewhat and there is a convergence of policies as countries learn from past experiences and improve their policies (van der Linden, Uyterlinde et al., 2005; California Energy Commission and California Public Utilities Commission, 2008; Commission of the European Communities, 2008) For example, states and countries with quota systems have begun enacting technology-specific obligations and requiring long-term contracts, including a number of U.S. states, while some with FIT policies adjust payments over time to account for changes in the market place and to encourage cost reductions (Commission of the European Communities, 2008). Generally, however, FITs are added to quota mechanisms rather than the other way around.

FIT policies on top of existing quota mechanisms, such as Renewable Portfolio Standards, can potentially provide: a steady stream of revenues required for obtaining project financing, and a high enough rate of return to support the additional risks that come with new or emerging technology projects; cost-effective procurement alongside or in place of competitive solicitations; a hedge against project delays and cancellations, since any qualified generator can obtain a supply contract; and rate-payer backing, which reduces risks to utilities (Couture and Gagnon, 2009; Couture and Gagnon, 2010). In the United States, several states now have fixed-price systems in place alongside RPS laws (Rickerson, Bennhold *et al.*, 2008; Cory, Couture *et al.*, 2009). FITs are being used or are under consideration to help meet RPS goals and/or to target specific policy goals, including advancing emerging technologies such as solar PV, enabling small-scale residential or community projects, and promoting in-state manufacturing, just as FITs have done in Europe(Rickerson, Sawin *et al.*, 2007) . Flanders moved PV out of the TGC mechanism in 2002 (Verbruggen and Lauber, 2009). The UK is implementing a FIT from 2010 for under 5 MW power plants. It is not that the two systems are combined, but they work in parallel.

Such developments demonstrate that policy makers are willing to consider using both mechanisms side-by-side and that FITs and quotas can function alongside one another. (Rickerson, Sawin *et al.*, 2007). Existing programs have rather simple structures and have seen limited success, although most are fairly new policies and time and research will be required to determine how effectively the mechanisms interact (Cory, Couture *et al.*, 2009).

11.5.2.1.4 Net Metering

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).

Net metering is considered a low-cost, easily administered tool for motivating customers to invest in small-scale, distributed power and to feed it into the grid (U.S. Department of Energy, 2008). According to the U.S. Department of Energy, "It increases the value of the electricity produced by renewable generation and allows customers to 'bank' their energy and use it a different time than it is produced giving customers more flexibility and allowing them to maximize the value of their production. Providers may also benefit from net metering because when customers are producing electricity during peak periods, the system load factor is improved." (U.S. Department of Energy, 2008).

Because laws differ greatly from place to place and are intertwined with other policy mechanisms and incentives, it is difficult to demonstrate specific cause and effect. 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).

According to Rose *et al* (2008), the best results are achieved when net metering laws do not limit system size or overall capacity, allow monthly carryover of excess electricity and permit customers to keep their RE credits, permit all renewable technologies and customer classes to participate, and protect customers from unnecessary red tape (Rose, Webber *et al.*, 2008). In this way, net-metering is an important stimulus for small-scale RE projects supported by a FIT, because other ways of integrating such projects (their surplus, back-up and make-up electricity flows) may grow cumbersome and become a way for incumbents to reap a significant share of the benefits (Verbruggen and Lauber, 2009).

11.5.2.2 Fiscal Incentives - Investment and Production Subsidies

Financial incentives of various forms—based on investment or production, and including tax credits, rebates and grants—can reduce the costs and risks of investing in RE by lowering the up-front capital costs associated with installation, increasing the payment received for energy generated with renewable sources, or reducing the cost of production.

Such incentives have been used extensively over the years in Europe, Japan, the United States and India, and more recently in several other developing countries, including Argentina, China and the Philippines (Sawin, 2004b). They can be used to promote centralized and/or distributed power generation, for both on- and off-grid systems—for example, Uganda offers an investment subsidy for off-grid solar PV (REN21, 2009a).

The impacts of production and investment support instruments like investment grants and tax rebates are difficult to measure as they are generally used as supplementary policy tools (European Commission, 2005; Klein, Held *et al.*, 2008). In the European Union, for example, only Finland and Malta use tax incentives and investment grants as their main support schemes (Klein, Held *et al.*, 2008). They have also been used as the primary means of support at the national level in the United States (Database of State Incentives for Renewables & Efficiency (DSIRE), 2009).

Tax credits can include income tax deductions or credits, VAT reductions, or property tax incentives, among others. To encourage investment in renewables in the 1980s, the U.S. government and state of California offered investors credit against their income taxes, allowing them to recoup a significant share of their investment in the first few years, thereby reducing their risk. The tax credits played a major role in a California wind energy boom, and the lessons learned and economies of scale gained through this experience advanced wind technology and reduced its costs (Sawin, 2001). India experienced a similar boom a decade later, sparked by a combination of investment tax credits, financing assistance and accelerated depreciation (Sawin, 2004a). But in both cases, investment-based subsidies combined with a lack of technology standards or production requirements encouraged wealthy investors to use wind farms as tax shelters, and many projects performed poorly; some in California never generated a kilowatt-hour of electricity (Cavallo, Hock *et al.*, 1993).

The European Commission (2008) determined that the effectiveness of fiscal incentives such as tax reductions or exemptions (e.g., from carbon taxes) depends on the applicable tax rate. In the Nordic countries, which apply relatively high energy tax rates, such tax exemptions can be sufficient to stimulate the use of renewable electricity; however, in countries with relatively low energy tax rates, they must be combined with other measures (European Commission, 2005). The current U.S. federal investment and production tax credits (which provide a credit against income tax for each kilowatt-hour of electricity produced), first enacted in the 1990s, have created strong growth in the nation’s wind and solar markets, but only when the credits have been in place for multiple years (Farrell, 2008), and only in those states with additional incentives (Sawin, 2004a).

Accelerated depreciation has been successful in encouraging small-scale wind in Sweden and Denmark, in particular, with depreciation rates of 30 percent. In Denmark, this policy contributed to a significant increase in farmer-owned wind turbines during the mid-1990s (Buen, 2005; Barry and Chapman, 2009).

In general, those countries that have relied heavily on tax-based incentives have often struggled with unstable or insufficient markets for wind power or biogas, for example (Lewis and Wiser, 2005). In the United States, this is due in part to the on-off nature of the tax credits, but could also result from the fact that only a small number of players have enough tax liability to take direct advantage of the credits, particularly the production tax credit (Metcalf, 2008). This challenge can be addressed by making tax policies more inclusive or finding other policies that encourage broader participation.(Mendonça, Lacey *et al.*, 2009)

Beyond tax measures, some countries, like Japan and several U.S. states, have subsidized investment through grants or rebates and have been successful in promoting increased capacity (Sawin, 2004a). Grants and rebates can play a significant role in increasing market penetration of small, customer-sited projects particularly for emerging renewable technologies (Wiser and Pickle, 1997). They do not require a long-term policy and financial commitment to each specific project (Wiser and Pickle, 1997), but they have often failed to provide the stable conditions required to promote market growth and thus may not be effective at driving broad adoption of RE (Lantz and Doris, 2009). Rebate programs function well when the rebate amount is tailored to existing market and policy conditions, when they are matched with a clear set of goals, and when used to advance technologies from the prototype stage to mass production (Lantz and Doris, 2009).

Financial incentives tend to be most effective when combined with other policy mechanisms (International Energy Agency (IEA), 2008a). Japan's solar roofs program of the 1990s and early 2000s combined rebates that declined over time with net metering, low interest loans and public education. As a result, during the period 1993- 2003, PV capacity in Japan increased at an average annual rate of 43 percent, system costs dropped by more than 80 percent, and Japan became the world's leader manufacturer of solar PV (Sawin, 2004a).

Experience to date suggests that payments and rebates may be preferable to tax credits because the benefits of payments and rebates are equal for people of all income levels and thus promote broader investment and use (Sawin, 2001). Also, because they are generally provided at or near the time of purchase or production, they result in more even growth over time (rather than the tendency to invest in most capacity toward the end of a tax period) (Sawin, 2001). The European Commission (2008) has found that tax-based incentives tend to promote only the most mature and cheapest available technologies (Sawin, 2001). In addition, according to a 2009 UN Environment Program report, the global economic slow-down of 2008-2009 made clear that markets driven by tax credits are generally not effective in a downturn (United Nations Environment Programme (UNEP) and New Energy Finance Limited (NEF), 2009).

Incentives that subsidize production are generally preferable to investment subsidies because they promote the desired outcome—energy generation (Sawin, 2001). However, policies must be tailored to particular technologies and stages of maturation, and investment subsidies can be helpful when a technology is still relatively expensive. Many have argued, for example, that wind power never would have taken off in California in the 1980s without investment credits because the risks and capital costs were high. Alternatively, production incentives can be paired with other policies that help to reduce the cost of capital (Sawin, 2001).

11.5.2.3 Integration and Market Access for RE Electricity

Chapter 8 is focused on cross-cutting integration issues, and this section does not replicate that discussion. However, there are policies that promote RE access to networks and successful incorporation with markets, and this section briefly discusses that topic.

11.5.2.3.1 Connection, charging and grid access.

RE projects need to connect to networks in order to sell their electricity. The ease, and cost of doing this, is also central to the ability for projects to raise finance..Once connected, the generation has to be sold or ‘taken’ by the network. These two requirements: connection and then sale of generation are two different requirements and it is important that barriers to both are overcome.

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 offtake 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 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). 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 (Verburggen and Lauber, 2009; Jacobbson et al, 2009).

11.5.2.3.2 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. 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 policy 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, 2008). 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 (Rodriguez, JM et al., 2008). In parallel, it helps RE if electricity markets incorporate shorter timescales relative to the traditional model of long-term bilateral contracts, through spot markets, and shorter gate closure times within such markets enable faster response to fluctuating supply and demand. An increasingly flexible approach to trading reduces the impact of forecast errors, both in supply and demand, and increases access to the existing flexibility resource, reducing the need for additional fast response power plants, interconnection or storage [IEA, 2008]. 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 O., et al, 2008].

11.5.2.4 Policies for Rural and Off-grid Electrification

Although success stories for off-grid electricity programs are still limited, there are examples of successful mini-grid programs in rural areas. 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. Benefits of this system included creation of a large market to provide critical mass for commercially sustainable business 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. The government subsidized 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 et al, 2000). This system has been duplicated in a number of other developing countries, including Benin, Cape Verde, South Africa and Togo (Osafo and Martinot, 2003; Reiche et al, 2000).

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).

In the early 2000s, the Chinese government undertook an ambitious program to electrify—with mini-grids—more than 1,000 townships within 20 months. The effort began with township "seats," followed by an additional 20,000 administrative villages (Ku et al, 2003).

11.5.3 Policies for Deployment - heating and cooling

Currently, heating and cooling processes account for 40-50 percent of global energy demand *(IEA, 2007; Seyboth, Beurskens et al., 2008)* with consequent implications for emissions from fossil fuels. Historically, renewable energy policy has focused on renewable electricity initially, with increasing activity in support of biofuels for transportation over the last decade. However, renewable energy sources of heat have gained support in recent years as awareness of its potential has been increasingly recognized.

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 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., 2009)*. A significant complicating factor as regards application to heat is that care must be taken to ensure that subsidies are not spent on generation that does not meet demand. 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 biomass based substitute natural gas, for example *(Connor, Bürger et al., 2009)*. 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 various investment incentives; regulatory policies (including mandates); and educational efforts (as discussed in 11.6) and there is significant potential for other instruments to also be applied. *(DEFRA/BERR, 2007; Bürger, Klinski et al., 2008; Connor, Bürger et al., 2009)*

11.5.3.1 Investment incentives

There are a wide variety of financial incentive instruments that can be applied with the aim of addressing the investment cost gap between RE and current conventional direct or indirect heating or cooling technologies. These can be categorized into financial incentives and fiscal incentives.

Financial instruments include capital grants and rebates, operation grants, soft loans, fixed bonus payments against generation and tradable certificates earned for renewable generation.

11.5.3.1.1 Capital Grants and Rebates

Capital grants and rebates assist directly with reducing the capital investment of a plant, with a government typically providing a certain level of financial support, for example a refund per megawatt of installed capacity or a percentage of total investment, up to a specified 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 instruments applied 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., 2009)*. They are easy to apply but their relative economic efficiency has led to recent efforts in some nations to devise new instruments. 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, 2007; Roulleau and Lloyd, 2008; Walker, 2008b; Gillingham, 2009)*.

11.5.3.1.2 Bonus Mechanisms and Quotas

The bonus mechanism and the quota or renewable portfolio standard (RPS) are the two key variations for RES-E. The bonus mechanism (roughly, the equivalent to the RES-E feed-in tariff) 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.

The quota mechanism awards tradable certificates per unit of renewable energy generated while at the same time obliging energy supply companies to purchase a minimum amount of energy, represented by the certificates, thus creating a market and a demand for the certificates. Funding of this nature is beneficial in that it incentivises developers to maximise energy output, a considerable advantage over grants. The comparative usefulness of tariffs and quotas has been the subject of considerable debate as regards application to RES-E, with growing evidence to suggest that tariff mechanism may have the advantage as regards delivery and economics *(IEA, 2008; Couture and Gagnon, 2010)*.

Currently, no RES-H/C centred quota mechanism has been applied in practice. Efforts to legislate a RES-H quota mechanism in the UK in 2005 were unsuccessful. The UK has now adopted legislation for a RES-H bonus mechanism with a projected April 2011 adoption (DECC, 2009). Germany also favours a bonus mechanism for RES-H, but legal issues have prevented adoption as yet.

Key differences between the RES-E tariff and the RES-H bonus include the many more renewable heat generators expected and the fact that generation will generally be at the same site as the load. This has the potential to see substantial complexity and costs due to metering and administration. The proposed solution is via 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)*. Assessment of the level of subsidy on this basis will require either metering (more appropriate for large-scale application) or some form of estimation of output, and of how this matches demand, based on assumptions about load, weather conditions, location and other factors in order to draw conclusions concerning about the level of subsidy that should be applied *(Bürger, Klinski et al. 2008)*.

11.5.3.1.3 Financing

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, 2007). 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, 2007).

11.5.3.1.4 Tax Policies

Fiscal incentives include tax credits, reductions and exemptions and accelerated depreciation of capital expenditure. Fiscal incentives are another tool for lowering the financial burden of investing in RE, as with financial instruments setting the correct level of incentive requires care to ensure expansion without an excessive public burden (IEA 2007).

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. 2009)*.

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.

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, 2007).

Parallel to the level of support, it is important to consider the level of technological and market maturity of the RET at issue. Some support instruments will be more appropriate to early growth while others will be more useful as technologies approach commerciality *(Foxon, Gross et al., 2005b; Connor, Bürger et al., 2009)*. For example, investment tax credits might be more appropriate for an early deployment of high cost, emerging technologies; whilst production tax credits would apply to more mature technologies, providing tax relief for the amount of heat actually produced, and therefore, also favouring target achievement *(Foxon, Gross et al. 2005)*.

11.5.3.2 Regulatory Issues

There are a number of ways for regulation to impact on development of renewable heating and cooling.

One simple application is to mandate the inclusion of the basic 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. Integration of the technology for later connection to district heating or cooling is one potential application that might have a better fit with later investment *(Connor, Bürger et al. 2009)*.

Applications of building regulations can go as far as compelling the adoption of RES-H/C technologies, as in the case of the ‘Use Obligation’ instrument. 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. Early applications tend to compel new buildings to ensure a specified fraction of energy use is from renewable sources, with variations as to the eligible technologies. The goal is the stimulation of an initial market for the technology and of the attendant necessary infrastructure. More stringent variations may compel that RE sources be included in refurbishment. The main criticism is that the instrument can place costs arbitrarily and unfairly, with particular stakeholders bearing the brunt of stimulating new technology. 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 (Bürger, Klinski *et al.*, 2008; Puig, 2008).

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. Moreover, the obligation on new buildings can help to create a minimum critical mass within the market, thus leading to lower costs and higher use of renewable heating technologies *(ESTIF 2006).*

As with other support instruments, 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 ensure proper compliance with the mechanism; a monitoring system including periodic examinations of installations and/or minimum quality standards is advisable *(Connor, Bürger et al., 2009)*. Restriction of non-compliance is fundamental to the success of the use obligation (Bürger, Klinski *et al.*, 2008).

