TS

Technical Summary

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1. Overview of Climate Change and Renewable Energy

1.1 Background

All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, communication) and to serve productive processes. For development to be sustainable, delivery of energy services needs to be secure and have low environmental impacts. Sustainable social and economic development requires assured and affordable access to the energy resources necessary to provide essential and sustainable energy services. This may mean the application of different strategies at different stages of economic development. To be environmentally benign, energy services must be provided with low environmental impacts and low greenhouse gas (GHG) emissions. However, the IPCC Fourth Assessment Report (AR4) reported that fossil fuels provided 85%[1] of the total primary energy in 2004, which is the same value as in 2008. Furthermore, the combustion of fossil fuels accounted for 56.6% of all anthropogenic GHG emissions (CO_2eq)[2] in 2004. [1.1.1, 9.2.1, 9.3.2, 9.6, 11.3]

Renewable energy (RE) sources play a role in providing energy services in a sustainable manner and, in particular, in mitigating climate change. This Special Report on *Renewable Energy Sources and Climate Change Mitigation* explores the current contribution and potential of RE sources to provide energy services for a sustainable social and economic development path. It includes assessments of available RE resources and technologies, costs and co-benefits, barriers to up-scaling and integration requirements, future scenarios and policy options. In particular, it provides information for policymakers, the private sector and civil society on:

- Identification of RE resources and available technologies and impacts of climate change on these resources [Chapters 2–7];
- Technology and market status, future developments and projected rates of deployment [Chapters 2–7,10];
- Options and constraints for integration into the energy supply system and other markets, including energy storage, modes of transmission, integration into existing systems and other options [Chapter 8];
- Linkages among RE growth, opportunities and sustainable development [Chapter 9];
- Impacts on secure energy supply [Chapter 9];
- Economic and environmental costs, benefits, risks and impacts of deployment [Chapters 9, 10];
- Mitigation potential of RE resources [Chapter 10];
- Scenarios that demonstrate how accelerated deployment might be achieved in a sustainable manner [Chapter 10];
- Capacity building, technology transfer and financing [Chapter 11]; and
- Policy options, outcomes and conditions for effectiveness [Chapter 11].

The report consists of 11 chapters. Chapter 1 sets the scene on RE and climate change; Chapters 2 through 7 provide information on six RE technologies while Chapters 8 through 11 deal with integrative issues (see Figure TS.1.1). The report communicates uncertainty where relevant.[3] This Technical Summary (TS) provides an overview of the report, summarizing the essential findings.

While the TS generally follows the structure of the full report, references to the various applicable chapters and sections are indicated with corresponding chapter and section numbers in square brackets. An explanation of terms, acronyms and chemical symbols used in the TS can be found in Annex I. Conventions and methodologies for determining costs, primary energy and other topics of analysis can be found in Annex II. Information on levelized costs of RE can be found in Annex III.

GHG emissions associated with the provision of energy services is a major cause of climate change. The AR4 concluded that "Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHG (greenhouse gas) concentrations." Concentrations have continued to grow since the AR4 to over 390 ppm CO_2 or 39% above pre-industrial levels by the end of 2010. Since approximately 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, leading to a rapid growth in carbon dioxide (CO_2) emissions [Figure 1.6]. The amount of carbon in fossil fuel reserves and resources not yet burned [Figure 1.7] has the potential to add quantities of CO_2 to the atmosphere—if burned over coming centuries—that would exceed the range of any scenario considered in the AR4 [Figure 1.5] or in Chapter 10 of this report. [1.1.3, 1.1.4]

Despite substantial associated decarbonization, the overwhelming majority of the non-intervention emission projections exhibit considerably higher emissions in 2100 compared with those in 2000, implying rising GHG concentrations and, in turn, an increase in global mean temperatures. To avoid such adverse impacts of climate change on water resources, ecosystems, food security, human health and coastal settlements with potentially irreversible abrupt changes in the climate system,

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[1] The number from AR4 is 80% and has been converted from the physical content method for energy accounting to the direct equivalent method as the latter method is used in this report. Please refer to Section 1.1.9 and Annex II (Section A.II.4) for methodological details.

[2] The contributions from other sources and/or gases are: CO_2 from deforestation, decay of biomass etc. (17.3%), CO_2 from other (2.8%), CH_4 (14.3%), N_2O (7.9%) and fluorinated gases (1.1%).

[3] This report communicates uncertainty, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of the approval of this report, IPCC uncertainty guidance was in the process of being revised.

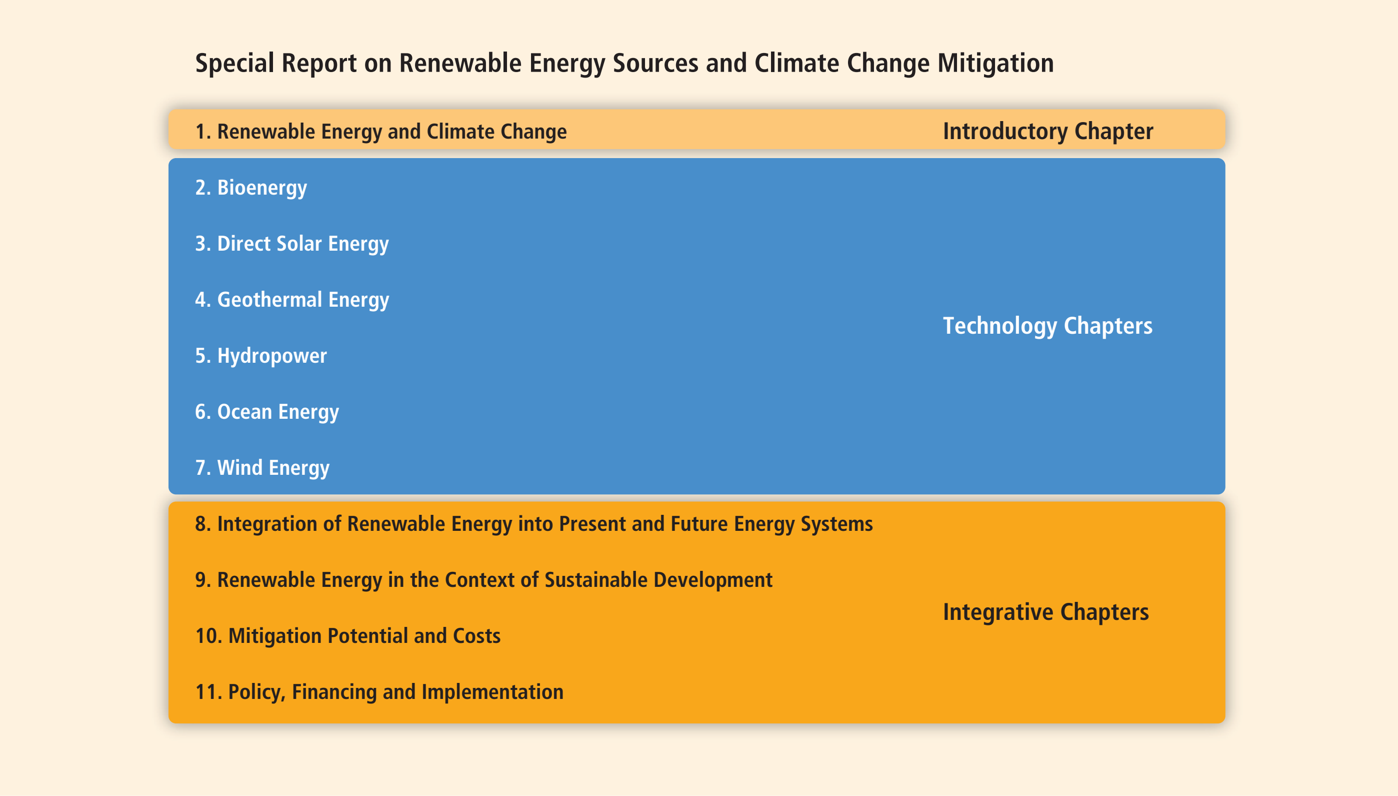

Figure TS.1.1 | Structure of the report. [Figure 1.1]

the Cancun Agreements call for limiting global average temperature rises to no more than 2°C above pre-industrial values, and agreed to consider limiting this rise to 1.5°C. In order to be confident of achieving an equilibrium temperature increase of only 2°C to 2.4°C, atmospheric GHG concentrations would need to be stabilized in the range of 445 to 490 ppm CO_2eq in the atmosphere. This in turn implies that global emissions of CO_2 will need to decrease by 50 to 85% below 2000 levels by 2050 and begin to decrease (instead of continuing their current increase) no later than 2015. [1.1.3]

To develop strategies for reducing CO_2 emissions, the Kaya identity can be used to decompose energy-related CO_2 emissions into four factors: 1) population, 2) gross domestic product (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). [1.1.4]

CO_2 emissions = Population x (GDP/population) x (TPES/GDP) x (CO_2/TPES)

The annual change in these four components is illustrated in Figure TS.1.2. [1.1.4]

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 2008. In the past, carbon intensity fell because of improvements in energy efficiency and switching from coal to natural gas and the expansion of nuclear energy in the 1970s and 1980s that was particularly driven by Annex I countries.[4] In recent years (2000 to 2007), increases in carbon intensity have been driven mainly by the expansion of coal use in both developed and developing countries, although coal and petroleum use have fallen slightly since 2007. In 2008 this trend was broken due to the financial crisis. Since the early 2000s, the energy supply has become more carbon intensive, thereby amplifying the increase resulting from growth in GDP per capita. [1.1.4]

On a global basis, it is estimated that RE accounted for 12.9% of the 492 EJ of total primary energy supply in 2008. The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) of the biomass fuel used in traditional cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well.[5] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4%. (Figure TS.1.3). In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE). [1.1.5]

Deployment of RE has been increasing rapidly in recent years. Under most conditions, increasing the share of RE in the energy mix will require policies to stimulate changes in the energy system. Government policy, the declining cost of many RE technologies, changes in the prices of fossil

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[4] See Glossary (Annex I) for a definition of Annex I countries.

[5] Not accounted for here or in official databases is the estimated 20 to 40% of additional traditional biomass used in informal sectors. [2.1]

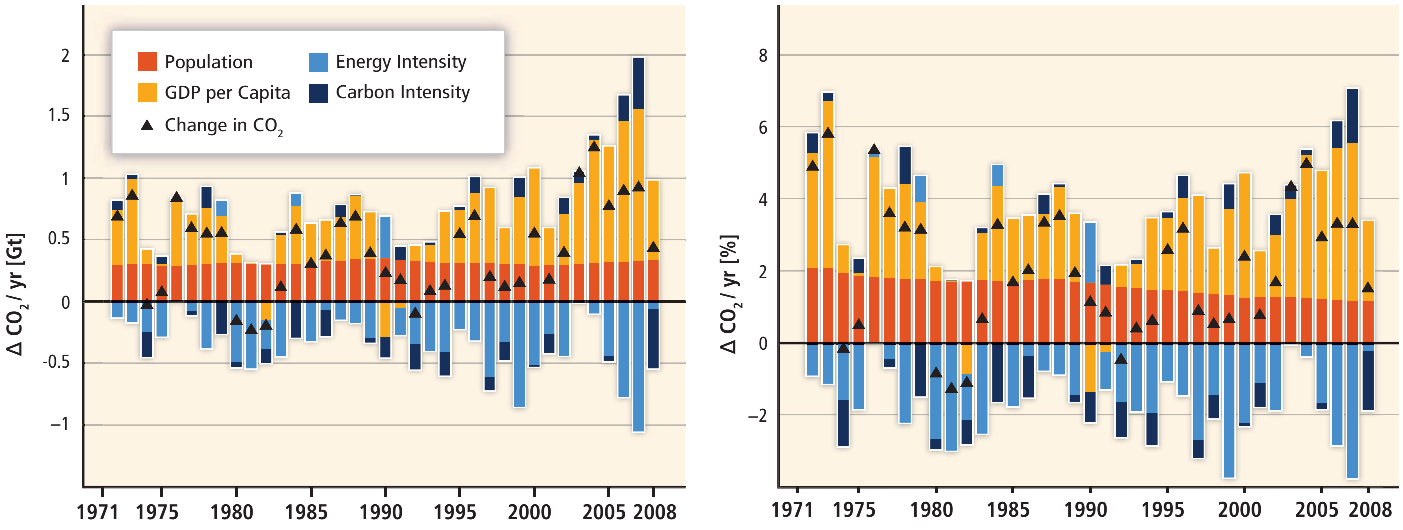


Figure TS.1.2 | Decomposition of (left) annual absolute change and (right) annual growth rate in global energy-related CO$_2$ emissions by the factors in the Kaya identity; population (red), GDP per capita (orange), energy intensity (light blue) and carbon intensity (dark blue) from 1971 to 2008. The colours show the changes that would occur due to each factor alone, holding the respective other factors constant. Total annual changes are indicated by a black triangle. [Figure 1.8]

fuels and other factors have supported the continuing increase in the use of RE. While the RE share is still relatively small, its growth has accelerated in recent years as shown in Figure TS.1.4. In 2009, despite global financial challenges, RE capacity continued to grow rapidly, including wind power (32%, 38 GW added), hydropower (3%, 31 GW added), grid-connected photovoltaics (53%, 7.5 GW added), geothermal power (4%, 0.4 GW added), and solar hot water/heating (21%, 31 GW$_{th}$ added). Biofuels accounted for 2% of global road transport fuel demand in 2008 and nearly 3% in 2009. The annual production of ethanol increased to 1.6 EJ (76 billion litres) by the end of 2009 and biodiesel production increased to 0.6 EJ (17 billion litres). Of the approximate 300 GW of new electricity generating capacity added globally from 2008 to 2009, about 140 GW came from RE additions. Collectively, developing countries host 53% of global RE electricity generation capacity (including all sizes of hydropower), with China adding more RE power capacity than any other country in 2009. The USA and Brazil accounted for 54 and 35% of global bioethanol production in 2009, respectively, while China led in the use of solar hot water. At the end of 2009, the use of RE in hot water/heating

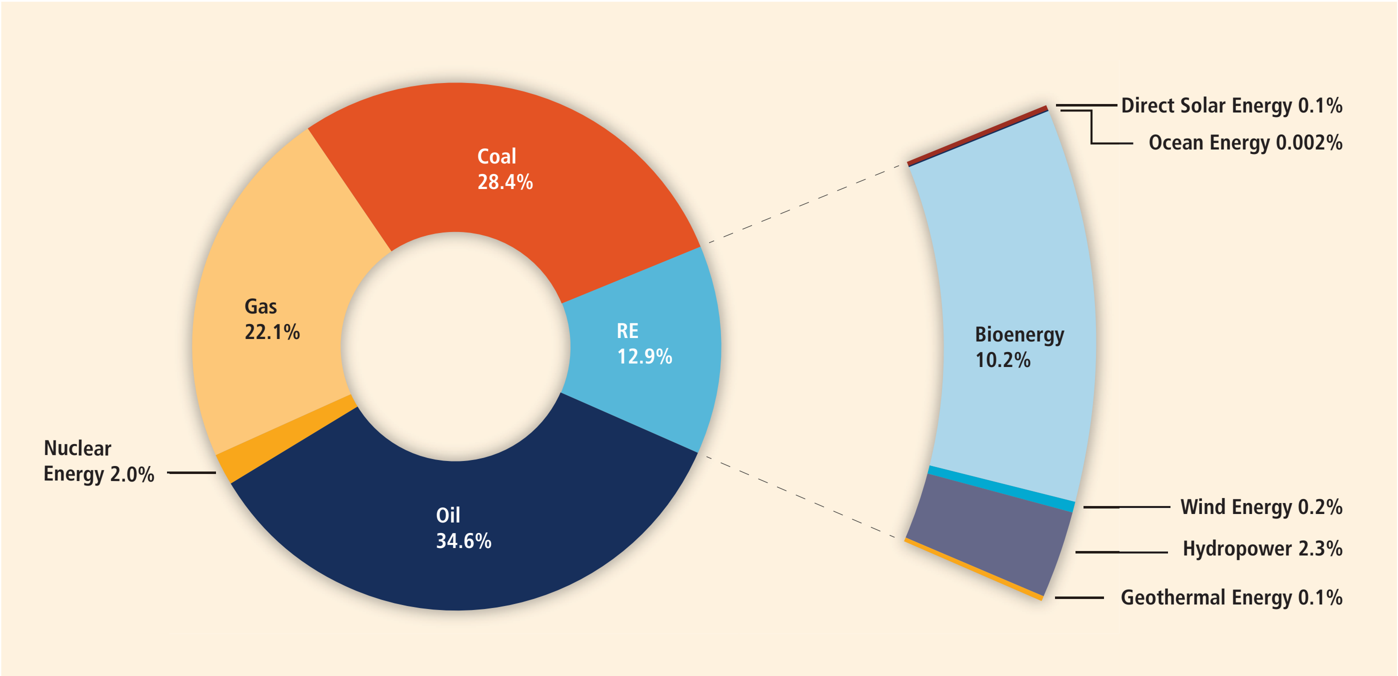


Figure TS.1.3 | Shares of energy sources in total global total primary energy supply in 2008 (492 EJ). Modern biomass contributes 38% of the total biomass share. [Figure 1.10]

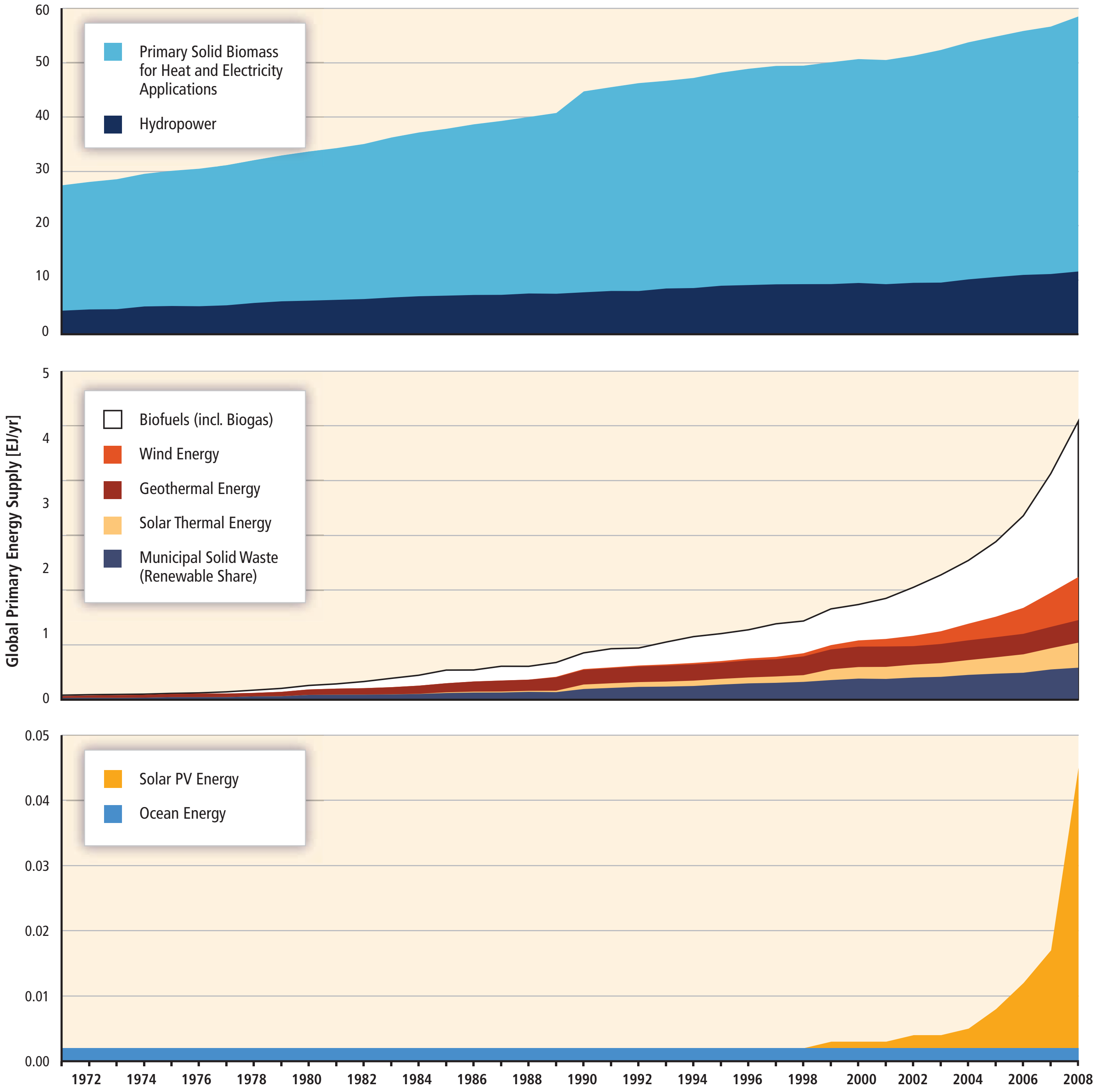


Figure TS.1.4 | Historical development of global primary energy supply from renewable energy from 1971 to 2008. [Figure 1.12]

Note: Technologies are referenced to separate vertical units for display purposes only. Underlying data for the figure has been converted to the 'direct equivalent' method of accounting for primary energy supply [1.1.9, Annex II.4], except that the energy content of biofuels is reported in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses [2.3, 2.4]).

markets included modern biomass (270 GW_{th}), solar energy (180 GW_{th}), and geothermal energy (60 GW_{th}). The use of RE (excluding traditional biomass) in meeting rural energy needs has also increased, including small-scale hydropower stations, various modern biomass options, and household or village photovoltaic (PV), wind or hybrid systems that combine multiple technologies. [1.1.5]

There are multiple means for lowering GHG emissions from the energy system while still providing desired energy services. The AR4 identified a number of ways to lower heat-trapping emissions from energy sources while still providing energy services: [1.1.6]

- Improve supply side efficiency of energy conversion, transmission and distribution, including combined heat and power.
- Improve demand side efficiency in the respective sectors and applications (e.g., buildings, industrial and agricultural processes, transportation, heating, cooling and lighting).
- Shift from high-GHG energy carriers such as coal and oil to lower-GHG energy carriers such as natural gas, nuclear fuels and RE sources.
- Utilize CO_2 capture and storage (CCS) to prevent post-combustion or industrial process CO_2 from entering the atmosphere. CCS has the potential for removing CO_2 from the atmosphere when biomass is processed, for example, through combustion or fermentation.
- Change behaviour to better manage energy use or to use fewer carbon- and energy-intensive goods and services.

The future share of RE applications will heavily depend on climate change mitigation goals, the level of requested energy services and resulting energy needs as well as their relative merit within the portfolio of zero- or low-carbon technologies (Figure TS.1.5). A comprehensive evaluation of any portfolio of mitigation options would involve an evaluation of their respective mitigation potential as well as all associated risks, costs and their contribution to sustainable development. [1.1.6]

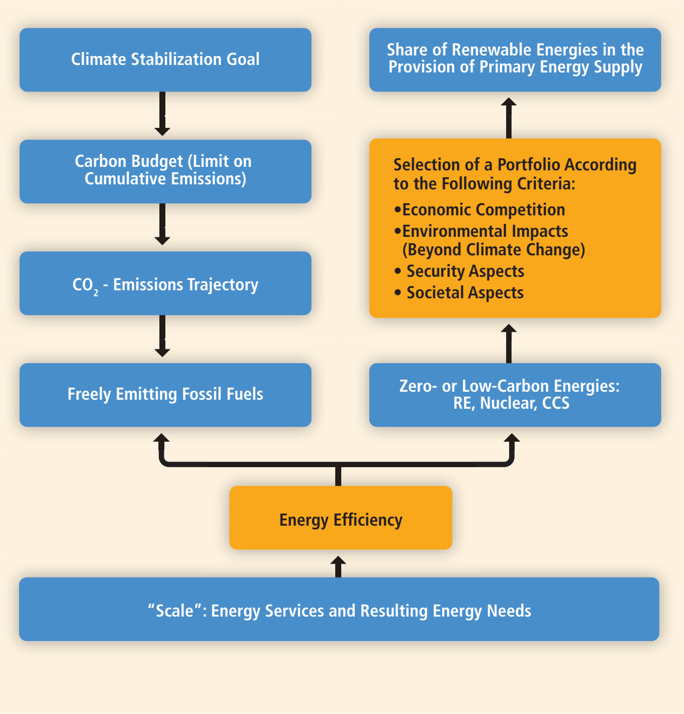


Figure TS.1.5 | The role of renewable energies within the portfolio of zero- or low-carbon mitigation options (qualitative description). [Figure 1.14]

Setting a climate protection goal in terms of the admissible change in global mean temperature broadly defines a corresponding GHG concentration limit with an associated CO_2 budget and subsequent time-dependent emission trajectory, which then defines the admissible amount of freely emitting fossil fuels. The complementary contribution of zero- or low-carbon energies to the primary energy supply is influenced by the 'scale' of the requested energy services. [1.1.6]

As many low-cost options to improve overall energy efficiency are already part of the non-intervention scenarios, the *additional* opportunities to decrease energy intensity in order to mitigate climate change are limited. In order to achieve ambitious climate protection goals, energy efficiency improvements alone do not suffice, requiring additional zero- or low-carbon technologies. The contribution RE will provide within the portfolio of these low-carbon technologies heavily depends on the economic competition between these technologies, a comparison of the relative environmental burden (beyond climate change) associated with them, as well as security and societal aspects (Figure TS.1.5). [1.1.6]

The body of scientific knowledge on RE and on the possible contribution of RE towards meeting GHG mitigation goals, as compiled and assessed in this report, is substantial. Nonetheless, due in part to the site-specific nature of RE, the diversity of RE technologies, the multiple end-use energy service needs that those technologies might serve, the range of markets and regulations governing integration, and the complexity of energy system transitions, knowledge about RE and its climate mitigation potential continues to advance. Additional knowledge remains to be gained in a number of broad areas related to RE and its possible role in GHG emissions reductions: [1.1.8]

- Future cost and timing of RE deployment;
- Realizable technical potential for RE at all geographical scales;
- Technical and institutional challenges and costs of integrating diverse RE technologies into energy systems and markets;
- Comprehensive assessment of socioeconomic and environmental aspects of RE and other energy technologies;
- Opportunities for meeting the needs of developing countries with sustainable RE services; and
- Policy, institutional and financial mechanisms to enable cost-effective deployment of RE in a wide variety of contexts.