While appropriate application of building regulations could assist with the growth of renewable heating and cooling there is a potential for conflict concerning application of building regulations concerning energy efficiency. Where efforts are being made to compel increases in the energy efficiency standards of new buildings or upgrades of old buildings, optimal benefit is likely to result from a coherent approach that ensures regulations are complementary and avoids potential unnecessary costs through, for example, overcapacity (Connor, Bürger *et al.*, 2009).

Where additions to buildings are compulsory, 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.*, 2009).

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).*

One interesting 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. District heating (DH) is the grid based delivery of heat energy to domestic or other premises, with the aim of improving efficiency of energy use, with grids varying from the small- and local-scale to city-wide installations. Despite considerable potential there are a number of potential problems with expansion of DH. Much of the costs associated with DH come from the initial investment in infrastructure for heat (or cooling) delivery, making the technology unattractive to investors. Since ensuring a return on this investment will require some years of supplying heat, the question of regulation becomes a complex choice of whether to allow closed or open competition, including allowing third party access to the grid, or to allow consumers to use other heat sources *(Grohnheit and Mortensen, 2003)*. Third Party access, that is, allowing other heat generators access to sell their heat, is a complex with regards to the infrastructure investor seeing a return, but also of the potential for increased competition to the benefit of the consumer. Sweden has previously rejected such access on the grounds of the potential additional costs it might imply for all system users, but is again considering it *(Ericsson and Svenningsson, 2009)*. A DH system requires strong oversight if the consumer is to be protected from being locked in to high energy prices. As seen in the relevant case study box, Sweden provides an interesting example of a successful DH system using a significant share of biomass.

11.5.3.3 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 means that development and application of policy instruments is less complex *(IEA, 2007; Desideri, Proietti et al., 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.

District cooling is likely to be subject to considerations very similar to district heating as regards the problems of potential lock-in to heating systems, third party access and high initial investment again, with similar need for protection of both investors and consumer. The economics of its application will tend to favour its use where there is a corresponding demand for a district heating system (Pöyry/Faber Maunsell, 2009).

11.5.4 Policies 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.

11.5.4.1 Direct Use of RE for Transport - Biofuels

A range of policies have been implemented to support the deployment of biofuels in countries and regions around the world. 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. Currently, robust biofuels industries exist only in countries where government supports have enabled them to compete in markets dominated by fossil fuels. 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 et al 2008; Felix 2008).

11.5.4.1.1 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 [Authors: Reference is missing].

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 [Authors: Reference is missing]. 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 liter[TSU: Also needs to be presented in 2005 US$/liter] with plans to scale up the tax up to 45 euro cents/liter[TSU: Also needs to be presented in 2005 US$/liter] 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/liter[TSU: Also needs to be presented in 2005 US$/liter] 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 (German Federal Ministry for the Environment (BMU), 2009).

11.5.4.1.2 Renewable Fuel Mandates and Targets

National targets are key drivers in the development and growth of most modern biofuels industries. In fact, 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 [Authors: Reference is missing].

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 EU 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 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 [Authors: Reference is missing].

11.5.4.1.3 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).

11.5.4.1.4 Sustainability Standards

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 EU, 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 et al, 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 (U.S. 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).

11.5.4.1.5 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 et al., 2004; Kintner-Meyer, 2007). Making these secondary forms of energy carriers cost-effective and efficient is one condition for providing renewable energies for transport. Again, this is discussed in more detail in Chapter 8, the technology integration chapter but again 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 (e.g., 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 (TfL, 2009) [TSU:Reference missing from reference list], or free parking for electric cars (Williams, 2008) [TSU:Reference missing from reference list].

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 gCO2/km by 2015; and a commitment to further reduce this to 90gCO2/km by 2020 (EC, 2009; Arnold, 2009; CCC, 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, 2009).

11.5.5 Cross Cutting Issues

This subsection discusses additional issues that are not end-use specific. These include public procurement of RERE technologies and electricity, heat and fuels, as well as policies to finance deployment of RE and related infrastructure.

11.5.5.1 Public Procurement

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, 2009).

Public procurement of RE has multiple benefits to the private sector. First, it can guarantee a stable market. Second, mass produced technologies exhibit a consistent 'learning curve' where 10-30 percent cost declines are routinely observed for every cumulative doubling of the total number of units produced. This relationship, with a central tendency of a 20 percent decline can be a powerful stimulus for public purchases, and for forward pricing to expedite movement to lower cost (See Figure 11).

Recent examples of this approach include the 2009 European Council and the European Parliament adoption of a new directive on the promotion of clean energy and energy efficient road transport vehicles. Similar efforts have been undertaken in the United States, and have also been used to lower up-front costs of not only RE systems, but also compact fluorescent lighting, and efficient appliances [Authors: Reference is missing].

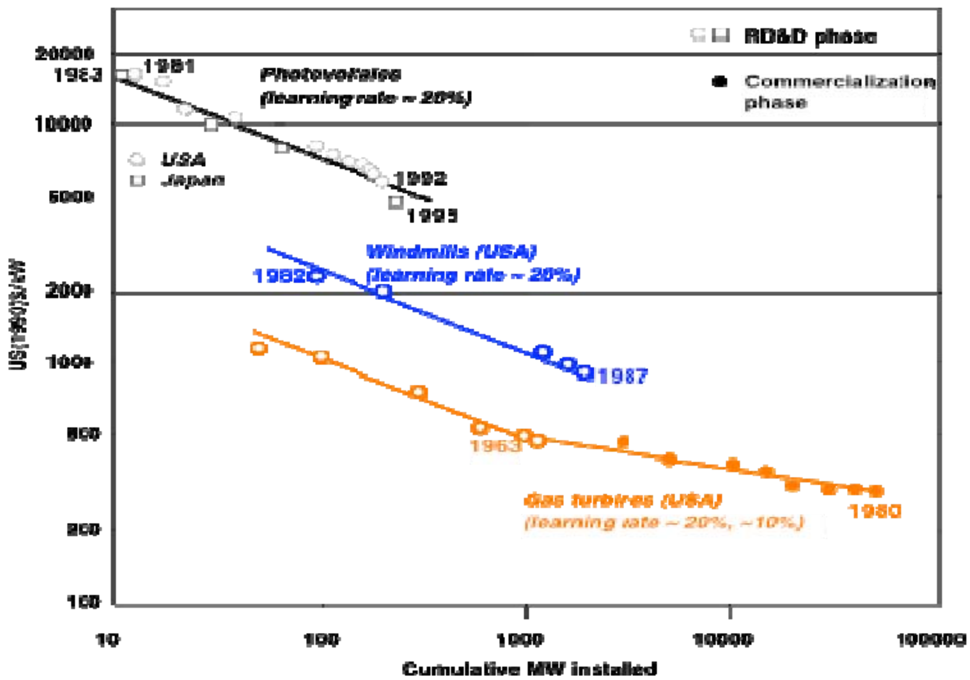


Figure 11: Cost Curves for Several Energy Technologies [TSU: Figure will need to be redrawn, presented in 2005 US$, and cited with a source]

11.5.5.2 Policies to Finance Deployment and Infrastructure

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). Uncertainties inherent in new technologies drive up the cost of capital which, in turn, decreases the net present value of projects to the point where many become uneconomic. All of these factors highlight the importance of government financing for RE deployment and infrastructure.

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). Developed country governments can also provide support for new technology development and deployment through strategically targeted Public Finance Mechanisms (PFMs) aimed at leveraging private sector financing, for example, by using government credit ratings to spur low-cost capital flows to private sector players.

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.

11.5.5.2.1 Investment Decisions and Public Financing

RE infrastructure 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 (Sonntag-O'Brien and Usher, 2004).

Financiers make lending and investment decisions based on their estimation of both the risks and returns of a project. Financial institutions want to make a return proportional to the risk they undertake: more risk means a greater return will be expected. The RE sector utilises finance from across the entire risk-reward spectrum. All financiers will want to understand risks they may face, and set up legal or other means for minimising or managing these issues.

For many RE projects, gaps in commercial financing can often only be filled with financial products created through the help of PFMs. Public financing can also be required for helping the commercial investment community gain experience with the new types of revenue streams that RE projects provide, including carbon, but also “green“ revenues (e.g. renewable premiums) that may be 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.

11.5.5.2.2 Elements of Project Financing

This section provides an overview of the various types of financing needed to plan and build RE projects, and the public financing mechanisms often required to fill gaps in this commercial financing continuum.

Table 5 provides an overview of the described mechanisms, the barriers they help to remove and the circumstances in which they are typically applied.

11.5.5.2.2.1 Project Development Capital

Project preparation for RE infrastructure projects is generally carried out by large energy companies or specialised project-development companies. Energy companies finance project preparation from operational budgets. Specialised companies are expected to finance project development work through private finance, capital markets, or with risk capital from venture capitalists, private equity funds, or strategic investors (e.g. equipment manufacturers). However infrastructure development is risky and can take several years and significant resources to prepare. In less mature financial markets it can be difficult to secure financing from commercial investors, and therefore the need for public support arises. Public finance mechanisms can help developers make it to financial closure by cost-sharing some of the more costly and time intensive project development activities, such as permitting, power purchase negotiations, grid interconnection and transmission contracting. These project development facilities can be on a grant, contingent grant, or soft loan basis and must be carefully structured to target the right projects and align interests on project development (UNEP Finance Initiative, 2009). Rather than directly supporting project developments, some facilities also channel project development support through private intermediaries[6].

11.5.5.2.2.2 Equity Finance

If a concept successfully passes through the development stages, the project developer will usually then need to attract external financing. To secure loans, developers and their equity sponsors will generally need to provide 25-50 percent of the capital required for a project in the form of shareholder equity. As the risk (real or perceived) associated with a project increases, lenders will require that equity play a larger role in the financing structure since more equity means a lower risk of loan default. This not only strains a developer's capital resources, it raises the cost of the entire project, since the cost of equity capital is always higher than the cost of debt capital.

Due to the many risk- and capacity-related challenges involved, there are significant gaps in the availability of equity financing for RE projects 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. Thus, there is a need for equity-focused public financing mechanisms that are structured 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.

11.5.5.2.2.3 Debt Finance

The bulk of the financing needed for infrastructure projects is in the form of loans, termed debt financing. 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 RE infrastructure projects require. In these situations PFMs 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.

[6] Some examples include the seed finance company E+Co, the Seed Capital Assistance Facility, and the infrastructure companies Infraco and InfraVentures.

Credit lines can be an effective means of providing the needed liquidity for medium to long-term financing of RE 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.

11.5.5.2.3 Risk Management

An integral element of deal structuring is financial risk management. This process entails using financial instruments to transfer specific risks away from the project sponsors and lenders to insurers and other parties better able to underwrite or manage the risk exposure. Among other important factors, financial risk management is one of the keys to deployment of RE technologies.

Applied correctly, certain financial risk management instruments can help mitigate the perceived risks associated with RE and affect the degree and terms of investment into such projects. However, there are currently constraints on the availability of such risk management instruments, which relate to factors such as the willingness and capacity of insurance and capital markets to respond (United Nations Environment Programme (UNEP), 2004).

There are still many insurance gaps. Projects of less than US $15 million[TSU: Needs to be presented in 2005 US$] have difficulty finding insurance cover and, as a result, financing. Only niche insurance operations with low overheads are able to service small-scale developers and even then, there is a steep learning curve and indeterminate risk reward ratio for many projects. For emerging markets, targeted enhanced political risk insurance is needed that covers the risk in the case of default in performance of obligation by government or other entity. Such insurance can come from government or from public-private entities, for instance export credit agencies.

Public guarantees are another option, and often needed where commercial financial institutions have adequate medium to long-term liquidity, yet are unwilling to provide financing 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 in the credit risk of project loans that commercial banks make with their own resources. Guarantees are generally appropriate only in financial markets where borrowing costs are at reasonable levels and where a good number of commercial banks are interested in the targeted market segment.

Typically guarantees are partial, meaning they cover a portion of the outstanding loan principal (50-80 percent is common), thereby ensuring that the commercial banks remain at risk for a certain portion of their portfolio to ensure that they lend prudently, and take responsibility for remedial action in the event of loan default.

1 **Table 5:** Overview of Public Finance Mechanisms for RE Deployment[7]

Mechanism		Description	Barriers	Financial Markets
Debt	**Credit Line for Senior Debt**	Credit line provided by Development Finance Institutions (DFIs) to Commercial Finance Institutions (CFIs) for on-lending to projects or corporations as senior debt	CFIs lack funds and have high interest rates	Underdeveloped financial markets where there is lack of liquidity, particularly for long-term lending, and borrowing costs are high
	Credit Line for Subordinated Debt	Credit line provided by DFI to CFIs for on-lending to projects with subordinated repayment obligations	Debt-Equity gap, whereby project sponsors lack sufficient equity to secure senior debt	Lack of liquidity in both equity and debt markets
	Guarantee	Shares project credit (i.e. loan) risks with CFIs	High credit risks, particularly perceived risks	Existence of guarantee institutions & experience with credit enhancements
	Project Loan Facility	Debt provided by DFIs directly to projects	CFIs unable to address the sector	Strong political environment to enforce contracts and enabling laws for special purpose entity
Equity	**Private Equity Fund**	Equity investments in companies or projects	Lack of risk capital; restrictive debt-to-equity ratio	Highly developed capital markets to allow equity investors to exit from the investee
	Venture Capital Fund	Equity investments in technology companies	Lack of risk capital for new technology development	Developed capital markets to allow eventual exits.
Grants	**Project Development Grants**	Grants "loaned" without interest or repayment until projects are financially viable	Poorly capitalised developers; costly and time consuming development process	Can be needed in any financial market context
	Loan softening programmes	Grants to help CFIs begin lending their own capital to end-users initially on concessional terms.	Lack of FI interest in lending to new sectors; limited knowledge of market demand.	Competitive local lending markets
	Inducement Prizes	"Ex-ante prizes" to stimulate technology development. Unproven in climate sector.	High and risky technology development costs and spill-over effects	Sufficient financing availability to deploy winning technologies

[7] Adapted from UNEP, Public Finance Mechanisms to Mobilise Investment in Climate Change Mitigation, Paris, 2008.

Risk Transfer	**Currency Risk Management Instruments**	Establishment of Currency Exchange Funds by Donors, DFI, CFI	Volatility of local currency; Investment costs, loans and revenues in different currency	Most emerging markets
	Power Purchasing Guarantees	Guarantee by developing country government for non-prolongation of PPA by local utility	Very limited duration of power purchasing agreement or renewable premium	In immature policy environments
	Exploitation Risk Insurance	Risk Mitigation Fund set-up to cover costs of drilling	Poorly quantifiable up-front risk for initial investment for	Specific to some types of renewable like geothermal energy
Revenue Support	**RE Premiums**	Partial funding of renewable premiums by DFI e.g. as part of a nationally appropriate mitigation actions (NAMAs) via Trust Fund	Lack of project development capital; lack of cash flow for additional security;	All countries in which a given technology is lacking a sufficient cash-flow to ensure economic viability
	Carbon Finance	Monetisation of future cash flows from the advanced sale of Carbon Credits to finance project investment costs	Lack of project development capital; lack of cash flow for additional security; uncertain delivery of carbon credits	Availability of underlying financing for projects. Adequate institutional capacity to host CDM/JI project and to enforce contracts.
	Carbon Transactions in post-2012 credits	Contracting for the purchase of Carbon Credits to be delivered after 2012	Lack of regulatory framework and short-term compliance driven buyers.	Availability of underlying financing. Adequate institutional capacity to host CDM/JI project and to enforce contracts.

11.5.6 Overview of Cross-cutting Lessons Learned to Date

In conclusion, RE policies are required for their deployment, but simply enacting policies is not enough. Support schemes are often assessed using two main criteria: one measuring effectiveness (for example, the ability to deliver an increase of the share of renewable electricity consumed) and the other criterion measuring efficiency (e.g., comparison of the total amount of support received and the generation cost, or new capacity or generation relative to amount of support received). Details of design and implementation are key for policies to be effective and efficient. Overall, the effectiveness and efficiency of RE policies requires the following elements (International Energy Agency (IEA), 2008a).