Though much is already known in each of these areas, as compiled in this report, additional research and experience would further reduce uncertainties and thus facilitate decision making related to the use of RE in the mitigation of climate change. [1.1.6]

1.2 Summary of renewable energy resources and potential

RE is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydropower, tide and waves, ocean thermal energy and wind energy. However, 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. On the other hand, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the Earth. Fossil fuels (coal, oil, natural gas) do not fall under this definition, as they are not replenished within a time frame that is short relative to their rate of utilization. [1.2.1]

There is a multi-step process whereby primary energy is converted into an energy carrier, and then into an energy service. RE technologies are diverse and can serve the full range of energy service needs. Various types of RE can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs. Figure TS.1.6 illustrates the multi-step conversion processes. [1.2.1]

Since it is energy services and not energy that people need, the process should be driven in an efficient manner that requires less primary energy consumption with low-carbon technologies that minimize CO_2 emissions. Thermal conversion processes to produce electricity (including biomass and geothermal) suffer losses of approximately 40 to 90%, and losses of around 80% occur when supplying the mechanical energy needed for transport based on internal combustion engines. These conversion losses raise the share of primary energy from fossil fuels, and the primary energy required from fossil fuels to produce electricity and mechanical energy from heat. Direct energy conversions from solar PV, hydro, ocean and wind energy to electricity do not suffer thermodynamic power cycle (heat to work) losses although they do experience other conversion inefficiencies in extracting energy from natural energy flows that may also be relatively large and irreducible (chapters 2-7). [1.2.1]

Some RE technologies can be deployed at the point of use (decentralized) in rural and urban environments, whereas others are primarily employed within large (centralized) energy networks. Though many

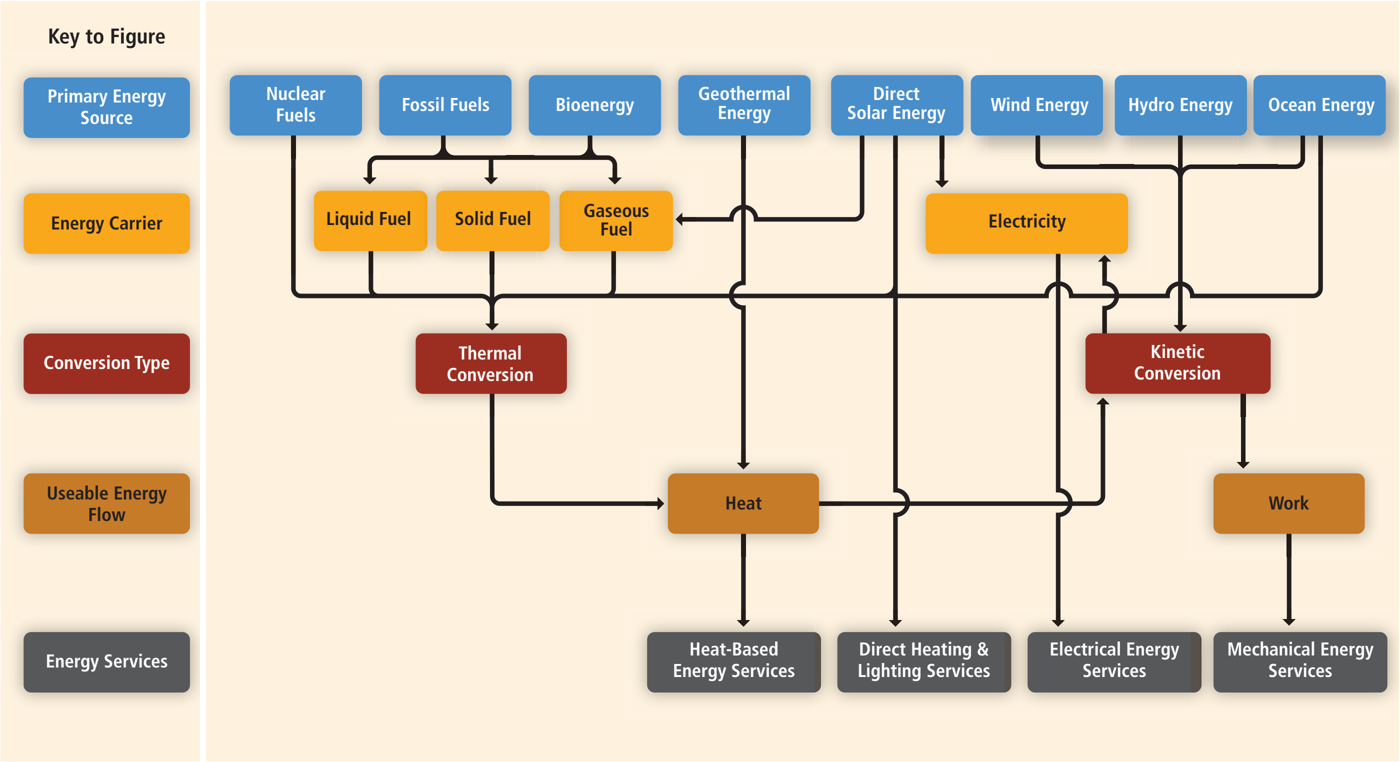


Figure TS.1.6 | Illustrative paths of energy from source to service. All connected lines indicate possible energy pathways. The energy services delivered to the users can be provided with differing amounts of end-use energy. This in turn can be provided with more or less primary energy from different sources, and with differing emissions of CO_2 and other environmental impacts. [Figure 1.16]

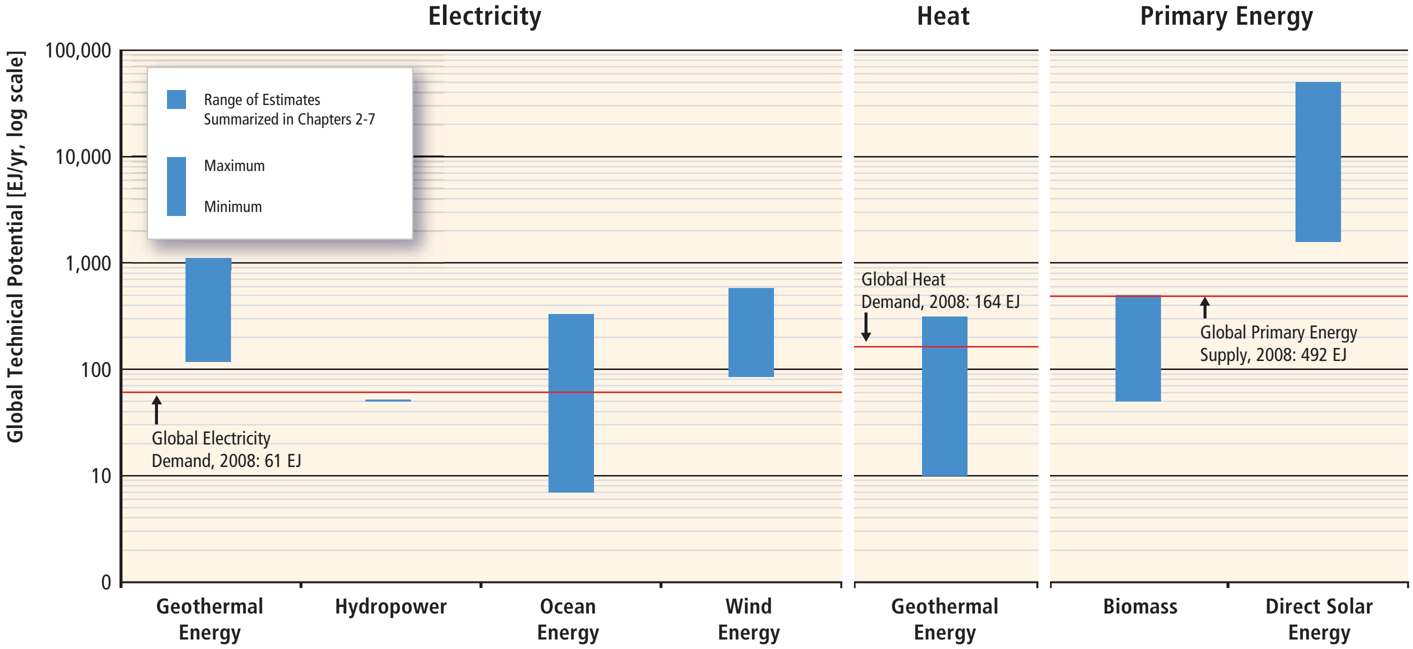
RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment. [1.2.1]

The theoretical potential for RE exceeds current and projected global energy demand by far, but the challenge is to capture and utilize a sizable share of that potential to provide the desired energy services in a cost-effective and environmentally sound manner. [1.2.2]

The global technical potential of RE sources will also not limit continued market growth. A wide range of estimates are provided in the literature but studies have consistently found that the total global technical potential for RE is substantially higher than both current and projected future global energy demand. The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all forms of RE. The absolute size of the global technical potential for RE as a whole is unlikely to constrain RE deployment. [1.2.3]

Figure TS.1.7 shows that the technical potential[6] exceeds by a considerable margin the global electricity and heat demand, as well as the global primary energy supply, in 2008. While the figure provides a perspective for the reader to understand the relative sizes of the RE resources in the context of current energy demand and supply, note that the technical potentials are highly uncertain. Table A.1.1 in the Annex to Chapter 1 includes more detailed notes and explanations. [1.2.3]

RE can be integrated into all types of electricity systems from large, interconnected continental-scale grids down to small autonomous buildings. Whether for electricity, heating, cooling, gaseous fuels or liquid fuels, RE integration is contextual, site specific and complex. Partially dispatchable wind and solar energy can be more difficult to integrate than fully dispatchable hydropower, bioenergy and geothermal energy. As the penetration of partially dispatchable RE electricity increases, maintaining system reliability becomes more challenging and costly. A portfolio of solutions to minimize the risks and costs of RE integration can include the development of complementary flexible generation, strengthening and extending network infrastructure and interconnections, electricity demand that can respond in relation to supply availability, energy storage technologies (including reservoir-based hydropower), and modified institutional arrangements



Range of Estimates of Global Technical Potentials

Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Figure TS.1.7 | Ranges of global technical potentials of RE sources derived from studies presented in Chapters 2 through 7. Biomass and solar are shown as primary energy due to their multiple uses. Note that the figure is presented in logarithmic scale due to the wide range of assessed data. [Figure 1.17]

Notes: Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized. Note that RE electricity sources could also be used for heating applications, whereas biomass and solar resources are reported only in primary energy terms but could be used to meet various energy service needs. Ranges are based on various methods and apply to different future years; consequently, the resulting ranges are not strictly comparable across technologies. For the data behind the figure and additional notes that apply, see Table A.1.1 (as well as the underlying chapters).