- **The removal of non-economic barriers to renewables.** To date, as mentioned in Section 11.2, only a handful of countries have implemented effective support policies that have accelerated the diffusion of renewable technologies. The International Energy Agency concluded in a major study of RE policies that, although there exists a wide variety of policy mechanisms that can be used effectively to promote renewables, non-economic barriers have impeded their effectiveness and driven up costs in many countries (International Energy Agency (IEA), 2008a).

- **A steadily growing market and fair rate of return to attract investment, create strong industries, and drive down costs.(Sawin, 2004b; REN21, 2005)** For RE to make a significant contribution to lower greenhouse gas emissions as well as other goals such as economic development, job creation, and reduced oil dependence, it will be essential to improve the efficiency of technologies, reduce their costs and develop mature, self-sustaining industries to manufacture, install and maintain RE systems. The goal must not be simply to install capacity, but to provide the conditions for creation of a sustained and profitable industry, which, in turn, will result in increased RE capacity and generation, and will drive down costs (Sawin, 2004b; REN21, 2005).

- **To achieve this end, a viable, predictable, clear and long-term government commitment and policy framework are critical**.(International Energy Agency (IEA), 2008a). 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).
- **Transitional incentives that decline over time, and appropriate incentives that guarantee a specific level of support that varies according to technology and level of maturity.** 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).
- **A mix of instruments is essential for success.**(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), 2008a).

Increasingly, analysts are also noting that transparency and broad participation and ownership are critical to the expansion and long-term sustainability of RE (Bolinger, 2004; Sawin, 2004b; Farrell, 2008; Mitchell, 2008; Mendonça, Lacey *et al.*, 2009). As the density of RE projects increases, the need for local and political acceptance of RE will be even more important (Hvelplund, 2006). “Ownership can change the perspective of citizens by creating energy producers instead of energy consumers, as well as unlocking a deeper interest in energy efficiency and local energy solutions.” (Farrell, 2008)

Ultimately, 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).

Finally, there is also 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 (Nitsch et al, 2001/2002; Fischedick et al, 2002) [TSU: References missing from reference list]. Jacobsson 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 (Jacobson and Delucchi, 2009).

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. This pathway has been described as a succession of phases from R&D to full market deployment, but these phases do not happen in a linear way. Their development requires market as well as social and institutional changes. Technology is thus best pictured as being embedded in these dimensions and technological change is conditioned by an enabling environment, which encompasses RE policies. It includes other institutions, such as other policies and regulations, the business and finance communities, the civil society, the material infrastructures for accessing RE resources and markets, the politics of international agreements for facing the challenge of climate change or developing technology transfer.

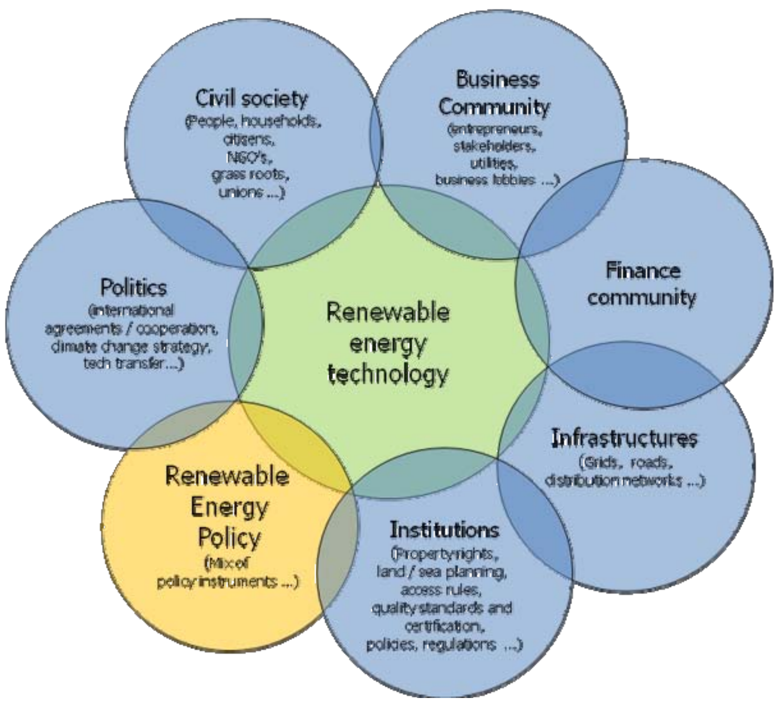


Figure 12: RE technology is embedded in an enabling environment, RE policy is one decisive dimension of this environment, but not the only one

A critical issue in deploying clean energy innovations relates to this environment. RE policies cannot be developed in isolation of other policies. Thus, such an environment must address the social and global dimension of the energy transition and the articulation of RE policies with other policies such as climate policy. And in such an environment, well-designed policies are more likely to emerge and they will be more effective in rapidly scaling up RE. This “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).

We utilize the term and concept of ‘enabling environment’ to reflect a larger set of issues operating at a higher level than individual policies such as the precise form of a carbon price or a RE subsidy provided. As such, this notion points at a larger framework which, if developed and settled, greatly facilitates the sustainable emergence and the development of a new technology or set of practices. Section 11.7 takes this one step further, and examines the requirements beyond the energy system to enable the structural shift to RE as the standard energy provider.

This does not mean to say that such an environment has to be set before any policy is put in place. It is often necessary to proceed with a policy before an enabling environment is established. Successful experiences suggest that developing such an environment largely contributes to the emergence of well-designed policies and their success. A number of important enabling conditions exist. We first describe the main issues associated with the systemic dimension/character/property of innovation pathways. We then analyse these enabling conditions, organizing them by broad themes – i.e., risk and uncertainty, access to financing, social innovation, fair access to RE resources and market, technology transfer and articulation to climate policy - in order to evaluate the extent to which each of these conditions is present or absent in the context of RE technologies.

11.6.1 System change and innovation pathways

It is often argued that the success of a radically different technology requires a change in the overall momentum of the technological system. What this means is a change in the social, institutional and economic arrangements and infrastructures that have grown up to support the existing pattern and technological use, sometimes described as the technological regime [Authors: Reference is missing]. The process of changing technological regimes is described as a transition or transformation (Geels, 2005c).

The current transition is different from earlier ones in that it has to be deliberate, meaning that action must be taken to make it happen because it will not occur on its own in a business-as-usual energy system, and it must happen on a short time scale The current view about how this should, or could occur (“transition management”) suggests exploring various options (niches) for guiding variation-selection processes in more sustainable directions. It is about transformative change in societal systems though a process of searching, learning, and experimenting that relies on modern types of governance.

It is assumed that all levels of government play an important role in facilitating the necessary changes (Rotmans, Kemp et al. 2001b; van den Bergh and Bruinsma 2008 XX) but individuals and communities are also important. The state being embedded within wider networks in civil society and market systems, state actors rely upon non-state actors in the formulation and implementation of public policy. In turn, managing transition plays on different modes of collective action; it critically involves networks and coalitions in order to build guiding visions and transfer skills

Such a view draws upon an evolutionary understanding of technological paths and the approach to strategic niche management (e.g. Smith et al. 2005; Kemp et al., 1998 XX). According to this understanding, transition might occur thanks to the interplay between deep structural trends (also termed 'landscape') such as: economic growth patterns, immigration, predominant political positions and cultural values), technological regimes and technological niches (radical novelties). Regimes are stable because of their strongly interlinked elements. In stable situations, regimes select and retain preferred niches so that innovation tends to be incremental. If the regime is confronted with changes at the level of structural trends, the linkages may become looser and actors are able to search for new solutions or new ways of doing things. This creates opportunities for 'niche break-out' (Geels, 2006) meaning new ways of doing things or for strategic niche management, as described in the above. New technologies may develop with the old, there are reconfigurations and a chance for more change. In this way, niche applications gradually increase and further reinforce change.

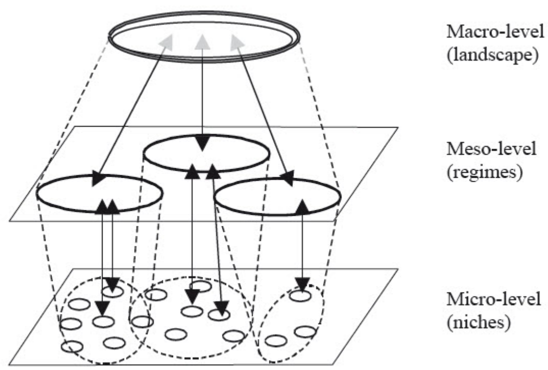


Figure 7:Interaction of innovation processes between different scale levels (Geels and Kemp, 2000)

Figure 13: Interaction of innovation processes between different scale levels (Geels and Kemp, 2000) [TSU: Figure needs to be redrawn – eliminating original figure title]

The way a country views innovation, or the process of change, is thus very important for a country's ability 'to do things differently' and engage into the transition (Mitchell, 2008). If the specific goal is to innovate and rapidly disseminate RE technologies throughout the world in the span of just a few decades, the innovation system – that is the evolution from micro-level (niche) to meso-level (part of the new technological regime) - must be understood and exploited by a host of key actors, including policy makers, international agencies, businesses, regulators, RE technologists, financial institutions, educators and urban and regional planners. Collectively, these actors must provide the "enabling environment" for advancing a "RE technology innovation system."

The key challenges posed by innovation relate to its systemic nature. Researchers in technological innovation increasingly depict the innovation process as an "innovation system." By this they mean that, even if a pathway can be followed (such as R&D, demonstration, deployment, diffusion, and commercial maturity) (Haites et al, 2008) [TSU: Reference missing from reference list] this rarely occurs in a linear sequence that starts from a single invention of an individual innovation to its dissemination in the marketplace. Instead, a given innovation is more likely to occur in concert with several other associated or overlapping innovations, each providing "spillover" benefits to the development of the other. It is in this sense that the literature sometimes refers to "innovation clusters," "innovation pathways," and "innovation webs."

(Smith et al, 2005) Awareness of this "system" character of technological innovation can help policy makers avoid some of the less successful approaches of the past, such as one sided or isolated "product push" (financial and/or regulatory support to the developers and producers) or "demand pull" approaches (support to market demand). Such supports have more chance of long-run success if they do not ignore other critical characteristics and components of the innovation system (Grubler, 1998, Mowery and Rosenberg, 1989).

The main challenges posed by innovation systems are the following.

First, technological innovation refers not only to "inventions" of hardware (equipment, structures, artifacts), but also the software (scientific knowledge, design and operating specifications, wisdom) and the "orgware" (institutions, organizations, social networks, human relations) associated with a particular idea or thing. "Innovation" is thus successful when it meets a private or societal want or need. Second, technological innovation is the consequence of at least three distinct drivers: R&D (or RDD&D)[8], learning-by-doing[9] and spillovers[10] (Freeman, 1994; Grubler, 1998). Because spillovers benefits are uncompensated, the RD&D effort that created the innovation has public good (positive externality) attributes and will generally be underprovided by private markets alone, thereby providing a rationale for public expenditure on R&D (Arrow, 1962).

Third, incumbent technologies usually benefit from "economies-of-scale"[11] which reduces their cost. High up-front costs make it difficult for a small firm with a technological innovation to enter the market even if its innovation could eventually be cost-competitive were it to gain a large enough market share to realize its own economies-of-scale. At the same time, as noted in Section 11.4, the high fixed costs make large, incumbent firms resistant to those technological innovations that might revolutionize the industry – even if these are generated within their own firm – because these might render obsolete their existing investments in equipment, industrial processes, buildings and even infrastructure. In electricity, some long-run forecasters believe that renewables-based, decentralized electricity production (especially solar) might one day pose a similar threat to the massive capital investments in fixed electricity distribution lines.

[8] [Authors: To be submitted to SRREN Glossary] "R&D": R&D extends along a continuum from fundamental research at one end to applied research at the other. To the extent that the latter is intimately associated with the commercial appearance of a new product, process or idea, it is sometimes referred to as RDD&D (research, development, demonstration and deployment).

[9][Authors: To be submitted to SRREN Glossary] "Learning-by-doing": refers to the technological advances, usually of a cost saving nature, that result as the innovation is adopted in growing numbers. The effect of learning by doing is sometimes depicted by "experience curves,"

[10] [Authors: To be submitted to SRREN Glossary] "Spillovers": Spillovers is cited as one of the primary sources of knowledge that drives innovation (Klevorick et al., 1995). Spillover is the knowledge benefits that transfer deliberately or inadvertently from the originator of an innovation to other entities – often to competing companies.

"Experience curves": Experience curves show the decline in cost of a technological innovation as its production levels rise (Argote and Epple, 1990; Yelle, 1979 XX). Such curves have even been estimated for some energy technologies (McDonald and Schrattenholzer, 2001 XX).

[11] [Authors: To be submitted to SRREN Glossary] "Economies-of-scale": Economies-of-scale are associated with production and/or delivery systems that have high fixed costs, such as a distribution networks (in electricity delivery). As these fixed costs are spread over many customers, average costs fall, meaning that large firms can provide the good or service more cheaply than several smaller firms.

Fourth, technological innovations that are "evolutionary" tend to have an advantage over innovations that are "disruptive" or "revolutionary" – the former can diffuse within the existing technological system while the latter require a profound transformation of that system (Mackay and Metcalfe, 2002). A new hybrid gasoline-electric car ("evolutionay") can mesh with the existing refuelling infrastructure, while a hydrogen fuel-cell car ("disruptive") requires major new investments to produce hydrogen and a new network infrastructure to deliver it. If society wants the hydrogen outcome for some reason, it must overcome economies-of-scale and other challenges to revolutionary technological innovation. All these elements confer advantage to incumbent technologies not only at the hardware level, but also at the "software" and "orgware" levels. Actors (e.g. researchers, engineers, technicians, business managers, entrepreneurs, educators, policy makers ...), institutions (e.g. codes, standards ...) and even the very structure of the economy (e.g. industrial organisation, population location ...) or the social norms and values (e.g. consumer preferences, political expectations and perceptions of investment risk ...) end up depending to some degree on the existing technological path (Nelson and Winter, 1982[TSU:Reference missing from reference list]). This is why analysts of technological change use terms like "path dependence" and "lock-in" to describe the systemic advantages that incumbent technological systems have over revolutionary technologies (Grubler et al., 1999; Unruh, 2000; Arthur, 1989).

Overcoming these advantages requires both an understanding of just how systemic they are as well as an ability to mobilize a wide diversity of resources and agents for wholesale change.

Entrepreneurs, the finance community, decision makers, elites and civil society all have decisive roles to play in structural change, but they should not pursue separate paths. Entrepreneurs cannot make miracles happen. For example, if their innovation has a great social value in one respect (for example, zero greenhouse gas emissions) but this value is not recognized in the market place (because of unpriced externalities) and not recognized in policy (e.g., emissions pricing, capping emissions or restricting the use of emitting technologies), or if the changes in tastes and social norms required for this technology to be adopted are not addressed by existing policy frameworks, then it won't be taken up. R&D is a critical component of technological innovation, but R&D that is not intimately connected via social and institutional networks (government, researchers, entrepreneurs, consumers) to the commercialization and deployment process, is not likely to benefit from spillovers from these other activities and actors. Decision makers and elites play a key role in signalling social and technological goals, even though such a statement might initially be vague, and then in ensuring the existence of favourable market conditions, notably the "artificial niche market"[12] that helps renewables-based technological innovations cross the "valley of death" (see Section 11.5.1).

Finally, the disruptive change implied by a dramatic increase in the market share of RE requires the general mobilisation of financial and human resources necessary to sustain and legitimize the new technological innovation system. This mobilisation involves not only financial, technical and educational resources, it also requires innovative policies by government, education efforts by societal leaders and the counter resistance to the dominant technological system by fostering

[12] [Authors: To be submitted to SRREN Glossary: "Valley of death": The valley of death the tenuous phase between the introduction of the first commercial products – which therefore do not yet benefit from economies-of-scale and economies of learning – and widespread market diffusion (Grubb, M., 2004 XX)

coalitions of entrepreneurs, environmentalists and technology advocates who will support it (ensuring access to land for wind turbines and to land and water for small-scale hydropower).

11.6.2 Addressing Risk and Uncertainty

Reducing risk for RET investors is central. 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, has to occur. This is the notion of the *risk reward ratio*, where the risk is reduced such that the reward is acceptable to induce investmentRecent evidence, notably in relation with the development of wind energy, has pointed at two important lessons: i) Beyond well adjusted policy instruments such as taxes, FITs or quotas, political stability and inventive institutional setting can significantly contribute to policy success by reducing the risk for investors; ii) Clear, long-term, consistent signals and robust policies often result in high rates of innovation, policy compliance, and the evolution of efficient (low-cost) solutions.

Three different dimensions of the enabling environment can reduce uncertainty: political stability, political commitment, inventive institutional settings.

11.6.2.1 Political stability

Political stability relates to the stability of a political vision, so that the policy frameworks which are adopted in order to sustain the deployment of renewable energies can be perceived, by investors, as stable and credible enough over the term needed for this deployment. Political stability ranges from mere regime stability to the uncertainty implied by political alternation. For instance, Van der Horst & Evans (forthcoming 2010) have explored farmers' choice in the context of recent developments in biomass energy in the Yorkshire region in the UK. They point at the technical risk incurred by farmers in opting for biomass plants (e.g., Miscanthus or Willow) which have expected lifecycles that are much longer than that of the (agricultural) policies that seek to persuade them to do so. Thus, the perception of the risk associated with this change is clearly dependent on the stability of a political vision beyond the current political power and the currently implemented energy or agricultural policies.

11.6.2.2 Political commitment

Commitment relates, in a stable political context, to the commitment to both a vision and a definite policy framework in favour of RE. RE deployment has been much more successful in the countries where governments have 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 & Lauber, 2006 XX) or Denmark approach to wind power policy. The recent experience with these successful cases proves the critical character of political commitment. Even in these stable environments, any threat to the political commitment has resulted in a direct slowdown in the deployment of RE capacity. This was the case in Denmark when political uncertainty ruled the debate over the recent change in wind power policy (from FIT to incentive based system) (Agnolucci, 2007a XX). It was also the case in Germany, in three instances when either national factors or the political vision of the European Commission increased uncertainty as regards to the future of the RE policy framework (Agnolucci, 2006 XX). Symmetrically, the lack or delayed development of such long-range and stable political commitment has been shown to explain the differences in wind power development in different countries (Meyer, 2007, Soderholm et al., 2007 XX).

11.6.2.3 Innovative institutional settings

Innovative institutional settings are a third and important factor for risk reduction. They are for instance long term contracts, new investment vehicles, or community ownership. The development of these settings often relies on the initiative of the private sector but, combined with RE policy incentives, they succeed in securing investment channels.

Long-term contracts, for instance, have played a decisive role in stabilizing investors' expectations, such as in Texas (Langniss and Wiser, 2003). Without such contracts, RE developers are faced with highly uncertain returns and electricity retailers risk not being able to procure the requisite number of certificates per year. Supply constraints or market manipulation might result in certificate prices that are too high prices for the market?? Long-term contracts also ensure developers a stable revenue stream, which eases their access to low-cost financing. The contract terms can also penalize project construction lags or operational problems, as they did in Texas, which helps to accelerate RE deployment.

The broader institutional environment can foster the emergence of these new institutional settings in many ways, be it only by providing reliable institutions for their enforcement and flexibility for private parties to innovate in this area. Public institutions can also get directly involved into public-private partnerships, as they did in Spain for wind power (Dinica, 2008). The high investment risk in the first versions of the Spanish FIT was mitigated through the implication of a specific public agency, which acted as an investing partner into the wind power projects.

Risk reduction is also decisive for private household- and micro-generation. Changing energy systems presents 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 and local banks as well as local entrepreneurs (Pokharel et al., 2008). However, if risks are lower, households prefer to have their individual choice. Best examples can be taken from community owned micro-hydro systems and individual solar home systems. Micro-hydro has higher investment and risk could be high, however in the case of solar home systems, investment requirements are lower and risk is thus relatively low. So policies must also be formulated accordingly.

Inventive business models have become part of the new institutional settings. Emphasis has recently been put on the role of new business models (i.e., partnerships between global companies and government, local enterprises, donors or NGOs) in reaching the 4 billion poorest people, the "base of the pyramid" (BoP) (Hart & Christensen 2002; Prahalad 2006; Kandachar & Halme 2008; IIED, 2009 XX). Since 2000, a number of projects have been launched to meet the demands in the BOP markets. Collaborations with non-traditional partners have been tried in order to understand the cultural values in the potential market, to adapt cost structures, distribution channels and marketing approaches. The cases show that business targeting BOP markets can contribute to poverty alleviation and to energy access (e.g., IIED, 2009). A key challenge for policies is to develop support for starting up and scaling up business activities that are aimed at the poorest people.

While the majority of the BOP cases have focused on activities of multinational companies in developing countries, less is known about the dynamics of models deriving from small and medium-sized enterprises (SME) that constitute most of the private sector. Smaller local firms are often the ones that reach the poor more effectively and shall be associated with these new business models. Social enterprises or social investments tied to a core business also play a decisive role.

Finally, in spite of encouraging outcomes, more knowledge shall still be gained about the actual departure in sustainability practices of these experiences.

11.6.3 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 [ADB, 2007]. In 2005 the private sector accounted for well over 90 percent of all investment in the RE sector [UNFCCC, 2007].

The universe of private capital sources most relevant to the RE sector include corporate investors such as utilities, banks, institutional investors[13], 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 [ADB, 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 and country risks* – concerns regarding political risks can influence investor attitudes, capital allocation strategies of fund managers, and risk premiums.
- *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

[13] Institutional investors are most commonly pension funds, insurance companies or sovereign wealth funds – entities with a mandate to make long term investments for their shareholders.

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.
- *Currency risks* – the risk of currency devaluation in cross border and cross currency investments can hinder access to financing particularly in less developed economies. Currency hedging instruments exist to help investors manage this risk, but only in the more developed financial markets.
- *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 [ADB, 2007].

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

11.6.4 Sustaining Social Innovation

Social innovation is about the ability of people and/or institutions to adapt to the emergence of new social norms or institutional organisation. The process of technological change and deployment is a systemic one; national government plays an important role in this process but civil society (individuals and communities) is also important. The reasons why people do not change or are able to change differs. This is also true for institutions; they can continue with the way they do policy or follow a more reflexive path and learn from the outcome of policies that have already been implemented. These dimensions are interlinked. The way in which civil society and the institutional dimension are combined into enlarged governance, or undertake some sort of reciprocal empowerment, is decisive for the ability of the system to foster technological deployment. Social innovation, especially in the implementation phase, is a resource for policy success. In the following subsections, social innovation is analysed along three dimensions: the factors that influence changes in people's values and attitudes (evolving social norms); factors behind institutional learning, and the role of civil society in the implementation of RE policies

11.6.4.1 Changing values and attitudes, evolving social norms

RE policy has typically focused on policies that create obligations or alter incentive structures for innovation and diffusion (e.g., regulation, price mechanisms, and R&D support). We focus here on information and education-based approaches that seek to create an enabling environment for RE. These "new tools for environmental protection" have been widely used in the energy sector but in the context of energy demand and efficiency rather than RE (Dietz & Stern, 2002).

11.6.4.2 Values and Attitudes: Targets for Education and Information Policies

Public education on RE is typically targeted at a general audience through mass media channels. It seeks to change values through moral suasion 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 (Poortinga et al. 2004; Gatersleben et al. 2002). 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, Abel, Guagnano & Kalof 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 (see Ajzen 1991 and Oskamp 2000 respectively). Positive attitudes are further reinforced by public commitments and targeted feedback (Staats, Harland & Wilke 2004).

A number of recent reviews discuss the role of information and attitudes in behavioural models and settings relevant to the environment (Jackson 2005; Halpern et al. 2005; Wilson & Dowlatabadi 2007; Darnton 2008). 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 1995; Armitage & Connor 2001).

For RE, key elements of context include capital costs and availability, and regulations on, for example, local planning, grid connections and power sales. The alignment of, and consistency among, the various components of a RE policy framework are also important (Owens & Driffill 2008; Stern 2000). Other contextual constraints relevant to RE include capital availability, perceived landscape values, and community governance traditions. Past experiences and habits of residential customers also explain their reluctance to switch electricity suppliers, even when information on the benefits of switching is provided to them (Brennan 2007). More generally, systems of energy provision and use are deeply embedded in household routines and social practices (Shove 2003; Shove 2004). 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 et al. 2009).

11.6.4.3 Passive and Active Behaviours, and Energy Citizenship

Behaviours targeted by education and information-based policies may involve either ‘active’ or ‘passive’ support for RE (Stern 2000). Examples of passive support include subscribing to a campaigning NGO, or supporting a policy to increase the share of RE in the supply mix. Examples of active support or engagement include adopting a distributed RE technology (Sauter & Watson 2007), or switching to a RE electricity supply at a premium over conventional tariffs (Brennan 2007).

Context exerts a stronger influence on active forms of engagement that require specific and deliberate behavioural choices. This creates 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 DG and RE (McGowan & Sauter 2005; Bell et al 2005). This gulf is particularly evident in the outright opposition to wind power projects (discussed with examples in the case of New Zealand - Graham 2009 and in the UK - van der Horst 2007).

The concept of “energy citizenship” describes a further deepening of active support for RE into an active participation within the energy system (Devine-Wright 2007). “Energy citizenship” is enabled by a decentralisation of energy system governance which in turn allows hitherto consumers to take on a variety of roles including that of producer (Sauter & Watson 2007).

Active behavioural support for RE can “spillover” into other energy and environment behaviours (and vice versa). As examples, individuals may be more likely to install micro-generation at home if they are already involved in community-based RE projects, or may reduce residential energy use to a greater extent if they have already installed a PV system (Devine-Wright et al, 2007; Preston et al, 2009).

11.6.4.4 Social Norms and Social “Visibility”: Other Policy Targets

Education and information may also target social norms. These are shared rules and expectations about behaviour. They may or may not be tacitly sanctioned (Cialdini 1990). Norms are transmitted through personal networks of peers, reference groups and role models. Consequently, normative approaches are often focused at the community level (McKensie-Mohr & Smith 1999). Research has found social norms to explain and also influence energy-related behaviour (Wilson 2008; Nolan et al. 2007).

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 (Rogers 2003, Archer et al. 1987; Jager 2006). The literal visibility of residential wind or solar may help RE become a normative talking point (Hanson 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 (Jager 2006; Kaplan 1999).

11.6.4.5 Allowing for institutional learning

RE policies are most effective when they are tailored to the local needs and conditions. Coordinating RE policies with other policies in key development sectors contributes in achieving this. The capacity of the institutional environment to involve various stakeholders and policy communities in the policy process, so as generate collective learning and new institutional capacity, has been highlighted as a favourable factor behind policy success. Bringing different communities (e.g. energy, environment, land planning, expert, NGOs, pressure groups ...) into a common policy network enables policy making to become more comprehensive and reflexive. When policy communities are heterogeneous it is easier to evolve and adapt policies so as to better respond to local political, economic, social and cultural needs and conditions [Authors: Reference is missing].

Breukers at al. (2007) have compared wind power policy processes and institutions in three European countries (Netherlands, United Kingdom and Germany). They have analyzed the ways in which the energy, planning, environmental communities and policy domains were (or not) integrated into a wind power policy community in each of these countries. The comparison points to a positive relationship between successful wind power deployment and the emergence of a heterogeneous policy community, whose demands are taken into account at the various levels of the government (national, regional, local). This was, for instance, the case in Germany (state of North Rhine Westphalia) where the policy approach was very responsive to the wind sector and to the strong pro-wind grassroots movement, and allowed the early consolidation of a mixed policy community. In the Netherlands or the United Kingdom, this did not take place partly because of a dominance of the conventional energy sector or because of a more fragmented, less committed approach to wind power policy.

Similar types of evidence have been shown in other countries in which centralized energy institutions, techno-institutional lock in into some type of conventional energy or a tradition of corporatism reserving the access to the policy arena to certain groups, have also made the emergence of such policy community more difficult (e.g. Nadai, 2007; Szarka, 2007 for France).

Such institutional capacity can also be fostered at the international level. In the field of bio energy, the Global Bioenergy Partnership (GBEP, http://www.globalbioenergy.org [TSU: URLs are to be cited only in footnotes or reference list.]) provides a forum for high-level policy dialogue on bioenergy. It aims at supporting national and regional bioenergy policy-making and market development, and at facilitating international cooperation. Partners can organize, coordinate and implement targeted international research, development, demonstration or commercial activities, with a particular focus on developing countries. GBEP also provides a forum for implementing effective policy frameworks, identifying ways and means to support investments, and removing barriers to collaborative project development and implementation.

Table 6: The integration of policy domains into the German wind power policy community (adapted from Breukers and Wolsink, 2007)

Energy policy domain >>	No dominance of the energy sector . Not involved in wind power, trying to impede development	Late liberalisation . 1998 -> Limited impact on wind policy	Grass roots citizens' projects . Later less locally based ownership (companies, investors funds)	Successful Turbine industry . Strong home market, export product	Stable Financial support . Focused on yield, encouraging diversity
Planning policy domain >>	General tendency . Decentralised with a centralising tendency	Local planning . Local authority obliged to take pro-active decision	Wind power planning policy . Privileging wind turbines, focus regional	Project planning approach . From grass-roots, tendency to less locally based projects	
Environmental policy domain >>	Grass-roots environmentally inspired local initiatives, increasing leverage, matched with policy priorities and strategy	Environmental concern, early institutionalisation In policy and politics	Policy integration, particularly North Rhine Westphalia		
Policy community formation >>	Early formation network . Bottom up, founded by anti-nuclear movement	Early consolidation on various levels	Local grass-roots Pro-wind strong, anti-wind emerging	Government commitment Federal and state policy, committed to ecological modernization and responsive to the wind sector	

11.6.4.6 Civil society and the implementation capacity

Because of risk aversion, habits, inertia to change or acceptance issues, civil society (the "social") has often been framed by policy analysts as a source of barriers to the deployment of RE technologies. However, recent evidence has also pointed to its positive role, notably in policy implementation. The taking into account of this role is now part of a "new policy paradigm that reaches beyond measures to increase production capacity per se to embrace both the institutional dynamics of innovation processes and the fostering of societal engagement in implementation processes" (Szarka 2006b).

The notion of "implementation capacity" (IC) (Agterbosch 2004, 2009) has been proposed in relation to wind power policy. It points to a set of technical, economic, institutional and social conditions that jointly contribute in enhancing the performance of different types of private actors (e.g. regional distributors, small wind power entrepreneurs). IC is defined as the capacity of these actors to deal with prevailing institutional structure (i.e. electricity regulation, nature conservation norms; planning procedures) through social skills (e.g. management styles, informal contacts) and social conditions (e.g. trust or social coherence) so as to get their wind power project developed. This inside look shows that social relations at the local level facilitate coordinated actions and project development. They add to the scope and structure of knowledge of private actors and to their bargaining position as small private investors on the liberalizing electricity market, and they contribute to clarify implementation and social acceptance.

The key role of non-state actors (i.e. Natural Regional Parks, bird protection NGO's) has also been pointed at in France, where they have contributed to evolving planning and siting frameworks for wind power, notably through the renewal of landscape values or bird protection approaches at the local level (Nadaï & Labussière, 2009 and 2010 XX). The recent politics of wind power has led to the broader view that the acceptance or rejection of RE projects does not result from subjective whim, but that it is governed by a set of norms, related to the national and local contexts. These rules of the game (also called *acceptability*), which frame implementation processes, shall be regarded as a (local) social contract that is constantly evolved under the pressure of collective renegotiation and learning from policy implementation (Szarka, 2007).

Technology cooperation within social networks is another way in which civil society can enhance policy success. Alexandra Mallet has analysed the diffusion of passive solar heater (PSH) in Mexico city (Mallet,). 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 offset the shortcomings of public policy, especially its lack of leadership, coordination and readability.