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[6] See Annex I for a complete definition of technical potential.

including regulatory and market mechanisms. As the penetration level of RE increases, there is need for a mixture of inexpensive and effective communications systems and technologies, as well as smart meters. [1.2.4]

Energy services are the tasks performed using energy. A specific energy service can be provided in many ways and may therefore be characterized by high or low energy efficiency, implying the release of relatively smaller or larger amounts of CO_2 (under a given energy mix). Reducing energy needs at the energy services delivery stage through energy efficiency is an important means of reducing primary energy demand. This is particularly important for RE sources since they usually have lower power densities than fossil or nuclear fuels. Efficiency measures are often the lowest-cost option to reducing end-use energy demand. This report provides some specific definitions for different dimensions of efficiency. [1.2.5]

Energy savings resulting from efficiency measures are not always fully realized in practice. There may be a rebound effect in which some fraction of the measure is offset because the lower total cost of energy (due to less energy use) to perform a specific energy service may lead to utilization of more energy services. It is estimated that the rebound effect is probably limited by saturation effects to between 10 and 30% for home heating and vehicle use in Organisation for Economic Co-operation and Development (OECD) countries, and is very small for more efficient appliances and water heating. An efficiency measure that is successful in lowering economy-wide energy demand, however, lowers the price of energy as well, leading in turn to a decrease in economy-wide energy costs and additional cost savings (lower energy prices and less energy use). It is expected that the rebound effect may be greater in developing countries and among poor consumers. For climate change, the main concern with any rebound effect is its influence on CO_2 emissions. [1.2.5]

Carbon leakage may also reduce the effectiveness of carbon reduction policies. If carbon reduction policies are not applied uniformly across sectors and political jurisdictions, then it may be possible for carbon emitting activities to move to a sector or country without such policies. Recent research suggests, however, that estimates of carbon leakage are too high. [1.2.5]

1.3 Meeting energy service needs and current status

Global renewable energy flows from primary energy through carriers to end uses and losses in 2008 are shown in Figure TS.1.8. [1.3.1]

Globally in 2008, around 56% of RE was 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. On the other hand, only a small amount of RE is used in the transport sector. Electricity production accounts for 24% of the end-use consumption. Biofuels contributed 2% of global road transport fuel supply in 2008, and traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat in 2008. [1.3.1]

While the resource is obviously large and could theoretically supply all energy needs long into the future, the levelized cost of energy for many RE technologies is currently higher than existing energy prices, though in various settings RE is already economically competitive. Ranges of recent levelized costs of energy for selected commercially available RE technologies are wide, depending on a number of factors, including, but not limited to, technology characteristics and size, regional variations in cost and performance and differing discount rates (Figure TS.1.9). [1.3.2, 2.3, 2.7, 3.8, 4.8, 5.8, 6.7, 7.8, 10.5, Annex III]

The cost of most RE technologies has declined and additional expected technical advances would result in further cost reductions. Such cost reductions as well as monetizing the external cost of energy supply would improve the relative competitiveness of RE. The same applies if market prices increase due to other reasons. [1.3.2, 2.6, 2.7, 3.7, 3.8, 4.6, 4.7, 5.3, 5.7, 5.8, 6.6, 6.7, 7.7, 7.8, 10.5]

The contribution of RE to primary energy supply varies substantially by country and region. The geographic distribution of RE manufacturing, use and export is now being diversified from the developed world to other developing regions, notably Asia including China. In terms of installed renewable power capacity, China now leads the world followed by the USA, Germany, Spain and India. RE is more evenly distributed than fossil fuels and there are countries or regions rich in specific RE resources. [1.3.3]

1.4 Opportunities, barriers, and issues

The major global energy challenges are securing energy supply to meet growing demand, providing everybody with access to energy services and curbing energy's contribution to climate change. For developing countries, especially the poorest, energy is needed to stimulate production, income generation and social development, and to reduce the serious health problems caused by the use of fuel wood, charcoal, dung and agricultural waste. For industrialized countries, the primary reasons to encourage RE include emission reductions to mitigate climate change, secure energy supply concerns and employment creation. RE can open opportunities for addressing these multiple environmental, social and economic development dimensions, including adaptation to climate change. [1.4, 1.4.1]

Some form of renewable resource is available everywhere in the world, for example, solar radiation, wind, falling water, waves, tides and stored ocean heat or heat from the Earth. Furthermore, technologies exist that can harness these forms of energy. While the opportunities [1.4.1] seem great, there are barriers [1.4.2] and issues [1.4.3] that slow the introduction of RE into modern economies. [1.4]

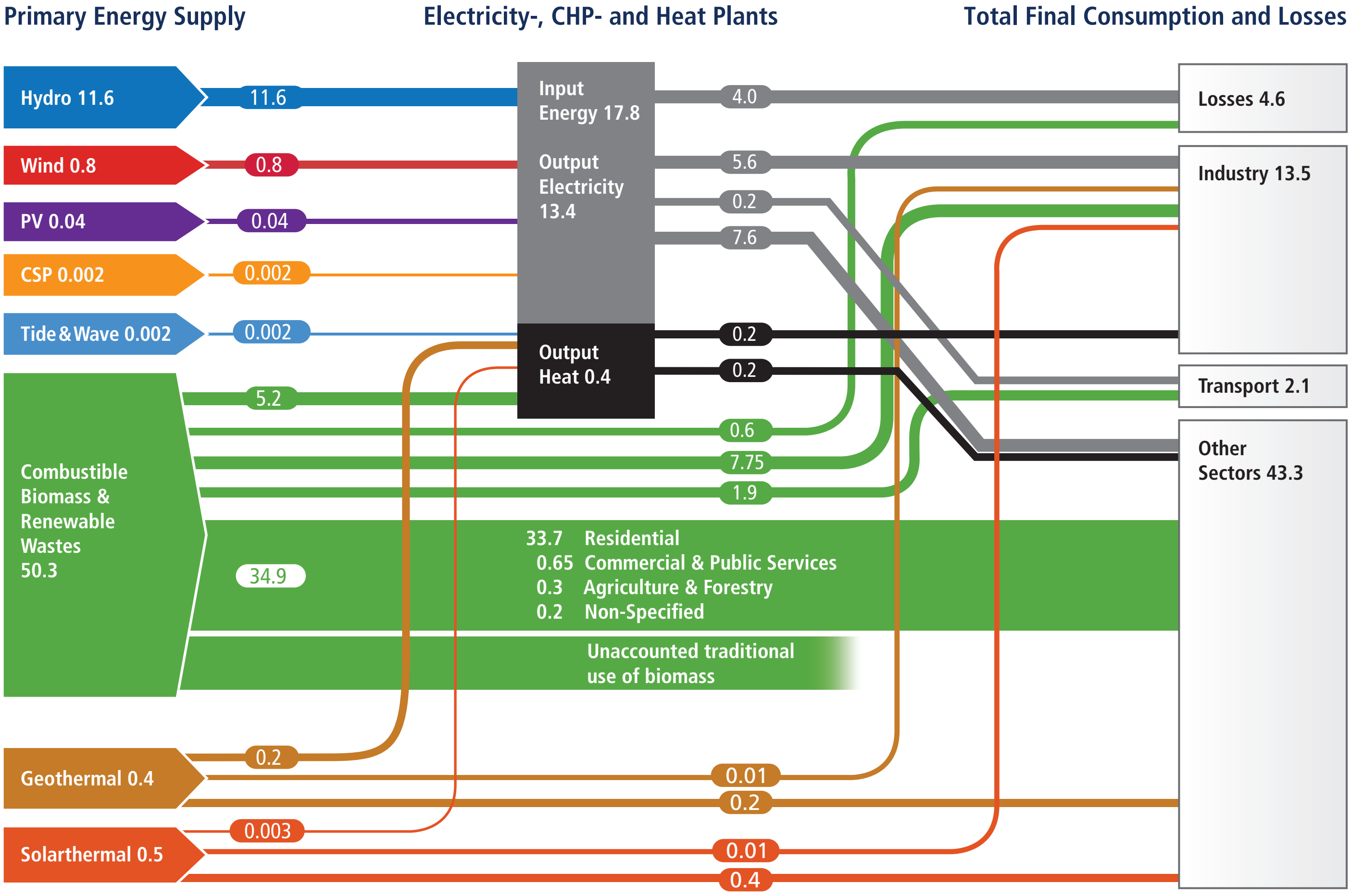


Figure TS.1.8 | Global energy flows (EJ in 2008) from primary RE through carriers to end-uses and losses (based on International Energy Agency (IEA) data). 'Other sectors' include agriculture, commercial and residential buildings, public services and non-specified other sectors. 'Transport sector' includes road transport, international aviation and international marine bunkers. [Figure 1.18]

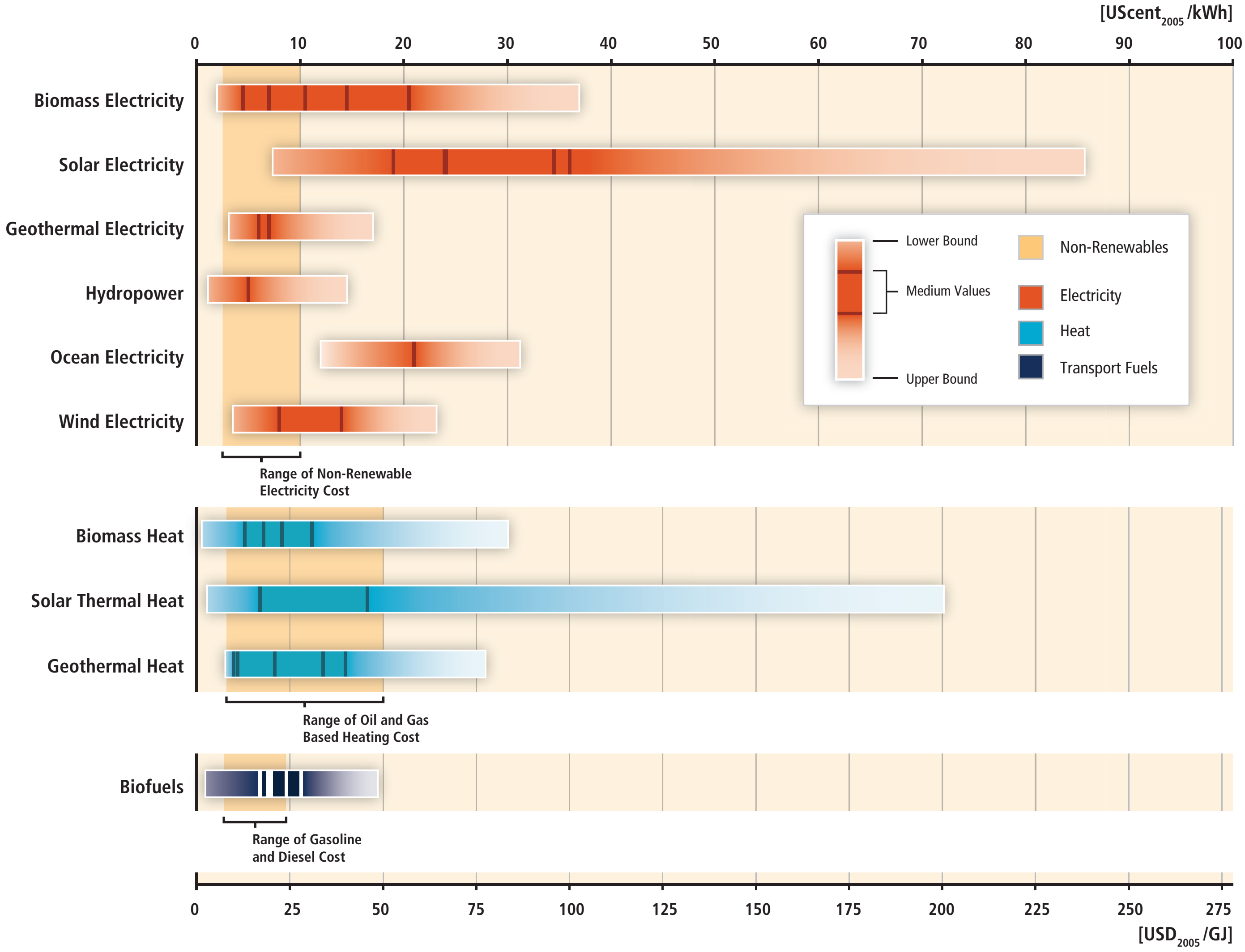
Opportunities can be defined as circumstances for action with the attribute of a chance character. In the policy context that could be the anticipation of additional benefits that may go along with the deployment of RE but that are not intentionally targeted. These include four major opportunity areas: social and economic development; energy access; energy security; and climate change mitigation and the reduction of environmental and health impacts. [1.4.1, 9.2–9.4]

Globally, per capita incomes as well as broader indicators such as the Human Development Index (HDI) are positively correlated with per capita energy use, and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. Economic development has been associated with a shift from direct combustion of fuels to higher quality electricity. [1.4.1, 9.3.1]