The social structure of RE projects has also been shown to underlay policy success in developing countries. For instance, community based micro-hydro systems seem to work better than privately owned ones, because the comparatively low but acceptable financial return (low load factor and revenue) of these small projects does matter for a community pursuing socio-ecological welfare enhancement (Chhetri, Pokharel and Islam 2009). Communities investing in these projects get a return on their money in many ways besides the financial interest they receive. They can also implement shared projects faster as there will be less conflict surrounding them. In this context, the role of the civil society in making people aware of the benefits of RET, their ease of implementation and management, is a large reason for growing acceptances of RET in developing countries.

11.6.5 Ensuring Access to and a Fair Distribution of Resources

RE policies are most effective if they are coordinated with other policies (agricultural, construction, transportation, etc.) in order to respond to local political, social and cultural needs and conditions. Innovation, including social innovation, is more likely to occur when conditions are met such that actors can access RE resources and the market for RE under conditions that provide for social and environmental justice. Property rights are decisive for ensuring that this takes place, but other institutional dimensions are also very important. These dimensions include: land use / landscape planning, standards and access rules, and infrastructure policies.

11.6.5.1 Property rights

Since few areas in the world are truly devoid of/lack traditional uses, conservation values or existing commercial interests, it is unavoidable that the growing deployment of RE technologies will create tensions. Where the interplay of stakeholders' interests, technological development and an uneven geography can create challenges for accessing high-yield resources , rules are needed to resolve resource conflicts. Past evidence from common pool resources such as water management, suggests that there is a need to strike a balance between exclusionary property rights and more adaptive frameworks of governance which take wider sustainability issues into account.

Whilst conflicts over large hydro-power schemes have been studied extensively, the rapid developments of other RE technologies are now also resulting in a growing number of conflicts, ranging from the more abstract (e.g. environmental ethics, landscape aesthetics, political ideology) to the more concrete, such as conflicts over rights of way, compulsory purchase, compensation for lost income, and nuisance at the construction or operational phase. Existing interests often receive protection through spatial zoning , but conflicts may also ensue between different users not just of the same space but of the same actual resource within that space. There is also a potential conflict of interest between individual operators who want an unobstructed access to the energy flux their device can capture, and the state, which wants to maximize the total amount of energy captured even if that means that the output of individual operators is somewhat diminished by local resource competition. Resource conflicts over 'new' renewables such as wave and tidal energy are still hypothetical. For on-shore wind they are now emerging, especially where dedicated wind farm zones are filling up. For small-scale solar energy in some urban areas, frequent resource conflicts have already led to the development of solar access laws (Bradbrook, 1989; Rose, 1990; Brown and Escobar, 2007; Cowell, 2010; Ohl and Eichhorn, 2010).

With the exception of biomass, renewables are fugitive or mobile resources. The Justinian Digest in 533AD, declared the five elements: air, water, oil, sea and seashore as free to all, and thus owned by no-one. This question of ownership was first challenged when these elements were starting to be used for specific purposes (Wiel, 1934). The earliest written evidence in Northwestern Europe of using wind for providing mechanical energy is in records of legal disputes relating to the establishing monopoly rights to building and using windmills (Sistrunk, 2006a; Sistrunk, 2006b).

According to the classical (Blackstone, 1832) and more contemporary (Demsetz, 1967) property theory for natural resources, there are three evolutionary stages in the allocation of rights. In the first stage the resource is plentiful. It is open to all and owned by no-one. In the second stage the resource is becoming less plentiful and is therefore appropriated by a group and consequently becomes subjected to somewhat diffuse common property arrangements which are often customary based. In the third and final stage the resource has become scarce enough to be subject to individual property rights.

However, as demonstrated for water mills, not every natural resource follows the evolutionary theory of property rights (Bone, 1986; Rose, 1990). When water as an energy resource was becoming locally scarce as a result of the industrialization in the 19th Century, the scarcity has led to less, rather than more, clearly defined property rights over water in the United States (Horwitz, 1977). In those instances where water was used for operating water mills, instead of human, industrial or agricultural consumption, water usage very soon developed the characteristics of a common pool resource (Ramseyer, 1989; Rose, 1990). In order to ensure the full use of this scarce resource, a legal environment had to be created that could prevent high transaction costs and could manage the natural resource as a partial public good. This historic example demonstrates that there should not be a universal presumption that private individual property rights should always dominate over the systems of collective ownership: courts have in the past considered the nature of the resource and the uses, private or public, to which it can be put under existing and evolving technologies (Rose, 1990; Hart, 1998).

The anomaly of resource management moving towards more common property characteristics when the value of the resource increases, can be explained by distinguishing between exclusion and governance (Smith, 2000). There are many examples of successful solutions to the 'tragedy of the commons' (Hardin, 1968) that rely on rules of use or governance rather than rules of access or exclusive ownership (Smith, 2002). Where RE is stimulated through state intervention, it can be anticipated that rules of governance will have an important role to play in resource allocation. Dedicated RE legislation will have to regulate, amongst others, zoning, planning objections, nuisance, property rights and contract rights. Considering the locally specific nature of many of these issues for smaller scale on-shore renewables, it would make sense for much of this governance to be devolved to the local level; a point that is supported by the Californian experience with modern solar access laws (Bradbrook, 1989).

11.6.5.2 Planning, land and sea use (AN)

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 can evolve social norms, enhance social visibility and contribute in clarifying social acceptance or conflicts of usages. Planning certainly runs the risk of multiplying administrative procedures, but an appropriate planning framework can also contribute in reducing hurdles at the project level, making it easier for RE developers, communities or households to access the RE resource and succeed with their projects. 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...), whose cumulative changes also gain in being regulated.

11.6.5.2.1 Wind Power

The local acceptance of wind power has been an issue in many countries. Even Denmark and Germany, which are known for their successful 'civic model' based on local ownership, are starting to face issues of local acceptance (Möller, 2009; Meyer, 2007). Land use / landscape planning is a way to regulate the access to the wind resource while accounting for the concern of the public and the local specificities (e.g. Nadaï & van der Horst, 2009). Its fine tuning is part of the challenges that policy makers face in adjusting the decentralization of energy policy to renewable energies (Kahn 2003; Soderholm & al., 2007 for Sweden; Smith, 2007 for the UK;

Nadaï, 2007 for France). The recent evidence as regards to wind power planning (Ellis & al. 2009 XX) shows that acceptance is a dynamic variable over the course of the planning / project process. Difficulties are increased by poor planning or project management, and insensitive decision-making processes such as: late public consultation, disqualification of opposition, adversarial climate, lack of neutral arbitrage ... (Cowell 2007, Toke 2005, Toke & al 2008, Meyer 2007, Wolsink 2000 XX). Top-down planning processes, because they rely on existing landscape norms/ values, tend to direct wind power deployment towards non-protected, allegedly 'less sensitive', areas and to increase social and environmental injustice (Cowell, 2009 XX). Conversely, planning approaches which are participative (Haggett, 2008 XX; Mclaren Loring, 2007 XX) and attentive to the potential for social innovation at the local level contribute to a fair access to the resource (Nadaï, 2009 JPTP; Labussière & Nadaï, 2009 & 2010).

11.6.5.2.2 Ocean Energy

The planning of sea space is necessary to coordinate national plans for the energy transition, to regulate/mitigate conflicts of usage, and to allow for simpler downstream administrative procedures in the development of RE projects.

The development Marine Spatial Planning (MSP) in Europe is recent. Only a few planning schemes have been completed (e.g. Belgium, Germany and Netherlands). They tend to emphasize the ecological dimension; the social and economic sustainability are not systematically integrated. These approaches still lack the necessary international perspective, notably concerning the Exclusive Economic Zones (EEZ) for which countries by international law have a responsibility towards sustainable use of its resources (Douvere & Ehler, 2009 XX; Stel & Loorbach, 2003).

Different from land planning, MSP was initially rooted in ecosystem and integrated management approaches, with an emphasis on ecology and place-based management. It is only recently that attention has been placed on managing the multiple uses of the marine space, including the production of renewable energies (offshore wind power and ocean energy) and the broader social and economic issues (e.g. Side et al. 2002 for the UK). Recently, guidelines for MSP have been developed under the umbrella of international institutions (Douvere & Ehler, 2009; UNESCO, 2009 XX), which propose an operational framework to conserve the value of the marine heritage while simultaneously allowing sustainable use of the economic potential of the ocean.

The development of MSP is likely to meet some resistance, as do ecosystem approaches to marine resource management (Murawsky, 2007). Indeed, both approaches imply broader stakeholder participation in the overall management of the sea space, which is new. In particular, the importance of the offshore activity to the onshore communities and economies is not always well integrated in these plans. First studies show nonetheless that local stakeholders can be positively disposed to a local MSP process if it incorporates meaningful local involvement (Flannery, 2008).

11.6.5.2.3 Other Renewable Energies

Small scale RE systems raise various types of planning issues. The German and Japanese experiences with solar energy have proved that the lower costs of this technology relied on a large array of factors (e.g. mature markets, lower non-R&D market barriers, improved distribution channels, installation practices, inter-connection) including siting and permitting conditions. In developing countries, the development of small solar systems (cookers, water heaters, PV) depends on the planning of the buildings while under construction (kitchen, veranda, roof). Micro/pico hydro systems also require proper planning in order to protect the quality of drinking water supply and to minimize ecological impacts, landslides and irrigational impacts.

In the case of biomass energy, nature conservation policies and targets for biodiversity protection determine the extent to which nature reserves are protected; they also set standards for the management of other lands. The regeneration of degraded lands (and required preconditions) is generally not attractive for market parties and requires government policies to be realized.

11.6.6 Innovation pathways in the context of a global economy: Supporting Technology Transfer

"Technology transfer" is broadly defined as 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 (Keller, 2004, IPCC, 2000). The focus in this section is on international technology transfer in keeping with Article 4.5 of the Framework Convention on Climate Change, which states that developed country Parties "shall take all practicable steps to promote, facilitate, and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention," and to "support the development and enhancement of endogenous capacities and technologies of developing country Parties."

The theory and practice of international technology transfer is, in many ways, still in its infancy. There is no dominant view as to the most effective means of transferring technology from developed to developing countries – and in some cases vice versa – although there are case studies of the many efforts that have been relatively ineffective in the past, as well as some of the few, more positive experiences.

A comprehensive framework for evolution of technology transfer has emerged, which recognized the necessary complementary aspects of hard ware, org ware and soft ware as detailed in Section 11.6.2, as well as opportunities for technology leapfrogging[14] Most importantly, the roles of government, the private sector, research and NGO organizations have become increasingly clear, in particular to create the enabling environments, education and investment mechanisms required to create sustainable, scalable businesses that take full advantage of the innovation cycle. As show in Figure 14 below, both technology push and market pull dimensions must be addressed to overcome barriers and enable sufficient technology diffusion at speed and scale via profitable businesses. Within this the role of government in providing not only a supportive policy environment, but also funding, fiscal policies, and the establishment of standards and regulation, is recognized as a critical element.

[14] Technology Leapfrogging has been defined as the use and development of advanced technologies in emerging economies that explicitly skips generations of technologies. For example, the development of and wide spread use of cellular phones for ubiquitous service, skipping the expansion of traditional physical wire networks.

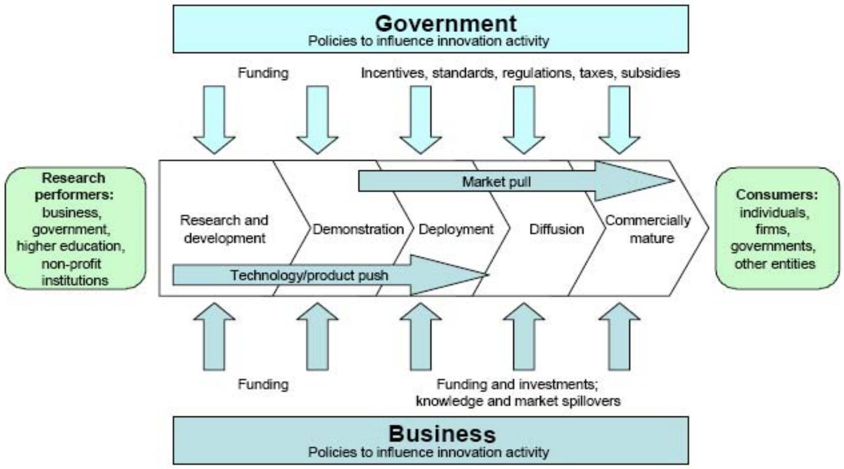


Figure 14: Factors influencing the Innovation Cycle (Metz et al, 2000)

Okwell et al (2008) have proposed a framework for technology transfer for low carbon technologies to developing countries. Principle considerations include:

(1) technology transfer needs to be seen as part of a broader process of sustained, low carbon technological capacity development in recipient countries;

(2) technical maturity as well as localization may be required for successful comprehensive "technology transfer" to occur. For example, photovoltaic lighting in rural emerging economies may be based on mature solar cell technologies, and includes the system design, installation and training that are specific to the local market conditions. Additionally, barriers to transfer and policy responses will vary according to the stage of technology development as well as the specific source and recipient country contexts. That is, less mature technologies may require government development support for maturation and localization, as well as policy and regulatory advances to address the recipient country market barriers.

(3) less integrated technology transfer arrangements, involving, for example, acquisition of different equipment from multiple manufacturers, are more likely to entail knowledge exchange and diffusion through recipient country economies. In this case, system design and integration will predominantly occur in the recipient country and will drive expansion of local knowledge as the market expands. Recipient firms that, as part of the transfer process, strategically aim to obtain technological knowhow and knowledge necessary for innovation during the transfer process are more likely to be able to develop their capacity as a result;

(4) the transfer of Intellectual Property Rights (IPRs) may sometimes be a necessary part of facilitating technology transfer, but they are not likely to be sufficient to lead to success. Business management, technology risk and adaptive capacity may be more critical considerations;

(5) national and international policy interventions have significant influence. For example, aggressive national policies for RE in China and India have provided significant influence on the development of locally-based solar and wind energy companies that are increasingly active internationally.

Further, as reported by the Expert Group on Technology Transfer (FCCC/SB/2009/3), a comprehensive framework for technology transfer includes the following key elements:

(a) Expanded **research, development and demonstration**;

(b) Enhanced **enabling environments and capacity-building** to overcome policy, information, capacity and infrastructure barriers to technology deployment and diffusion;

(c) Increased **financing facilitation and support** to increase the level of investment in technologies;

(d) Integrated industrial and societal **sectoral planning and cooperation** to implement technology transfer initiatives as part of broader programs.

The strength of domestic policy environment is critical to successful technology transfer and may lead to reverse transfers as well. Lewis and Wiser (2007) have looked at policy environments relative to wind industry development and technology transfer. They examine the importance of national and sub-national policies in supporting the development of successful global wind turbine manufacturing companies. Comparing across 12 countries, they report that strong domestic market conditions are critical to the establishment of a domestic industry and that "reverse" technology transfer can occur in instances where the strong developing country industry may then compete internationally.

Further, recent literature also reports on the importance of innovation of both technology and business models with examples from power systems design, manufacture, sales, operations and maintenance, to "segment specific" business and technology solutions. For example, business models such as Grameen Solar [Authors: country?] (Martinot 2001) or Thai Biopower [Authors: country ?] (Forsyth 2005) have been evaluated to show that technology transfer can occur successfully with relatively low technology risk, in combination with financial innovation and business model innovation, within the enabling frameworks of domestic and international policies. Similarly, once businesses are established with sufficient financial resources to support local innovation, opportunities arise for technology and solution development that then lead to expanded technology transfer either to other developing countries or in reverse to developed countries in which the new solutions open up new market segments and solutions. (Immelt, 2009).

Studies on technology leapfrogging* for RE and other low carbon technologies are just emerging. For example, Lewis has completed a comparative evaluation of wind technology transfer in India and China, noting 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, 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, Unruh et al (Unruh 2006) reports that industrializing nations will be subject to Carbon Lock-In due to the substantial investments 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.

11.6.7 The economic implications of interactions between change mitigation policies and RE support policies

Policies to promote climate change mitigation and support RE need to take into account the underlying 'market failures' that stand in the way of these objectives (See Section 11.4). But their interactions with the rest of the economy and each other need to be taken into account if they are to be cost-effective and to avoid or minimize undesirable side effects.

11.6.7.1 The role of multiple 'market failures'

Multiple 'market failures' warrant the use of multiple policy instruments, each targeting a particular failure but taking account of their consequences for the rest of the economy (Tinbergen, 1952). Market failures are phenomena that prevent private economic agents participating in markets producing by themselves a pattern of production and consumption over space and time in which no-one can be made better off without someone else being made worse off; that is, they prevent a 'Pareto efficient' outcome (Bator, 1958). When they are present, public policy interventions can, in principle and if properly designed, enhance overall wellbeing. Policies may also be needed to compensate for the adverse impact of other public actions ('government failures' e.g. due to lobbying).

The market failure underlying anthropogenic climate change is due to the externalities created by greenhouse gas emissions – emitters have no incentive to take into account the damage their emissions do to others. But various market failures also afflict innovation (Stern, 2007, Part IV; Jaffe *et al*., 2005). These include:

- First, there are spillovers from the creation of new knowledge, because its use by its creator does not prevent its use by others (the use of knowledge is 'non-rival').
- Second, the benefits to society as a whole from R&D investment are often much greater than the benefits captured by the firms undertaking the investment (section 11.6.1); in other words, the social returns exceed the private returns (Jaffe, 1986; Griliches, 1992), on average by a factor of four (Popp, 2006). Popp argues that the social returns in environmental and energy R&D are comparable to those in other fields. Some approaches to correcting this problem can create monopoly power, which can give rise to a market failure itself.
- Third, there are externalities from the adoption of new technologies, due to network effects, learning-by-using and learning-by-doing (Jaffe *et al*., 2003; Edenhofer *et al*., 2005). These can lead to path dependence of the choice of technologies and the 'lock-in' of high-carbon plant and equipment discussed in section 11.6.1 (Unruh,2000; Acemoglu *et al*., 2009).
- Fourth, the generation of knowledge is affected by uncertainties and asymmetric information (Böhringer *et al*., 2009).
- Fifth, market failures in the rest of the economy can have implications for climate change mitigation and RE support. For example, Sjögren (2009) and Guivarch *et al.* (2009) explore the interaction of environmental and labour market imperfections.

No single policy instrument can correct fully all the relevant market failures. Indeed, in general, there need to be at least as many policy instruments as there are objectives for policy-makers

(Tinbergen, 1952). Otherwise, objectives have to be traded off against each other, and the costs of achieving any one objective are higher, because other objectives have to be sacrificed to some extent.

Thus, in the context of climate change, carbon pricing on its own is likely to under-deliver investment in R&D of new technologies (Rosendahl, 2004; Fischer, 2008)An optimal portfolio of policies can achieve greenhouse gas emissions reductions at a significantly lower cost than any single policy – although models suggest that the bulk of the emissions reductions will be brought about by the pricing element of the policy package (Richels and Blanford, 2008; Otto *et al.*, 2008; Fischer, 2008; Fischer and Newell, 2008).

In Fischer and Newell's model, for example, the portfolio entails an emissions price, an R&D subsidy, and a renewable generation subsidy. Applying their model to the U.S. electricity industry, they find that the use of their assumed RE support policies allows the CO_2 emissions price to be 36 percent lower than it would have to be if hitting the chosen emissions target were to rely on the emissions price alone. The authors find that, using only one policy at a time, emissions pricing is the most cost effective, followed by the tradable performance standard, a fossil fuel energy tax, and finally by a quota (RPS). Popp (2006a) demonstrates that policy-induced R&D in zero-carbon 'backstop' technologies[15], such as RE, increases welfare (compared with when only an emissions price is available), despite the resource costs entailed in R&D activities. The less that R&D elsewhere in the economy is crowded out, the greater the benefits of induced R&D (Popp, 2006b). Grimaud and Lafforgue (2008) also find that the optimal policy portfolio entails both emissions pricing and subsidies to renewables R&D. If a 'green' R&D subsidy is impossible, the carbon tax has to be higher; and if the carbon tax is ruled out, the R&D subsidy has to be higher. The R&D subsidy reduces the adverse impact of climate-change policies on the welfare of younger generations.[16] The advantages of using multiple instruments are also evident when considering mitigation options other than RE, such as carbon capture and storage (CCS). Gerlach and van der Zwaan (2006) examine three emission reduction options – energy savings, transition to low-carbon energy technologies and CCS – and five possible policy instruments – carbon taxes, fossil fuel taxes, RE subsidies, a portfolio standard[17] for the carbon intensity of energy production, and a portfolio standard for the use of RE. They find that CCS helps to reduce the cost of climate policies, but it is still desirable to roll out RE technologies on a large scale. The most cost-efficient policy is a carbon-intensity portfolio standard, with carbon tax revenues being recycled to support RE deployment.

The path dependency of technological choices and its implications for climate policy have also been analysed. Schmidt and Marschinski (2009) note that new technologies (e.g. mobile telephones) have often reached a stage where economies of scale in production, and the incentive

[15] A 'backstop' technology is a technical process that can be used instead of fossil fuels and can be implemented at constant marginal cost (Nordhaus, 1973).

[16] 'Feed-in' tariffs can be thought of as a form of renewables subsidy, with an element of carbon pricing to the extent that higher tariffs for renewables are reflected in higher average electricity prices to the customer and/or lower profits for the energy utility. The tariff may be differentiated according to the maturity of the renewables technology and hence act as an implicit subsidy to renewables R&D. [Authors: FIT is defined at the front of the chapter. Is this footnote needed here?]

[17] A 'portfolio standard' mandates that the portfolio of processes used to generate energy does not exceed a certain carbon intensity or comprises some particular proportion of RE sources.

of rising returns to R&D as output rises, have started to reduce costs fast enough to permit very rapid diffusion throughout the economy. Using a model of energy generation in which R&D responds positively to rising returns and there are several market failures, they find that multiple equilibria are possible, and policy instruments have to be used to push the world economy towards an equilibrium with high RE use. The optimal policy mix entails a tax on fossil energy, a R&D subsidy, an investment subsidy and a fee for employing initial public knowledge equal to the patent fee charged for private knowledge. Acemoglu *et al.* (2009) examine technical change that responds to the relative incentives across industry sectors, in a growth model with environmental constraints and limited resources. Technical change has to be encouraged in 'green' sectors rather than sectors producing greenhouse gas emissions. They show that profit taxes or other instruments are required in addition to a carbon tax, such as taxes on fossil-fuel energy production and innovation. But if renewables and fossil fuels are sufficiently substitutable as inputs to production, fossil-fuel energy production and innovation only has to be taxed temporarily, until the increased incentive for R&D in renewables has reduced their production costs enough to switch the economy on to a low-emissions growth path.

11.6.7.2 Climate change mitigation, renewables support and endogenous fossil fuel prices

Emissions pricing to tackle climate change may not have the desired impact on emissions or the development of RE if it drives down the pre-tax price of fossil fuels. Policy-makers need to take into account constraints and general equilibrium feedbacks throughout the economy when designing policy instruments and should not assume that market prices necessarily reflect resource costs in real-world settings (Dreze and Stern, 1990). An important example in the context of climate change and renewables policies is provided by the market prices of fossil fuels. These reflect not only the resource costs of extracting the fuels but also the rents accruing to their owners due to their scarcity value. Carbon pricing may simply push down the price received by the producers of fossil fuels, without affecting the final price to users; the scarcity rents from fossil fuel owners would then just be transferred to the authorities applying a carbon tax or to the owners of carbon emission quotas and the rate of extraction of fossil fuels would not be affected.

Indeed, if carbon pricing reduces the producer prices of fossil fuels, that will stimulate demand for them in any jurisdictions not applying carbon pricing. The prospect of policies to combat climate change intensifying and the carbon price rising over time may encourage fossil fuel owners to deplete their exhaustible resources more rapidly, undermining policy-makers' objectives for both the climate and the spread of renewables technology (Sinn, 2008). Insecure property rights – perhaps made more so by the risk of coercive international action to curtail the use of fossil fuels – exacerbate the risk. Hence climate change mitigation policies and RE support policies could undermine each other through their impacts on fossil fuel extraction in the near term.

This analysis suggests that the optimal trajectory for the carbon price for maximising overall social welfare may not be a steady rise at the rate of interest, or the discount rate plus the rate of decay of greenhouse gases in the atmosphere, as often assumed in models of optimal climate-change mitigation policy (e.g. Paltsev *et al*., 2009). More attention needs to be given to the economics of exhaustible natural resources. Some analyses have suggested that the optimal trajectory is downward-sloping when there are negligible extraction costs, which is not a bad approximation for the largest OPEC oil producers. Such a trajectory would persuade resource owners at least to delay extraction, which would be beneficial because of discounting (Sinn, 1982; Sinclair, 1992, 1994). If these are correct, then policy makers risk undermining their objectives, including the large-scale adoption of RE, if they introduce a regime that leads to a rising carbon tax over time. Policies to promote renewables may shift the whole carbon price trajectory downwards, increasing emissions (Hoel, 2009).

But the availability of cheap fossil fuels need not undermine climate-change policies completely.

First, the optimal carbon price is likely to rise for some time, even in models where ultimately all the fossil fuels are extracted (Ulph and Ulph, 1994[TSU: Reference missing from reference list]). Hoel and Kverndokk (1996) show that, if the stabilisation of greenhouse gases in the atmosphere is possible with some residual steady-state greenhouse gas emissions, the carbon price should rise until some moment before stabilisation is reached and then fall, so that fossil fuels are conserved until they can be used cheaply and without harming the environment, alongside RE.

Second, except with very stringent atmospheric stabilisation goals, climate-change policy may actually raise demand over time for oil (especially for transport) , while reducing demand for higher-carbon-content heavy oils and synthetic carbon-based fuels, which are also more costly to produce (Persson *et al*., 2007). Oil exporters would therefore not need to rush to extract their oil prematurely. Meanwhile, policies to promote renewables would have the easier task of making them cost-competitive just with coal and synthetic fuels (Grubb, 2001).

Third, it is an empirical question how fossil fuel resource owners behave. Pindyck (1999) finds that the standard model of exhaustible natural resource pricing (e.g. Dasgupta and Heal, 1980), which underlies Sinn's argument, works well for oil but less well for coal and natural gas. Fossil fuel owners may not be motivated wholly by profit maximisation, so other theories of price determination – such as those emphasising geopolitical and fiscal factors, particularly the need to finance public spending – may be appropriate, especially when the owners are public authorities such as sovereign governments (e.g. Slaibi *et al*., 2005). Similarly, customers for fossil fuels may affect market prices through their influence on their governments, who may use trade, energy and other policies to promote energy security (defined in terms of reliability of supply or scope for switching among suppliers). The corollary is that the interaction of policy instruments for geopolitical objectives with instruments for climate change mitigation and renewables support also needs to be considered.

Fourth, other policy instruments can be used to complement the pricing of the greenhouse gas externality and support for renewables. Sinn (2008), for example, emphasises the strengthening of property rights in fossil fuel ownership; technical means of decoupling the accumulation of CO_2 from carbon consumption, such as CCS and afforestation; and the advantage of strictly imposed quantitative limits on emissions over a conventionally calculated carbon tax. And OPEC members have argued for compensation for revenue losses incurred if they conserve their oil (Persson *et al*., 2007).

11.6.7.3 Potential problems with policy interactions

In principle, both carbon pricing and support for RE reduce the cost gap between renewable and conventional electricity generation. But if both are applied simultaneously, their impacts may not be the same as the sum of each implemented separately (De Miera et al., 2008; De Jonghe et al., 2009). The interactions of technology-specific policies – including renewable portfolio standards and feed-in tariffs – with market mechanisms such as a carbon tax, if not properly anticipated by policy-makers, can undermine the efficacy of each individual policy tool, and the suite of climate policies overall (Sorrel and Sijm, 2003; Rathmann, 2007).

If quantity-based tools (such as quota-based instruments) are used to pursue both climate-change mitigation and renewables objectives, it is possible that the permit price for one scheme will fall to zero (Unger and Ahlgren, 2005; De Jonghe *et al*., 2009). Conversely, if one price-based and one quantity-based measure are used (e.g. a carbon tax and a renewable portfolio standard), the fixed price imposed by one measure could influence the market price of the quantity-based measure in undesirable ways. Hence coordination of policy instruments and an appreciation of how they will interact are crucial, both at the initial stages of policy formation and later, when circumstances change and uncertainties diminish (or increase) (De Jonghe *et al*., 2009; Rathmann, 2007; Blyth et al., 2009; Verbruggen and Lauber, 2009).

11.6.7.3.1 Effects of RE Policies on the Carbon Objective

One way in which renewables policies may affect the carbon objective is through their indirect impact on the carbon price in a market-based cap and trade system. By substituting electricity generation away from fossil fuels, renewable mandates reduce the electric sector's overall CO_2 emissions. If there is an existing cap on emissions, this reduces the sectoral demand for allowances, and along with it the carbon price. A lower carbon price means that electricity producers' costs decrease, the marginal cost curve shifts, and wholesale electricity prices decrease (Rathmann, 2007; De Jonghe *et al*., 2009; Stankeviciute and Criqui, 2008). That contributes to a 'rebound' effect, tending to increase energy demand. If the potential impact of renewables policies on emissions is not considered at the time that the emissions cap is set, their impact is likely to be entirely offset by this and other induced increases in demand. Introducing financial support for renewables in addition to a carbon price signal, without adjusting the overall cap on emissions, will tend to lower the carbon price, because it reduces the level of abatement required from emissions sources within the trading scheme. The supply of allowances is fixed by the cap and the price of allowances will fall to bring the demand for allowances back into balance with the supply; the renewables support will just have redistributed the sources of emissionsPolicy can therefore fall into a trap in which carbon markets appear more and more insufficient on their own, apparently justifying more and more direct, technology-specific, support (Blyth *et al*., 2009). The weakened carbon price signal can then point path-dependent technological development and investment away from low-carbon technologies.

11.6.7.3.2 Effects of Carbon Pricing on RE Objectives

The design and stringency of carbon policy has been shown to have significant effects on the efficacy of renewable support policies as well. Fischer (2008) finds that a renewable support policy is much more effective in the context of a carbon price signal. But the stringency of emissions targets under a cap-and-trade scheme (or, in the case of a tax, the level and expected rate of increase) matters as well. It affects not only the expected price of carbon, but also the risks associated with investment in abatement. Also, prices in carbon markets have in general been very volatile, which is not unusual in cap-and-trade schemes to control pollutants because of the inelastic supply of quotas (Metcalf, 2009 [TSU: Only Metcalf, 2008 is listed in reference list – incorrect date?]).

Some of the volatility is likely to be due to the fact that markets such as the EU Emissions Trading Scheme are not yet mature; greater depth and breadth would reduce liquidity problems and the scope for strategic behaviour (e.g. exercise of monopoly power) by participants. Carbon prices also seem to have been correlated with the wholesale prices of natural gas (one of the most volatile commodity prices), oil and coal, reflecting variations in energy demand and the scope for switching commercial energy supplies among sources (Mansanet-Bataller, Pardo and Valor, 2007; Geman, 2005). Such interplay has significant implications for investment in renewable technologies, especially those that may involve technological spillovers, learning-by-doing, or long ramp-up times (Blyth *et al*., 2009; Fischer, 2008). It is difficult for governments to guarantee credibly the high and rising future carbon prices that justify high current expenditure on R&D; governments cannot commit their successors, and private agents are likely to suspect that they will act in a time-inconsistent manner (Helm *et al*., 2003).

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, albeit indirectly, by reducing the incentive to deploy renewables technologies within the borders of the renewable mandate (P. del Rio *et al*., 2005). In a second-best world of below-optimal carbon pricing, stronger public support for innovation and R&D may be justified, particularly if spillover effects are significant (Fischer, 2008; Sorrell, 2003).

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 11.7 differs from the previous sections because it focuses on the requirements of achieving a structural shift from conventional energy sources to renewable energy. It explores what policies are required for RE to become the standard energy provider in a low-carbon energy economy. Section 11.5 set out available policies, and evidence about their success and failures. 11.6 explained the enabling environment which is required to maximise the success of those policies. 11.5 and 11.6 together highlight the ‘best practice’ policies available and any country which put in place both those policies and enabling environment could expect success in delivering renewable energy deployment.