Particularly for developing countries, the link between social and economic development and the need for modern energy services is evident. Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, contributing, inter alia, to economic activity, income generation, poverty alleviation, health, education and gender equality. Due to their decentralized nature, RE technologies can play an important role in fostering rural development. The creation of (new) employment opportunities is seen as a positive long-term effect of RE in both developed and developing countries. [1.4.1, 9.3.1.4, 11.3.4]

Access to modern energy services can be enhanced by RE. In 2008, 1.4 billion people around the world lacked electricity, some 85% of them in rural areas, and the number of people relying on the traditional use of biomass for cooking is estimated to be 2.7 billion. In particular, reliance on RE in rural applications, use of locally produced bioenergy to produce electricity, and access to clean cooking facilities will contribute to attainment of universal access to modern energy services. The transition to modern energy access is referred to as moving up the energy ladder and implies a progression from traditional to more modern devices/fuels that are more environmentally benign and have fewer negative health impacts. This transition is influenced by income level. [1.4.1, 9.3.2]

Energy security concerns that may be characterized as availability and distribution of resources, as well as variability and reliability of energy supply, may also be enhanced by the deployment of RE. As RE technologies help to diversify the portfolio of energy sources and to reduce the economy's



Notes: Medium values are shown for the following subcategories, sorted in the order as they appear in the respective ranges (from left to right):

Electricity

Biomass:
1. Cofiring
2. Small scale combined heat and power, CHP (Gasification internal combustion engine)
3. Direct dedicated stoker & CHP
4. Small scale CHP (steam turbine)
5. Small scale CHP (organic Rankine cycle)

Solar Electricity:
1. Concentrating solar power
2. Utility-scale PV (1-axis and fixed tilt)
3. Commercial rooftop PV
4. Residential rooftop PV

Geothermal Electricity:
1. Condensing flash plant
2. Binary cycle plant

Hydropower:
1. All types

Ocean Electricity:
1. Tidal barrage

Wind Electricity:
1. Onshore
2. Offshore

Heat

Biomass Heat:
1. Municipal solid waste based CHP
2. Anaerobic digestion based CHP
3. Steam turbine CHP
4. Domestic pellet heating system

Solar Thermal Heat:
1. Domestic hot water systems in China
2. Water and space heating

Geothermal Heat:
1. Greenhouses
2. Uncovered aquaculture ponds
3. District heating
4. Geothermal heat pumps
5. Geothermal building heating

Transport Fuels

Biofuels:
1. Corn ethanol
2. Soy biodiesel
3. Wheat ethanol
4. Sugarcane ethanol
5. Palm oil biodiesel

The lower range of the levelized cost of energy for each RE technology is based on a combination of the most favourable input-values, whereas the upper range is based on a combination of the least favourable input values. Reference ranges in the figure background for non-renewable electricity options are indicative of the levelized cost of centralized non-renewable electricity generation. Reference ranges for heat are indicative of recent costs for oil and gas based heat supply options. Reference ranges for transport fuels are based on recent crude oil spot prices of USD 40 to 130/barrel and corresponding diesel and gasoline costs, excluding taxes.

Figure TS.1.9 | (Preceding page) Range in recent levelized cost of energy for selected commercially available RE technologies in comparison to recent non-renewable energy costs. Technology subcategories and discount rates were aggregated for this figure. For related figures with less or no such aggregation, see [1.3.2, 10.5, Annex III]. Additional information concerning the cost of non-renewable energy supply options is given in [10.5]. [Figure 10.28]

vulnerability to price volatility and redirect foreign exchange flows away from energy imports, they reduce social inequities in energy supply. Current energy supplies are dominated by fossil fuels (petroleum and natural gas) whose prices have been volatile with significant implications for social, economic and environmental sustainability in the past decades, especially for developing countries and countries with high shares of imported fuels. [1.4.1, 9.2.2, 9.3.3, 9.4.3]

Climate change mitigation is one of the key driving forces behind a growing demand for RE technologies. In addition to reducing GHG emissions, RE technologies can also offer benefits with respect to air pollution and health compared to fossil fuels. However, to evaluate the overall burden from the energy system on the environment and society, and to identify potential trade-offs and synergies, environmental impacts apart from GHG emissions and categories have to be taken into account as well. The resource may also be affected by climate change. Lifecycle assessments facilitate a quantitative comparison of 'cradle to grave' emissions across different energy technologies. Figure TS.1.10 illustrates the lifecycle structure for CO_2 emission analysis, and qualitatively indicates the relative GHG implications for RE, nuclear power and fossil fuels. [1.4.1, 9.2.2, 9.3.4, 11.3.1]

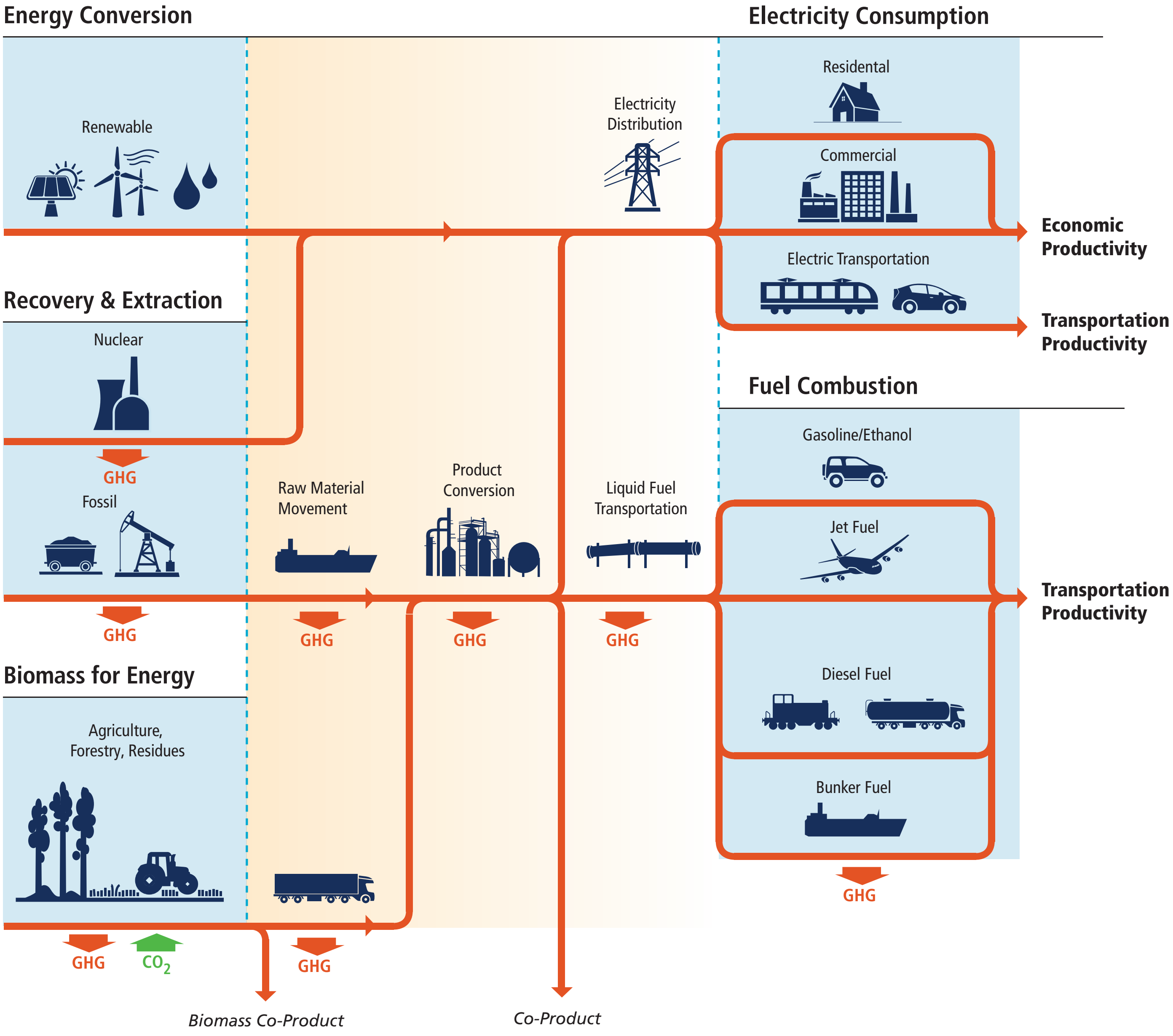


Figure TS.1.10 | Illustrative system for energy production and use illustrating the role of RE along with other production options. A systemic approach is needed to conduct lifecycle assessments. [Figure 1.22]

Traditional biomass use results in health impacts from the high concentrations of particulate matter and carbon monoxide, among other pollutants. In this context, non-combustion-based RE power generation technologies have the potential to significantly reduce local and regional air pollution and lower associated health impacts compared to fossil-based power generation. Improving traditional biomass use can reduce negative sustainable development (SD) impacts, including local and indoor air pollution, GHG emissions, deforestation and forest degradation. [1.4.1, 2.5.4, 9.3.4, 9.3.4, 9.4.2]

Impacts on water resources from energy systems strongly depend on technology choice and local conditions. Electricity production with wind and solar PV, for example, requires very little water compared to thermal conversion technologies, and has no impacts on water or air quality. Limited water availability for cooling thermal power plants decreases their efficiency, which can affect plants operating on coal, biomass, gas, nuclear and concentrating solar power. There have been significant power reductions from nuclear and coal plants during drought conditions in the USA and France in recent years. Surface-mined coal in particular produces major alterations of land; coal mines can create acid mine drainage and the storage of coal ash can contaminate surface and ground waters. Oil production and transportation have led to significant land and water spills. Most renewable technologies produce lower conventional air and water pollutants than fossil fuels, but may require large amounts of land as, for example, reservoir-based hydropower, wind and biofuels. Since a degree of climate change is now inevitable, adaptation to climate change is also an essential component of sustainable development. [1.4.1, 9.3.4]

Barriers are defined in AR4 as "any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy programme or measure". The various barriers to RE use can be categorized as market failures and economic barriers, information and awareness barriers, socio-cultural barriers and institutional and policy barriers. Policies and financing mechanisms to overcome those barriers are extensively assessed in Chapter 11. When a barrier is particularly pertinent to a specific technology, it is examined in the appropriate 'technology' chapters of this report [Chapters 2–7]. A summary of barriers and potential policy instruments to overcome these barriers is shown in Table 1.5 of Chapter 1. Market failures are often due to external effects. These arise from a human activity, when agents responsible for the activity do not take full account of the activity's impact on others. Another market failure is rent appropriation by monopolistic entities. In the case of RE deployment, these market failures may appear as underinvestment in invention and innovation in RE technologies, un-priced environmental impacts and risks of energy use as well as the occurrence of monopoly (one seller) or monopsony (one buyer) powers in energy markets. Other economic barriers include up-front investment cost and financial risks, the latter sometimes due to immaturity of the technology. [1.4.2, 1.5, 11.4]

Informational and awareness barriers include deficient data about natural resources, often due to site-specificity (e.g., local wind regimes), lack of skilled human resources (capacity) especially in rural areas of developing countries as well as the lack of public and institutional awareness. Socio-cultural barriers are intrinsically linked to societal and personal values and norms that affect the perception and acceptance of RE and may be slow to change. Institutional and policy barriers include existing industry, infrastructure and energy market regulation. Despite liberalization of energy markets in several countries in the 1990s, current industry structures are still highly concentrated and regulations governing energy businesses in many countries are still designed around monopoly or near-monopoly providers. Technical regulations and standards have evolved under the assumption that energy systems are large and centralized, and of high power density and/or high voltage. Intellectual property rights, tariffs in international trade and lack of allocation of government financial support may constitute further barriers. [1.4.2]

Issues are not readily amenable to policies and programmes. An issue is that the resource may be too small to be useful at a particular location or for a particular purpose. Some renewable resources such as wind and solar energy are variable and may not always be available for dispatch when needed. Furthermore, the energy density of many renewable sources is relatively low, so that their power levels may be insufficient on their own for some purposes such as very large-scale industrial facilities. [1.4.3]

1.5 Role of policy, research and development, deployment and implementation strategies

An increasing number and variety of RE policies—motivated by a variety of factors—have driven escalated growth in RE technologies in recent years. For policymakers wishing to support the development and deployment of RE technologies for climate change mitigation goals, it is critical to consider the potential of RE to reduce emissions from a lifecycle perspective, as addressed in each technology chapter of this report. Various policies have been designed to address every stage of the development chain involving research and development (R&D), testing, deployment, commercialization, market preparation, market penetration, maintenance and monitoring, as well as integration into the existing system. [1.4.1, 1.4.2, 9.3.4, 11.1.1, 11.2, 11.4, 11.5]

Two key market failures are typically addressed: 1) the external cost of GHG emissions are not priced at an appropriate level; and 2) deployment of low-carbon technologies such as RE create benefits to society beyond those captured by the innovator, leading to under-investment in such efforts. [1.4, 1.5, 11.1, 11.4]

Policy- and decision-makers approach the market in a variety of ways. No globally-agreed list of RE policy options or groupings exists. For the purpose of simplification, R&D and deployment policies have been organized within the following categories in this report: [1.5.1, 11.5]

- **Fiscal incentive:** actors (individuals, households, companies) are granted a reduction of their contribution to the public treasury via income or other taxes;

- **Public finance:** public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee); and

- **Regulation:** rule to guide or control conduct of those to whom it applies.