Some countries are fortunate in that they have mainly renewable energy systems based on an extraordinary resource – for example, Iceland, Norway, Costa Rica. Most countries, however, are in the position where they have to develop their available RE resources within an energy system dominated by fossil fuels and/or nuclear. Even those countries which are considered to have successful renewable energy policies in place are still reliant on ‘conventional’ energy sources for the majority of their energy. There are very few towns or communities around the world where renewable energy has moved from a conventional energy system to becoming a standard energy provider (ie where RE is the main provider of energy), and then usually only within a sector, ie within electricity or heat. Rarely is RE the provider of more than 50% of total energy of a community. In this sense, these towns and communities have undertaken a structural shift in their energy use and it is instructive to understand how it came about, and what it means for RE policies and financing.

This section explores:

- what the wider requirements are, beyond renewable energy policies and their enabling environments, to enable this structural shift;
- it highlights some of the key choices that policymakers, companies, investors and consumers face ;
- and what that means for societal activities, practices, institutions and norms.

Section 11.7.1 briefly revisits past transitions between energy systems and discusses lessons that can be learned for enabling a structural shift, as described above.

Section 11.7.2 explores energy transitions. However, its discussion of transitions is differentiated from Section 11.2 or 11.6, which provides an overview of the transition management literature. This section reviews what has been written about the enabling of a large structural shifts where the rate of deployment of RE could increase rapidly. This literature is minimal - as opposed to literature on transition change which is large and tends to focus on how a technological change begins and develops (Geels, 2005; Smith et al, 2005, van Bruinsma, 2008; Praetorius et al, 2007)

Section 11.7.3 describes what a world, in which RE is the standard provider, might look like. It assessed what the key components have come together in places, whether small cities and islands or larger examples, where RE has become a standard energy provider.

Section 11.7.4 explains what the key issues and policy choices are to achieve a structural shift in the way we use renewable energy, and what the implications of this are for policymakers, companies, investors and consumers. In doing so, this section explores ideas ofincremental versus step change or ‘bricolage versus breakthrough’ towards a structural shift. As such, this section points to the need for ‘deliberate’ policy.

11.7.1 Energy Transitions

Transition from one energy source to another have characterized human development and a shift from the current energy system to one that includes a high proportions 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).

As Figure 15 shows, movements from one energy source to another have occurred with clear patterns of rapidly increasing use and then a falling back as a new source of energy emerges and develops. Each new source of energy provided a new and desired service which displaced and augmented the services available from the previously dominant energy sources.

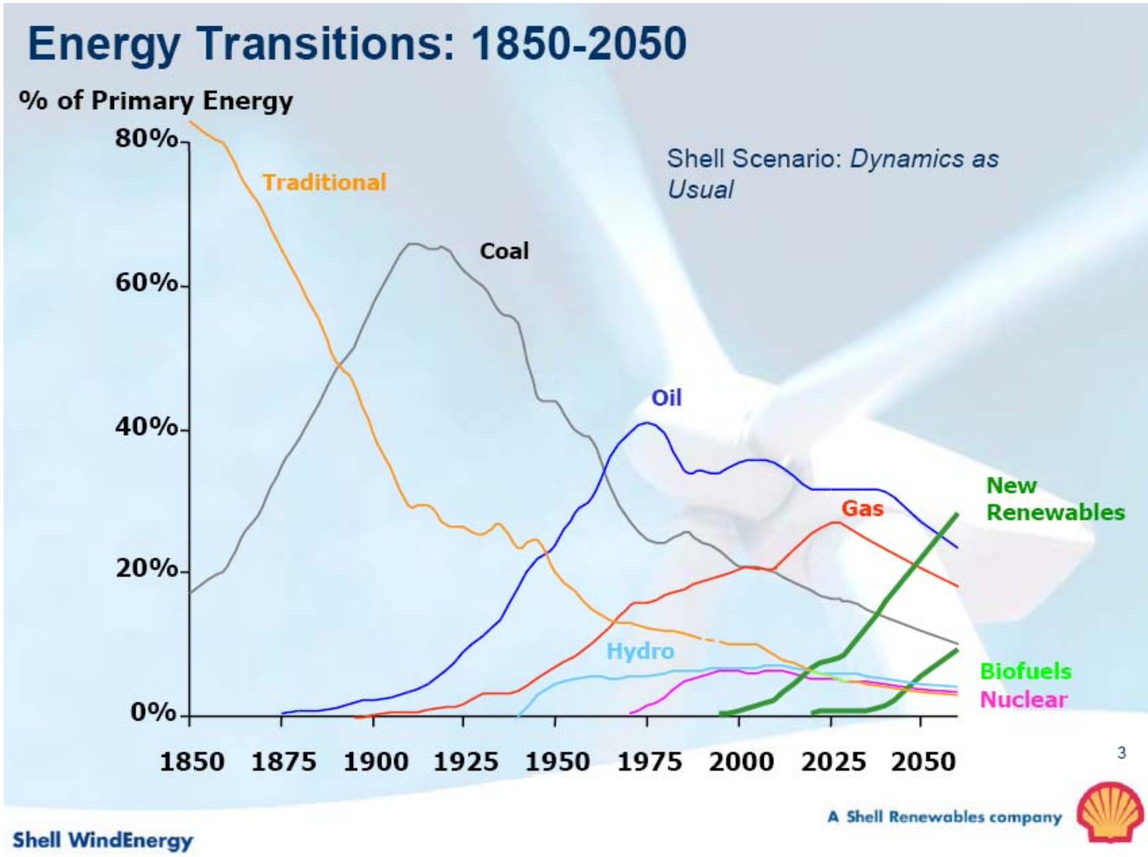


Figure 15:) [Authors: Title missing. SSREN Version of Figure Needed] (Poulson, S. 2002) (http://www.wind-energie.de/fileadmin/dokumente/Themen_A-Z/Ziele/Shell_Vortrag_EE_Strategie_2003.pdf) [TSU: URLs are to be cited only in footnotes or reference list.]

Until the early 18th century, muscles, firewood and charcoal were our main sources of energy, augmented by the limited use of water and windmills, with human lifestyles dependent on living within nature's productive capacity (Girardet and Mendonca, 2009). However, 'new' energy services were required and developed in order that the new indstrial technological innovations could be exploited. Coal is a compact high-density source of energy which was easily transportable and able to fuel the new energy services required by the industrial revolution and also the energy service requirements of the railways which were largely displacing canal and river haulage. Later it was also used as a fuel for electricity. Oil demand developed primarily to fuel automobiles and as another fuel for electricity. More recently, natural gas has displaced coal in certain countries for cheaper and more flexible electricity power plants and for domestic heating.

At the same time, new infrastructures are required to match the energy transition. For example, the societal desire for automobiles and mobility 'drove' the substantial infrastructure building required to satisfy demand. The timescales of these energy source and their linked infrastructure replacements or developments varied by countries but occurred over several decades. Moreover, each transition was supported and strengthened by policy intervention.

Thus, a transition to RE is different from those undertaken in the past because:

- It must occur more rapidly
- because RE provides similar services from other energy sources, except for their environmental benefits which are currently unvalued because most countries have failed to internalise all of their external costs
- while renewable energy have great potential and all countries have domestic resources , fossil fuels have advantages because of its greater energy density and portability

The range of RE sources and technologies can provide the same energy services as conventional energies (for example, light, heating and cooling, mobility). There are market niches around the world where RE has provided new and cheaper services similar to those that helped initiate past transitions to other energy sources (e.g. rural electrification). In addition, a very limited but increasing number of communities, cities and areas now run on 100 percent RE, or aim to do so (International Energy Agency (IEA), 2008a; Droege, 2009; International Energy Agency (IEA), 2009b). The number of these niches or small 'beacons' are likely to expand as their 'different' value become clearer, as technologies develop, and as the relative prices of conventional energy sources becomes more expensive relative to RE options.

Nevertheless, the move, in this niches, from the existing energy system dominated by non-renewable energies to renewable energies has, for the most part, been the result of deliberate policy intervention and has not been driven by societal demand alone. Further deliberate policies will be required to bring about a structural shift at national and global levels as well. Policy requirements will have to be RE policy and enabling environment focussed. But policy will also has to ensure that the benefits of RE, such as climate change mitigation or energy security, and their linked attributes of new jobs, new manufacturing or industrial opportunities (see Section 11.3) are valued highly enough so that they become viewed to be in the interests by society in order that they, along with Government, businesses and so on reciprocally support eachother to both pull and push RE into being the standard energy provider (Fri, 2003; Foxon and Pearson, 2008).

11.7.2 A Structural Shift

This section discusses the meaning of a structural shift; and explores whether that structural shift occurs as a result of a big step or through incremental, small changes; and how it might be stimulated.

11.7.2.1 What is a structural shift?

Policies and support may be provided which presage a different level, or type, of support. The building of Masdar, the RE powered city in Abu Dhabi, and the successful development of Desertec – the supergrid which is intended to link Europe, the Middle East and North Africa to transport solar power - are both examples of policies and aspirations intended to encourage a new scale of supply side options. Decentralised and distributed generation are other options which, if deployed sufficiently, may also represent a different level of support.

This is an example of a structural shift related to technological use. However, structural shifts may also occur in any of the sub-components of the energy system, which make up the enabling environment, for example a transformation of social norms would lead to a structural shift in society’s ‘normal’ attitude towards energy - thereby delivering a step change in energy use. Structural shifts may within institutions, the political, finance and business sphere (Fouquet and Johansson, 2008; International Energy Agency (IEA), 2008a; Droege, 2009).

It could be argued that Germany has undergone a structural shift in the political sphere in that RE is now so deeply embedded into German policies, that the attitude to renewables is structural to Germany and has moved beyond being a political position. For example, the German Chancellor Angela Merkel said during a speech in 2005: 'Increasing the share of electricity consumption covered by renewable energy sources to 20 percent is unrealistic.' (Pieprzyk and Hilje, 2009)’ Yet, the announcement by Angela Merkel of her new Government’s continued support for the RE policies in Germany (26/10/2009) combined with the data that Germany is now on its way to achieving its goal of 30 percent by 2020 ((Pieprzyk and Hilje, 2009)’ may be viewed that RE is becoming mainstream within the energy policy of a European country. In less than 20 years, Germany transitioned from having substantial coal subsidies and a powerful coal lobby to a nation with broad, multipartisan support for RE that helps to sustain and improve upon supportive policies for RE while phasing out those for fossil fuels.

11.7.2.2 Incremental versus Step-Change

This section argues that even though the energy system and society is likely to look very different, were RE the standard energy provider, it is not a big step which is required to get there rather a number of incremental steps, which over time results in a structural shift Garud and Karnoe (2003) been termed this ‘bricolage rather than breakthrough’.

Garud and Karnoe (2003) review the pre-2003 literature concerning big shifts. They analyse in detail the parallel efforts of the USA and Denmark in developing wind technology. They wanted to answer the question how it was that a bricolage approach that begins with a low-tech design but ramps up progressively is able to prevail over a high-tech breakthrough approach.

They argued that the latter has an inherent disadvantage in that in order to generate a breakthrough it ends up stiflying micro-learning processes that allow the mutual co-shaping of emerging technological paths to occur. Co-shaping occurs at several points of interaction between desiners and shop floor workers; between produces and users; and between policy makers and regulators. ‘Development of technologies entails not just an act of discovery by alert individuals or speculation on the future but also the creation of a new path through the distributed efforts of many’. Attempts at breakthrough can result in ‘dampening learning processes required for mutual co-shaping’ of technology development. However, bricolage preserves emergent properties. It is a process ofmoving 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. Garud and Karnoe go on to say that understanding these processes may be particular valuable in situations characterised by complex non-linear dynamics among the actors, artifacts and rules that constitute a technological path.

The conclusion to be drawn from this section by policy-makers, business, investors and individuals is not that achieving a future where RE is a standard provider is difficult, but that each step taken, whoever by and however small, is adding to that structural shift . But to achieve a step change to an energy future that is predominantly renewable and low-carbon will require that the rate and scale (e.g., not only Germany or small towns and communities) of transformation be rapid and broad. These factors are driven by the unlocking or removal of barriers and overcoming of hurdles by combinations of policies (International Energy Agency (IEA), 2008a; van den Bergh and Bruinsma, 2008; Praetorius, Bauknecht et al., 2009; UNFCCC, 2009).

11.7.2.3 Characteristics Where RE is the Standard Energy Provider

It is possible to sketch out conceptually the characteristics of a place, society or world where RE is the standard energy provider. We might expect that:

- the enabling environment set out in 11.6 is in place:
- an enabling environment combines technological, social, instiutional (including regulatory) and financial dimensions and recognises that technological change and deployment comes through a systemic and evolutionary, rather than linear, process.
- RE has become cost-competitive, if not cheaper, with non-RE sources through technology advances, economies of scale, and the incorporation of environmental externalities;
- fossil fuels are not eligible for tax breaks, or any other economic breaks/subsidies;
- companies also have ‘environmental’ bottom lines in addition to monetary valuations, so that companies, along with countries, can be assessed in terms broader than their economic value;
- an international system of technology and capacity transfer is in place to ensure the take-up of the most energy efficient technologies globally;
- individual behaviour and lifestyles reflect environmental and and understanding that countries and peoples around the world are inter-linked and dependent on eachother
- waste resources, agricultural practices and energy use fit seamlessly together;
- energy is used in the most efficient manner appropriate for a place or country

11.7.2.4 RE as the Standard Energy Provider

Although a great many towns, local authorities, small countries have decided to move toward sourcing 100% of their energy from RE, there are few examples of a structural shifts to RE (combined with energy demand reduction measures) that have actually occurred to date, where renewable energy is the standard energy provider. On the one hand, those locations that have made this transition offer limited potential for learning because they are at the forefront of an energy system change are unlikely to be representative of broader society; moreover, what worked for them may not work for wider global society. And yet their experiences can provide very useful insights by illuminating how and why such change occurred.

The chapter has a number of case study boxes (ie Box 1) of successful examples of RE deployment. Each box explains the key factors in how this has occurred. The primary sources for the examples are Droeghe’s 100% Renewables and the IEA’s Cities, Towns and Renewable Energy.

The lessons learnt from these Case Studies in terms of a structural shift are as follows:

- 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 have a number of factors in common: political will; broad-based support and stakeholder involvement; have taken advantage of synergies between RE and energy efficiency; they have targetted policies to support RE; they have generally relied on a variety of RE resources and technologies
- 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 eachother 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).

A recent IEA survey of RE cities and communities 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 there 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. These two visions are presented to stimulate the reader to contemplate the question of what sort of world people may want to inherit (IEA, 2009, p30). The key point is that technology and behaviour are intimately linked and should be viewed positively together. The case studies of the ‘beacon’ cities and communities supports this view and is represented in Figure 16 below.

Alternative Paths to -80% by 2050

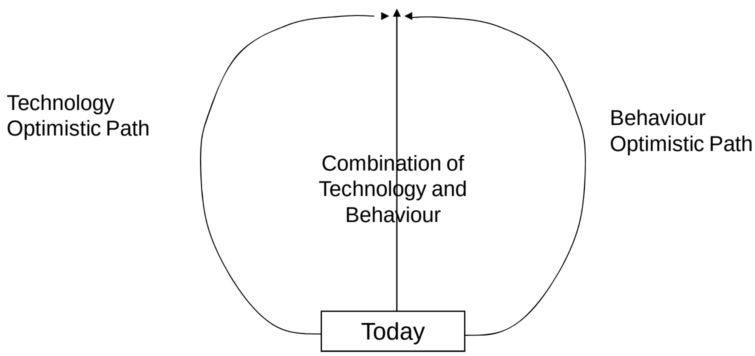


Figure: Alternative Pathways to RE on the standard energy Provider

Figure 16: Alternative pathways to RE on the standard energy provider [TSU: Repeated exactly in figure – caption drawn into figure can be deleted.]