R&D, innovation, diffusion and deployment of new low-carbon technologies create benefits to society beyond those captured by the innovator, resulting in under-investment in such efforts. Thus, government R&D can play an important role in advancing RE technologies. Public R&D investments are most effective when complemented by other policy instruments, particularly RE deployment policies that simultaneously enhance demand for new RE technologies. [1.5.1, 11.5.2]

Some policy elements have been shown to be more effective and efficient in rapidly increasing RE deployment, but there is no one-size-fits-all policy. Experience shows that different policies or combinations of policies can be more effective and efficient depending on factors such as the level of technological maturity, affordable capital, ease of integration into the existing system and the local and national RE resource base:

- Several studies have concluded that some feed-in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. Quota policies can be effective and efficient if designed to reduce risk; for example, with long-term contracts.

- An increasing number of governments are adopting fiscal incentives for RE heating and cooling. Obligations to use RE heat are gaining attention for their potential to encourage growth independent of public financial support.

- In the transportation sector, RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Other policies include direct government payments or tax reductions. Policies have influenced the development of an international biofuel and pellet trade.

One important challenge will be finding a way for RE and carbon-pricing policies to interact such that they take advantage of synergies rather than tradeoffs. In the long-term, support for technological learning in RE can help reduce costs of mitigation, and putting a price on carbon can increase the competitiveness of RE. [1.5.1, 11.1, 11.4, 11.5.7]

RE technologies can play a greater role if they are implemented in conjunction with 'enabling' policies. A favourable, or 'enabling', environment for RE can be created by addressing the possible interactions of a given policy with other RE policies as well as with other non-RE policies and the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. Since all forms of RE capture and production involve spatial considerations, policies need to consider land use, employment, transportation, agricultural, water, food security and trade concerns, existing infrastructure and other sectoral specifics. Government policies that complement each other are more likely to be successful. [1.5.2, 11.6]

Advancing RE technologies in the electric power sector, for example, will require policies to address their integration into transmission and distribution systems both technically [Chapter 8] and institutionally [Chapter 11]. The grid must be able to handle both traditional, often more central, supply as well as modern RE supply, which is often variable and distributed. [1.5.2, 11.6.5]

In the transport sector, infrastructure needs for biofuels, recharging hydrogen, battery or hybrid electric vehicles that are 'fuelled' by the electric grid or from off-grid renewable electrical production need to be addressed.

If decision makers intend to increase the share of RE and, at the same time, to meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical. To achieve international GHG concentration stabilization levels that incorporate high shares of RE, a structural shift in today's energy systems will be required over the next few decades. The available time span is restricted to a few decades and RE must develop and integrate into a system constructed in the context of an existing energy structure that is very different from what might be required under higher-penetration RE futures. [1.5.3, 11.7]

A structural shift towards a world energy system that is mainly based on RE might begin with a prominent role for energy efficiency in combination with RE. Additional policies are required that extend beyond R&D to support technology deployment; the creation of an enabling environment that includes education and awareness raising; and the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning. The appropriate and reliable mix of instruments is even more important where energy infrastructure is not yet developed and energy demand is expected to increase significantly in the future. [1.2.5, 1.5.3, 11.7, 11.6, 11.7]

2. Bioenergy

2.1 Introduction to biomass and bioenergy

Bioenergy is embedded in complex ways in global biomass systems for food, fodder and fibre production and for forest products as well as in wastes and residue management. Perhaps most importantly, bioenergy plays an intimate and critical role in the daily livelihoods of billions of people in developing countries. Figure TS.2.1 shows the types of biomass used for bioenergy in developing and developed countries. Expanding bioenergy production significantly will require sophisticated land and water use management; global feedstock productivity increases for food, fodder, fibre, forest products and energy; substantial conversion technology improvements; and a refined understanding of the complex social, energy and environmental interactions associated with bioenergy production and use.

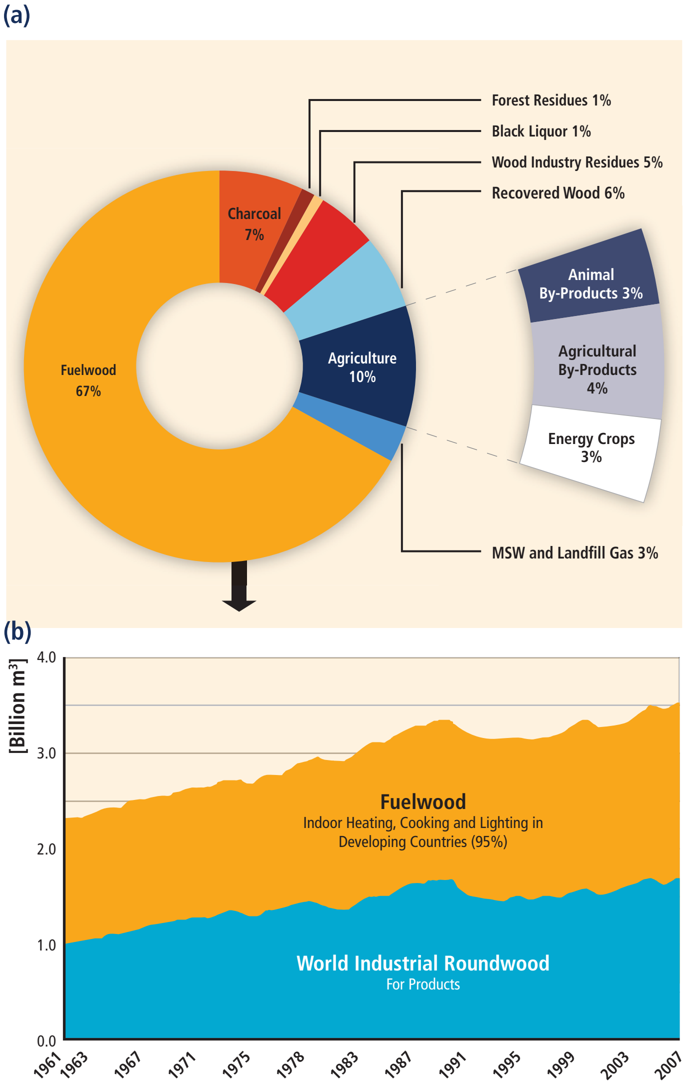


Figure TS.2.1 | (a) Shares of global primary biomass sources for energy; and (b) fuelwood used in developing countries parallels world industrial roundwood[1] production levels. [Figure 2.1]

Note: 1. Roundwood products are saw logs and veneer logs for the forest products industry and wood chips that are used for making pulpwood used in paper, newsprint and Kraft paper. In 2009, reflecting the downturn in the economy, there was a decline to 3.25 (total) and 1.25 (industrial) billion m³.

In 2008, biomass provided about 10% (50.3 EJ/yr) of the global primary energy supply (see Table TS.2.1). Major biomass uses fall into two broad categories:

- Low-efficiency traditional biomass[7] such as wood, straws, dung and other manures are used for cooking, lighting and space heating, generally by the poorer populations in developing countries. This biomass is mostly combusted, creating serious negative impacts on health and living conditions. Increasingly, charcoal is becoming secondary energy carrier in rural areas with opportunities to create productive chains. As an indicator of the magnitude of traditional biomass use, Figure TS.2.1(b) illustrates that the global primary energy supply from traditional biomass parallels the world's industrial wood production. [2.5.4, 2.3, 2.3.2.2, 2.4.2, 2.5.7]

- High-efficiency modern bioenergy uses more convenient solids, liquids and gases as secondary energy carriers to generate heat, electricity, combined heat and power (CHP), and transport fuels for various sectors. Liquid biofuels include ethanol and biodiesel for global road transport and some industrial uses. Biomass derived gases, primarily methane, from anaerobic digestion of agricultural residues and municipal solid waste (MSW) treatment are used to generate electricity, heat or both. The most important contribution to these energy services is based on solids, such as chips, pellets, recovered wood previously used and others. Heating includes space and hot water heating such as in district heating systems. The estimated total primary biomass supply for modern bioenergy is 11.3 EJ/yr and the secondary energy delivered to end-use consumers is roughly 6.6 EJ/yr. [2.3.2, 2.4, 2.4.6, 2.6.2]

Additionally, the industry sector, such as the pulp and paper, forestry, and food industries, consumes approximately 7.7 EJ of biomass annually, primarily as a source for industrial process steam. [2.7.2, 8.3.4]

2.2 Bioenergy resource potential

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize. Estimates in the literature range from zero technical potential (no biomass available for energy production) to a maximum theoretical potential of

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[7] Traditional biomass is defined as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues and animal dung for cooking and heating. All other biomass use is defined as modern biomass; this report further differentiates between highly efficient modern bioenergy and industrial bioenergy applications with varying degrees of efficiency. [Annex I] The renewability and sustainability of biomass use is primarily discussed in Sections 2.5.4 and 2.5.5, respectively (see also Section 1.2.1 and Annex I).

Table TS.2.1 | Examples of traditional and select modern biomass energy flows in 2008; see Table 2.1 for notes on specific flows and accounting challenges. [Table 2.1]

Type	Approximate Primary Energy (EJ/yr)	Approximate Average Efficiency (%)	Approximate Secondary Energy (EJ/yr)
Traditional Biomass			
Accounted for in IEA energy balance statistics	30.7	10–20	3–6
Estimated for informal sectors (e.g., charcoal) [2.1]	6–12		0.6–2.4
Total Traditional Biomass	37–43		3.6–8.4
Modern Bioenergy			
Electricity and CHP from biomass, MSW, and biogas	4.0	32	1.3
Heat in residential, public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road Transport Fuels (ethanol and biodiesel)	3.1	60	1.9
Total Modern Bioenergy	11.3	58	6.6

about 1,500 EJ from global modelling efforts. Figure TS.2.2 presents a summary of technical potentials found in major studies, including data from the scenario analysis of Chapter 10. To put biomass technical potential for energy in perspective, global biomass used for energy currently amounts to approximately 50 EJ/yr and all harvested biomass used for food, fodder and fibre, when expressed in a caloric equivalent, contains about 219 EJ/yr (2000 data); nearly the entire current global biomass harvest would be required to achieve a 150 EJ/yr deployment level of bioenergy by 2050. [2.2.1]

An assessment of technical potential based on an analysis of the literature available in 2007 and additional modelling studies arrived at the conclusion that the upper bound of the technical potential in 2050 could amount to about 500 EJ, shown in the stacked bar of Figure TS.2.2. The study assumes policy frameworks that secure good governance of land use and major improvements in agricultural management and takes into account water limitations, biodiversity protection, soil degradation and competition with food. Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues, etc.) are estimated to amount to 40 to 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the technical potential is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range. Surplus forestry products other than from forestry residues have an additional technical potential

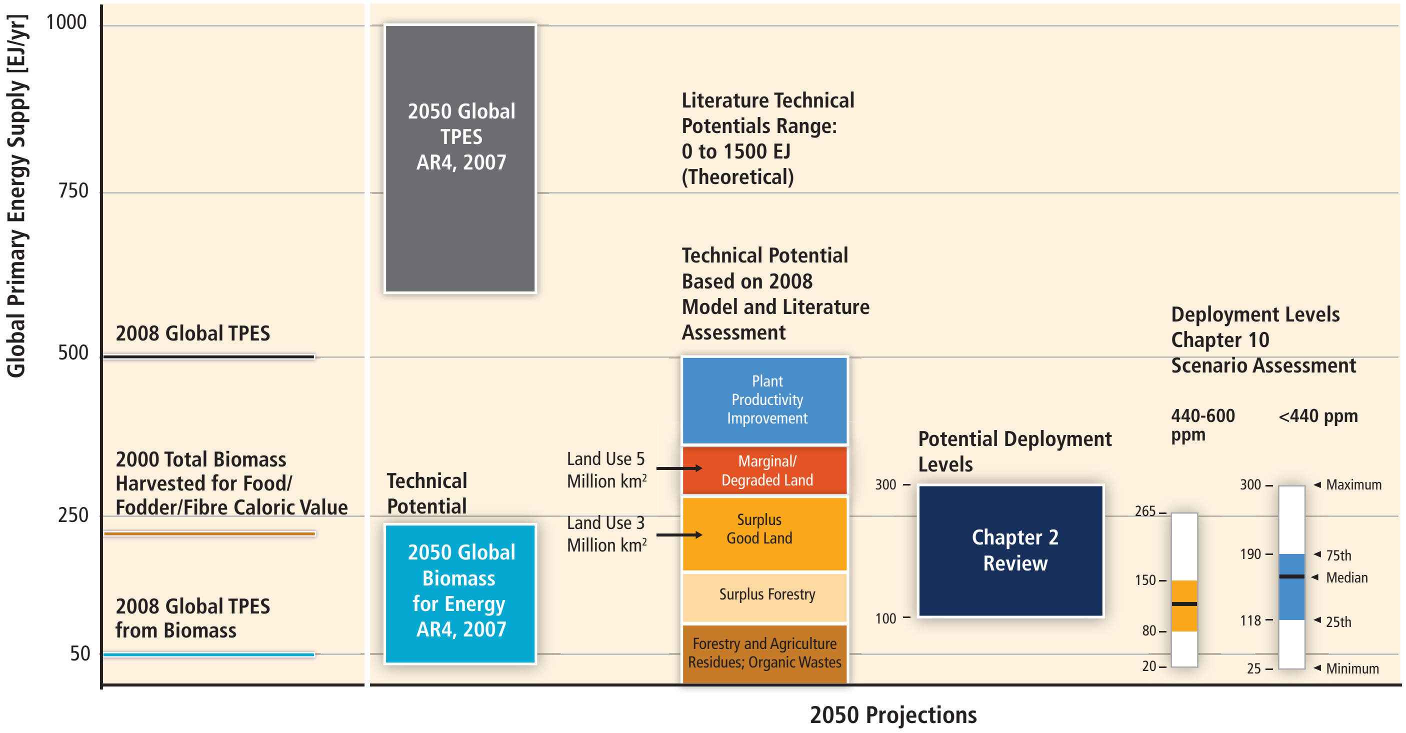

Figure TS.2.2 | A summary of major 2050 projections of global terrestrial biomass technical potential for energy and possible deployment levels compared to 2008 global total primary energy and biomass supply as well as the equivalent energy of world total biomass harvest. [Figure 2.25] of about 60 to 100 EJ/yr. A lower estimate for energy crop production on possible surplus, good quality agricultural and pasture lands is 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount to up to an additional 70 EJ/yr. This would comprise a large area where water scarcity imposes limitations and soil degradation is more severe. Assuming strong learning in agricultural technology for improvements in agricultural and livestock management would add 140 EJ/yr. The three categories added together lead to a technical potential from this analysis of up to about 500 EJ/yr (Figure TS 2.2).

Developing this technical potential would require major policy efforts, therefore, actual deployment would likely be lower and the biomass resource base will 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 a cheaper energy supply option compared to the main reference options (e.g., sugarcane-based ethanol production). [2.2.2, 2.2.5, 2.8.3]

The expert review conclusions based on available scientific literature are: [2.2.2–2.2.4]

- Important factors include (1) population and economic/technology development, food, fodder and fibre demand (including diets), and developments in agriculture and forestry; (2) climate change impacts on future land use including its adaptation capability; and (3) the extent of land degradation, water scarcity and biodiversity and nature conservation requirements.

- Residue flows in agriculture and forestry and unused (or extensively used thus becoming marginal/degraded) agricultural land are important sources for expansion of biomass production for energy, both in the near- and longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoidance of soil degradation set limits on residue extraction in agriculture and forestry.

- The cultivation of suitable plants (e.g., perennial crops or woody species) can allow for higher technical potentials by making it possible to produce bioenergy on lands less suited for conventional food crops—also when considering that the cultivation of conventional crops on such lands can lead to soil carbon emissions.

- Multi-functional land use systems with bioenergy production integrated into agriculture and forestry systems could contribute to biodiversity conservation and help restore/maintain soil productivity and healthy ecosystems.

- Regions experiencing water scarcity may have limited production. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable drought-tolerant energy crops can help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses.

Following the restrictions outlined above, the expert review concludes that potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ. However, there are large uncertainties in this potential, such as market and policy conditions, and there is strong dependence on the rate of improvements in the agricultural sector for food, fodder and fibre production and forest products. One example from the literature suggests that bioenergy can expand from around 100 EJ/yr in 2020 to 130 EJ/yr in 2030, and could reach 184 EJ/yr in 2050. [2.2.1, 2.2.2, 2.2.5]

To reach the upper range of the expert review deployment level of 300 EJ/yr (shown in Figure TS.2.2) would require major policy efforts, especially targeting improvements and efficiency increases in the agricultural sector and good governance, such as zoning, of land use.

2.3 Bioenergy technology and applications

Commercial bioenergy technology applications include heat production—with scales ranging from home cooking with stoves to large district heating systems; power generation from biomass via combustion, CHP, or co-firing of biomass and fossil fuels; and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol) as shown in the solid lines of Figure TS.2.3. The figure also illustrates developing feedstocks (e.g., aquatic biomass), conversion routes and products.[8] [2.3, 2.6, 2.7, 2.8]

Section 2.3 addresses key issues related to biomass production and the logistics of supplying feedstocks to the users (individuals for traditional and modern biomass, firms that use and produce secondary energy products or, increasingly, an informal sector of production and distribution of charcoal). The conversion technologies that transform biomass to convenient secondary energy carriers use thermochemical, chemical or biochemical processes, and are summarized in Sections 2.3.1–2.3.3 and 2.6.1–2.6.3. Chapter 8 addresses energy product integration with the existing and evolving energy systems. [2.3.1–2.3.3, 2.6.1–2.6.3]

2.4 Global and regional status of markets and industry deployment

A review of biomass markets and policy shows that bioenergy has seen rapid developments in recent years such as the use of modern biomass for liquid and gaseous energy carriers (an increase of 37% from 2006 to 2009). Projections from the IEA, among others, count on biomass delivering a substantial increase in the share of RE, driven in some cases by national targets. International trade in biomass and biofuels has

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[8] Biofuels produced via new processes are also called advanced or next-generation biofuels, e.g. lignocellulosic.

also become much more important over recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only) traded internationally and one-third of all pellet production for energy use in 2009. The latter facilitated both increased utilization of biomass in regions where supplies were constrained as well as mobilized resources from areas lacking demand. Nevertheless, many barriers remain in developing effective commodity trading of biomass and biofuels that, at the same time, meets sustainability criteria. [2.4.1, 2.4.4]

In many countries, the policy context for bioenergy and, in particular, biofuels, has changed rapidly and dramatically in recent years. The debate surrounding biomass in the food versus fuel competition, and growing concerns about other conflicts, have resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in target levels and schedules for bioenergy and biofuels. Furthermore, support for advanced biorefinery and next-generation biofuel[9] options is driving bioenergy to be more sustainable. [2.4.5]

Persistent and stable policy support has been a key factor in building biomass production capacity and markets, requiring infrastructure and conversion capacity that gets more competitive over time. These conditions have led to the success of the Brazilian programme to the point that ethanol production costs are now lower than those for gasoline. Sugarcane fibre bagasse generates heat and electricity, with an energy portfolio mix that is substantially based on RE and that minimizes foreign oil imports. Sweden and Finland also have shown significant growth in renewable electricity and in management of integrated resources, which steadily resulted in innovations such as industrial symbiosis of collocated industries. The USA has been able to quickly ramp up production with alignment of national and sub-national policies for power in the 1980s to 1990s and for biofuels in the 1990s to the present, as

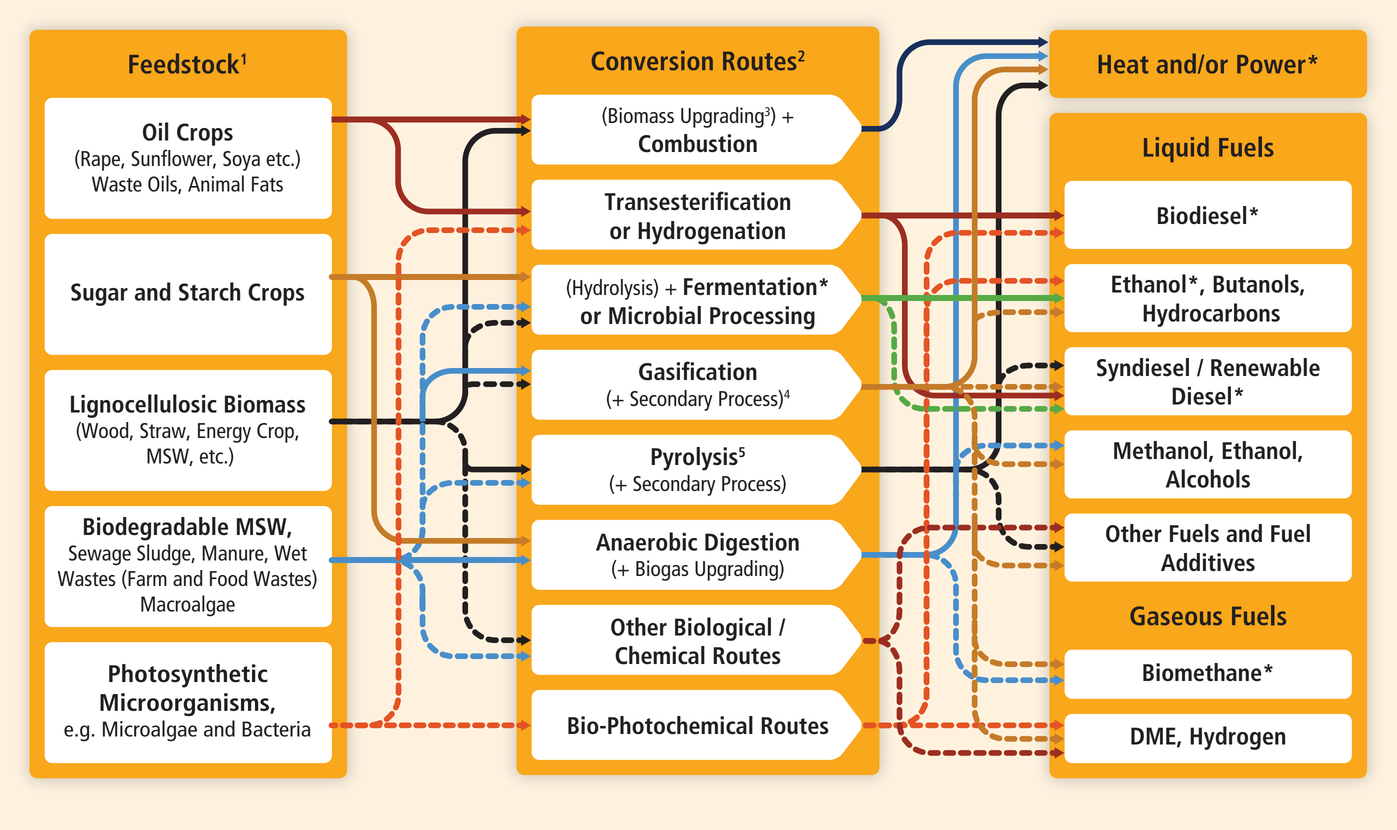

Figure TS.2.3 | Schematic view of the variety of commercial (solid lines) and developing bioenergy routes (dotted lines) from biomass feedstocks through thermochemical, chemical, biochemical and biological conversion routes to heat, power, CHP and liquid or gaseous fuels. Commercial products are marked with an asterisk. [Figure 2.2, 2.1.1]

Notes: 1. Parts of each feedstock could be used in other routes. 2. Each route can also make coproducts. 3. Biomass upgrading includes densification processes (such as pelletization, pyrolysis, torrefaction, etc.). 4. Anaerobic digestion processes to various gases which can be upgraded to biomethane, essentially methane, the major component of natural gas. 5. Could be other thermal processing routes such as hydrothermal, liquefaction, etc. Other chemical routes include aqueous phase reforming. DME=dimethyl ether.