11.7.3 Key Choices and Implications

Although to date RE has become the standard energy provider in only a few locations, a much broader shift is possible and it is possible to draw lessons from their experiences. Policy makers/governments face several key choices that will 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), 2009a; Praetorius, Bauknecht et al., 2009):

- the extent to which policy makers decide to undertake a 'step change', in other words become determined to increase RE deployment. If this occurs then other policies will follow: for example, the removal of non-economic barriers; the implementation of clear, consistent policies appropriate to technologies and place; and ensuring that an enabling environment occurs.
- the policy priority – whether this is for a technology optimistic view; whether one that sees individuals and lifestyles at its future, or one that sees them as needing to be inter-related
- the degree to which policies are devolved down from national to local governments, and open to individual choice
- the degree to which 'spillovers' or the side effects of renewables are a priority for example job creation, new company entrants to the energy world, manufacturing ability

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.

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), 2008a).

11.7.4 Conclusions

This chapter comes to a number of fundamental principles about RE deployment:

- Targeted RE policies are required to overcome numerous barriers that limit uptake and investment in private R&D and infrastructure and to accelerate RE deployment. Market signals alone—even when incorporating carbon pricing—have been insufficient 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. Good practice exists and it is important to learn from it.
- To be as effective as possible, policies must be well-designed and –implemented, taking into account the state of the technology, available RE resources, and responding to local political, economic, social and cultural needs and conditions.
- Well-designed policies are more likely to emerge, and they will be more effective in rapidly scaling up RE, in an enabling environment. An enabling environment combines technological, social, institutional and financial dimensions, and recognizes that technological change and deployment come through a systemic and evolutionary (rather than linear) process.
- The global dimension of climate change and the need for sustainable economic development call for new international partnerships on deploying RE that recognizes the diversity of countries, regions and business models. RE deployment can contribute to sustainable development, and new finance mechanisms are required to stimulate technology transfer, investment and RE deployment.
- A structural shift is required if RE is to become the standard energy provider in a low-carbon economy. Political will and effective policies for RE deployment will be required, in concert with improvements in energy efficiency, and important changes in societal activities, practices, institutions and social norms will be needed.

Box 1: Germany

(Droege, 2009; Sawin and Moomaw, 2009)

Germany enacted its first feed-in law in the early 1990s and within a decade was a world leader in RE capacity and production, despite the fact that its renewable resources are a fraction of those available in many other countries. Between 2000 and 2008, the share of Germany's electricity from RE increased from just over 6 percent to more than 15 percent (German Federal Ministry for the Environment, 2009). Over the past decade, electricity generation from wind in Germany has increased by a factor of 10, and from solar PV by a factor of more than 100 (Pieprzyk and Hilje, 2009). The contribution of renewables to the nation's final energy demand has tripled (Pieprzyk and Hilje, 2009), to almost 10 percent of final energy demand in 2008 (Pieprzyk and Hilje, 2009).

Box 2: Denmark

(Droege, 2009; Sawin and Moomaw, 2009)

Denmark's economy has grown 75 percent since 1980, while the share of energy from renewables increased from 3 percent to 17 percent by mid-2008.[18] In 2007, the country generated 21 percent of its electricity with the wind, and wind power occasionally meets more than 100 percent of peak demand in areas of western Denmark (Kanter, 2007). As part of the European Union's energy package that was finalized in 2009, the Danes aim to get nearly 20 percent of their total energy from renewable sources by 2012 and 30 percent by 2020 (Official Journal of the European Union, 2009). During the 1973-74 OPEC crisis, Denmark was 99% dependent on imported energy. Now, Danish firms currently produce one-third of the world's wind turbines - nearly a $6 billion export industry. The Danish government covered 30% of wind investment costs from 1979 to 1989, with loan guarantees later being provided for large turbine export projects. On the demand side, the government established utility purchase mandates at above market prices. The government also funded research support for wind turbine design and manufacturing improvements. Moreover, financial incentives such as tax free income for wind generated by cooperatives has led to a high degree of citizen participation in the wind industry, with 80% of Denmark's turbines owned by over 150,000 Danish families. This example illustrate that building a successful domestic renewable industry is a long-term investment that requires sustained consistent policies but that can lead to a thriving industry and export opportunities (Engel and Kammen, 2009; Garud and Karnoe, 2003).

[18] Denmark's economy quoted in European Wind Energy Association, "With Increased Research, Renewable Energy Can Supply More than 20% of Europe's Energy Demand," press release (Brussels: 3 April 2008); renewable share in 1980 from Ministry of Climate and Energy of Denmark, "The Danish Example—The Way to an Energy Efficient and Energy Friendly Economy" (Copenhagen, Denmark: February 2009), available at www.cop15.dk/en/menu/About-Denmark/The-Danish-Example; 2008 share and 2011 and 2020 goals from Karl Larsen, "Denmark Continues its Renewable Tradition," Renewable Energy Focus, July/August 2008, p. 66; Geoffrey Lean and Bryan Kay, "Four Nations in Race to be First to Go Carbon Neutral," (London) The Independent, 30 March 2008.

Box 3: China

(Droege, 2009; Sawin and Moomaw, 2009)

China leads the world in the use of solar water heating, small hydropower, and production of solar cells (REN21, 2009a). The nation has experienced explosive growth in its wind industry, with installed capacity increasing more than fivefold between 2005 and 2008, and China's wind capacity will soon surpass its nuclear capacity (REN21, 2009a).[19] In 2009, the government tripled its 2020 wind target, from 30 gigawatts (GW) to 100 GW, and recently pushed its 2020 solar target from 1.8 GW to 20 GW (Mendoza, 2009).

Box 4: Israel

(Droege, 2009; Sawin and Moomaw, 2009)

Israel is a world leader in per capita use of solar water heating. The technology has become mainstream thanks to a 1980s law requiring the use of solar energy for water heating in all new homes (European Solar Thermal Industry Federation, 2007).

Box 5: Güssing

(Droege, 2009; Sawin and Moomaw, 2009)

Güssing, Austria changed from being economically depressed to beng an an energy self-sufficient town that produced biodiesel from local rapeseed and used cooking oil, generated heat and power from the sun, and operated a new biomass-steam gasification plant that sold surplus electricity to the national grid (Austrian Federal Ministry for Transport, 2007).. This is an example of an 'active' choice for sustainable economic development.. Since the early 1990s, this town of 4000 inhabitants has reduced its carbon emissions by 90 percent, has created 1000 new jobs and attracted 60 new companies. It was kick-started by economic need: the town had a large electricity debt and set out to become self-sufficient in energy. Situated in a largely agricultural and wooded area of Austria, town leaders decided to move towards RE but with energy savings measures at its centre. Farmers are seen as the main energy providers, and have reportedly gained satisfaction at this community role. Güssing was transformed over a 15-year period to a community with high living standards, low unemployment and green tourism (IEA, 2008; Droege, 2009; IEA, 2009; Sawin and Moomaw, 2009).

[19] REN21, Renewables Global Status Report 2009 Update, pp. 8–9; China installed capacity from Shi Pengfei, "Wind Power in China," presentation in Guangzhou, China, 23 March 2007; Shi Pengfei, "2006 Wind Installations in China" (Beijing: China General Certification Center, 2007); GWEC, "US, China & Spain Lead World Wind Power Market in 2007," press release (Brussels: 6 February 2008); GWEC, Global Wind 2008 Report op. cit. note 5, p. 37; surpassing nuclear from "China to Have 100 GW Wind Power Energy Capacity by 2020," People's Daily, 4 May 2009.

Box 6: Kenya

(Droege, 2009; Sawin and Moomaw, 2009)

Kenya has achieved widespread acceptance and use of solar PV through informal information collection about performance of existing systems. Individual solar energy systems (20 watts or less) are now the largest form of rural electrification in Kenya (Kammen and Jacobson, 2005). Solar energy purchases have continued to grow in Kenya, with more than 35,000 systems sold each year aided largely by programs to improve consumer information, and only later with government support.

Box 7: Nepal

(Droege, 2009; Sawin and Moomaw, 2009)

Nepal - Domestic biogas development efforts has been started in early 90 in Nepal. The initiative has adopted public private partnership model. Only after implementing few thousand domestic biogas plants government has incorporated it into its programme policies and created a permanent institution in 1996. Renewable Energy policy has been promulgated in 2006 only. So in few developing countries like in Bangladesh, Nepal policies have been formulated only after few years of programme experiences.

Box 8: Bangladesh

(Droege, 2009; Sawin and Moomaw, 2009)

Bangladesh has brought the renewable energy policy in 2008, however, programme activities are already initiated before that. Policy is still not fully in place but Bangladesh is installing more than 12 thousands solar home systems monthly.

Box 9: El Hierro

(Droege, 2009; Sawin and Moomaw, 2009)

El Hierro, westernmost of the Canary Islands, aims to achieve 100 percent RE status by the end of 2010, a goal first set only 6 years earlier. The island is rich in wind, hydro, organic waste and solar resources and has been aided by European Commission subsidiesand Spanish support policies, including FITS. It is built on a background of positive experiences with RE and 'active' choice from an early solar energy programme, also supported by the regional Spanish ministry. This has been very successful from the point of view of jobs and skills for the island. From the 1980's onwards, El Hierro had investigated an economic development model which was not based on mass tourism and real estate values; and it was declared a World Biosphere Reserve by UNESCO in 2000. RE suited these other factors. It has a population of more than 10,600 people. The target is for all electricity, heat, and much of transport needs. Island inhabitants wanted to move away from mass tourism and needed model of development that would support their heritage. Policies included public education through publications, workshops, etc. and technical visits, training, etc. El Hierro is an example of achieving this goal on an island with weak, isolated grid. Expect to save >1.8 million euro/year in fuel imports and reduce CO_2 emissions by 19000 tons/year. (Droege, 2009, pp. 94-97; IEA, 2008; IEA, 2009).

Box 10: Samsø Island

(Droege, 2009; Sawin and Moomaw, 2009)

Samsø Island in Denmark has been an inspiration for other 100% RE islands around Europe. It won a Danish Government sponsored contest, as part of the 1996 Danish Energy Action Plan, to abandon fossil fuels. The islanders were not particularly pro-environment themselves at the beginning. Real effort on the part of those funded by the Action Plan gradually created a community spirit in support of it. Electricity was reasonably easily generated with wind power, but in order to fulfill the heating demand (with biomass, correct?), houses have been renovated to become energy efficient. Within an 8 year period from 1997-2005, heat demand declined by 10 percent while the share of demand met with RE increased from 25% to 65%Islanders now meet more than 100 percent of electricity demand with the wind and export the rest into the Danish grid. The positive 'spillovers' for Samsø's inhabitants include energy security, a booming ecotourism industry, income from sale of excess power, and expansion and diversification of the labor market (IEA, 2008; Droege, 2009; IEA, 2009)..

Box 11: Rizhao

(Droege, 2009; Sawin and Moomaw, 2009)

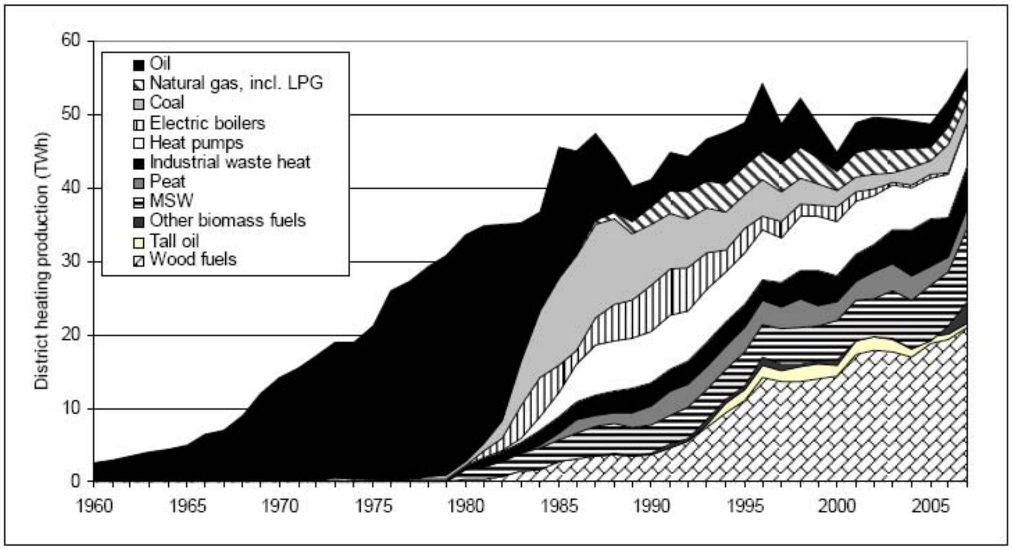
Rizhao, the 'solar city' of China set about in 2001 to adopt several policies and measures to popularize renewable technologies, including requiring solar water heating on all new buildings. Today, 99 percent of households in the city's central district use the sun to heat their water, most public traffic signals and streetlights are powered with solar PV, marsh gas from agricultural waste water is used to displace some coal for electricity generation and as cooking fuel, and more than 6,000 families use solar cookers (Bai, 2007). Rizhao has 3 million inhabitants. Air quality has improved considerably since the provincial government began investing in the industry to drive down costs of solar (esp. thermal); belief among city's leaders that cleaner environment will advance social, economic and cultural development {Xumei, 2007 #571. Also, solar heating is used for local greenhouses; marsh gas is captured and used as biogas for cooking.]

Box 12: Sweden

(Droege, 2009; Sawin and Moomaw, 2009)

Sweden has seen a major shift from fossil fuels to biomass for district heating over the past two decades (Sommestad, 2008). Thanks to taxes on energy and CO2, about 51 percent of the country's district heat is produced in combined heat and power (CHP) plants, and biomass and waste now account for 61 percent of total district-heat production. Although the first Swedish District Heating system was put in place in 1948, the rapid build-up started in the 1960's and now provides 86 percent and 69 percent of multi-dwelled and non-residential premises, respectively.

Figure 1 DH production in 1960-2007, broken down into fuels and energy sources. The curves have not been corrected for outdoor temperature variations



Source: 1960-69: approximations from DHA (2001); 1970-2007: SEA (2008a) [20]

Source taken from (Fig 3 taken from KEricsson, via Lars Nilsson)

1

[20] Lars J. Nilsson, Lund University, Sweden, e-mail to Catherine Mitchell, University of Exeter, U.K., 23 October 2009.

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APPENDIX 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; assume frozen technology or costs; or be described as “business 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
- **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) is the energy embodied in natural resources (e.g., coal, crude oil, natural gas, uranium) that has not undergone any anthropogenic conversion. It 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 **final energy** (e.g., electricity at the wall outlet), where it becomes **usable energy** (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.

- **Renewable energy**: Renewable energy is obtained from the continuing or repetitive currents of energy occurring in the natural environment and includes non-carbon technologies such as solar energy, hydropower, wind, tide and waves and geothermal heat, as well as low carbon technologies such as biomass. In this context, energy flow must exceed energy demand from that flow to be considered renewable and sustainable. For a more complete description see taxonomy of renewable energy types. Sometimes renewable technology is 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.
- **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 volcanoes, 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 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 switching 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, behaviour changes including consumer choices, lower population growth rates and geoengineering.

- **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 dioxide 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. Regions, Economic, IEA regions. Often the literature provides different categories such as economic regions as Developed Countries, Large Developing Countries, Other Developing Countries.
- **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, Oceania.
- **Regions, Economic (IEA)**:
  - 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
- **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**.
- **Solar Energy**: Energy from the sun that is captured either as heat, as light that is converted into chemical energy by natural or artificial 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 behaviour. 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 p0umping) or more commonly to run an electrical generator.

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APPENDIX II METHODOLOGY

A.II.1 Introduction

In any analysis that estimates the impacts of actions taken on reducing GHG emissions and climate change, one needs agreed upon assumptions that are both useful in providing direction and credible so that outcomes are seen as plausible. 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 some basic parameters use to analyse 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)
- 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 [TSU: in the appendix only] 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$[2]. Specific studies on which this document

[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.

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.

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)[3] equal to the discounted net expenses:

[2] Currency exchange rates and conversion factors for deflation used for the SRREN my be found at http://www.ipcc-wg3.de/internal/srren/fod

[3] This is also referred to as Levelised Price. Note that, in this case, MWh would be discounted.

$$LC = \frac{\sum_{j=0}^{n} \frac{Expenses_j}{(1+i)^j}}{\sum_{j=0}^{n} \frac{Quantities_j}{(1+i)^j}} \qquad (3)$$

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 3 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 formula 3.

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 technology 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 FAR (Sims, et al., 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.