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[9] Biofuels produced by new processes (e.g. from lignocellulosic biomass) are also called advanced biofuels.

petroleum prices and instability in key producing countries increased and to foster rural development and a secure energy supply. [2.4.5]

Countries differ in their priorities, approaches, technology choices and support schemes for further developing bioenergy. Market and policy complexities emerge when countries seek to balance specific priorities in agriculture and land use, energy policy and security, rural development and environmental protection while considering their unique stage of development, geographic access to resources, and availability and costs of resources. [2.4.5, 2.4.7]

One overall trend is that as policies surrounding bioenergy and biofuels become more holistic, sustainability becomes a stronger criterion at the starting point. This is true for the EU, the USA and China, but also for many developing countries such as Mozambique and Tanzania. This is a positive development, but by no means settled. The registered 70 initiatives worldwide by 2009 to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels, as well as agriculture and forestry, can lead to a fragmentation of efforts. The need for harmonization and international and multilateral collaboration and dialogue are widely stressed. [2.4.6, 2.4.7]

2.5 Environmental and social impacts

Bioenergy production has complex interactions with other social and environmental systems. Concerns—ranging from health and poverty to biodiversity and water scarcity and quality—vary depending upon many factors including local conditions, technology and feedstock choices, sustainability criteria design, and the design and implementation of specific projects. Perhaps most important is the overall management and governance of land use when biomass is produced for energy purposes on top of meeting food and other demands from agricultural, livestock and fibre production. [2.5]

Direct land use change (dLUC) occurs when bioenergy feedstock production modifies an existing land use, resulting in a change in above- and below-ground carbon stocks. Indirect LUC (iLUC) occurs when a change in production level of an agricultural product (i.e., a reduction in food or feed production induced by agricultural land conversion to produce a bioenergy feedstock) leads to a market-mediated shift in land management activities (i.e., dLUC) outside the region of primary production expansion. iLUC is not directly observable and is complex to model and difficult to attribute to a single cause as multiple actors, industry, countries, policies and markets dynamically interact. [2.5.3, 9.3.4.1]

In cases where increases in land use due to biomass production for bioenergy are accompanied by improvements in agricultural management (e.g., intensification of perennial crop and livestock production in degraded lands), undesirable (i)LUC effects can be avoided. If left unmanaged, conflicts can emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land and water resources use. Trade-offs between those dimensions exist and need to be managed through appropriate strategies and decision making (Figure TS.2.4). [2.5.8]

Most bioenergy systems can contribute to climate change mitigation if they replace traditional fossil fuel use and if the bioenergy production emissions are kept low. High nitrous oxide emissions from feedstock production and use of fossil fuels (especially coal) in the biomass conversion process can strongly impact the GHG savings. Options to lower GHG emissions include best practices in fertilizer management, process integration to minimize losses, utilization of surplus heat, and use of biomass or other low-carbon energy sources as process fuel. However, the displacement efficiency (GHG emissions relative to carbon in biomass) can be low when additional biomass feedstock is used for process energy in the conversion process - unless the displaced energy is generated from coal. If the biomass feedstock can produce both liquid fuel and electricity, the displacement efficiency can be high. [2.5.1–2.5.3]

There are different methods to evaluate the GHG emissions of key first- and second-generation biofuel options. Well-managed bioenergy projects can reduce GHG emissions significantly compared to fossil alternatives, especially for lignocellulosic biomass used in power generation and heat, and when that feedstock is commercially available. Advantages can be achieved by making appropriate use of agricultural residues and organic wastes, principally animal residues. Most current biofuel production systems have significant reductions in GHG emissions relative to the fossil fuels displaced, if no iLUC effects are considered. Figure TS.2.5 shows a snapshot of the ranges of lifecycle GHG emissions associated with various energy generation technologies from modern biomass compared to the respective fossil reference systems commonly used in these sectors. Commercial chains such as biomass direct power, anaerobic digestion biogas to power, and very efficient modern heating technologies are shown on the right side and provide significant GHG savings compared to the fossil fuels. More details of the GHG meta-analysis study comparing multiple biomass electricity generating technologies are available in Figure 2.11, which shows that the majority of lifecycle GHG emission estimates cluster between about 16 and 74 g CO_2eq/kWh.

The transport sector is addressed for today's and tomorrow's technologies. For light-duty vehicle applications, sugarcane today and lignocellulosic feedstocks in the medium term can provide significant emissions savings relative to gasoline. In the case of diesel, the range of GHG emissions depends on the feedstock carbon footprint. Biogas-derived biomethane also offers emission reductions (compared to natural gas) in the transport sector. [2.5.2, 9.3.4.1]

When land high in carbon (notably forests and especially drained peat soil forests) is converted to bioenergy production, upfront emissions may cause a time lag of decades to centuries before net emission savings are achieved. In contrast, the establishment of bioenergy plantations on marginal and degraded soils can lead to assimilation of CO_2 into soils

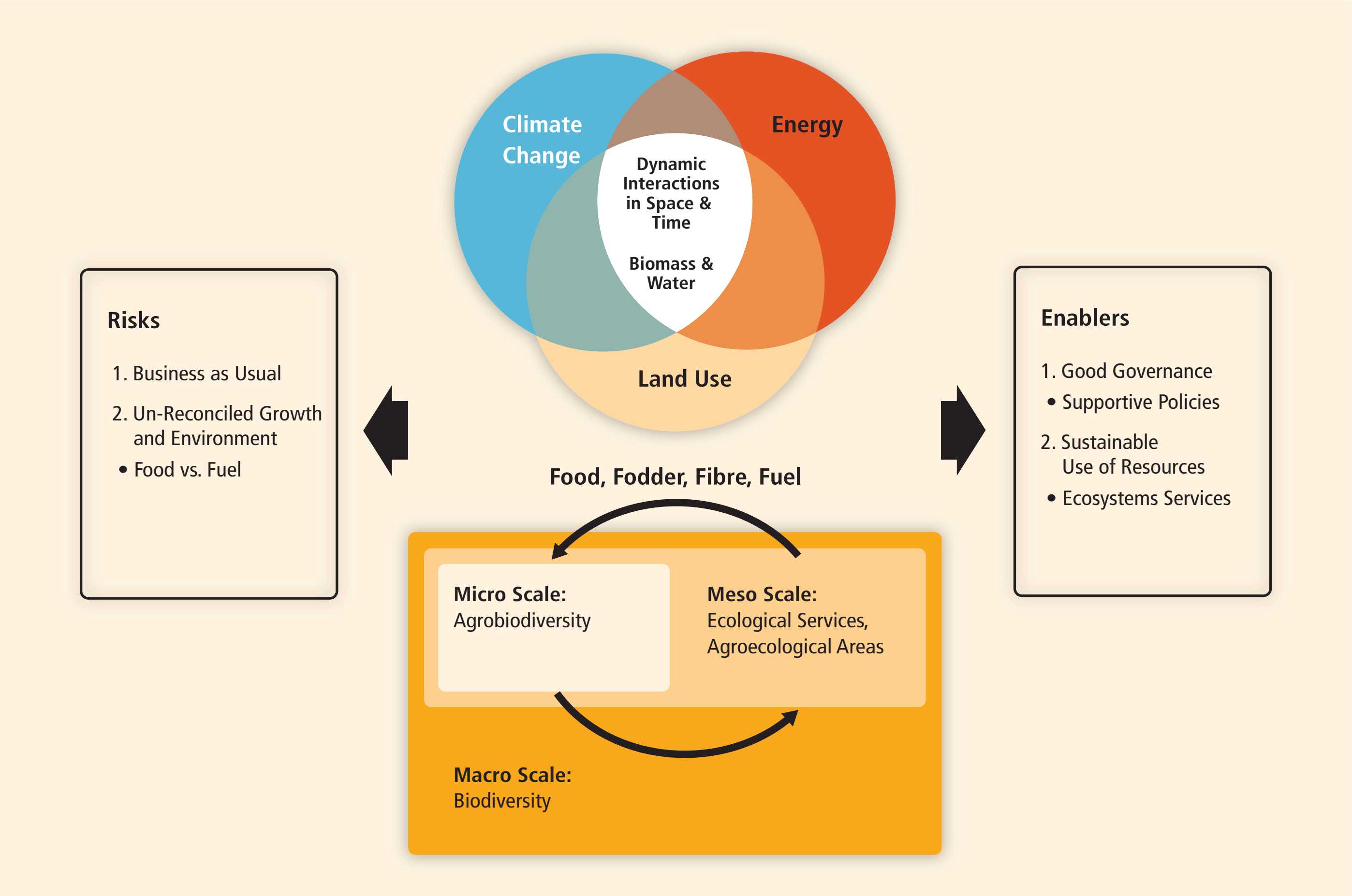


Figure TS.2.4 | The complex dynamic interactions among society, energy and the environment associated with bioenergy. Approaches of uncoordinated production of food and fuel that emerge in poor governance of land use are examples of business as usual practices. [Figure 2.15]

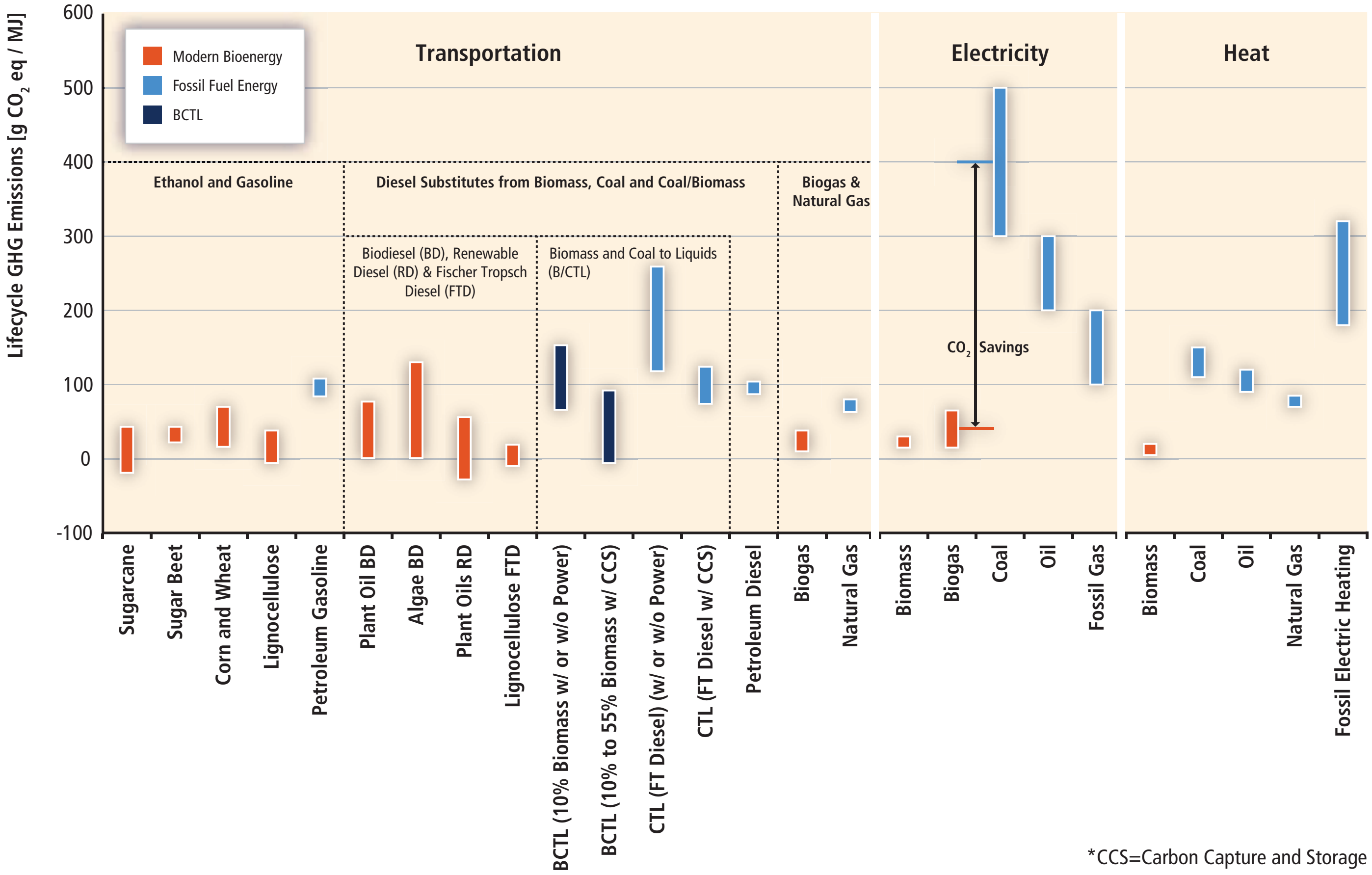
and aboveground biomass and when harvested for energy production it will replace fossil fuel use. Appropriate governance of land use (e.g., proper zoning) and choice of biomass production systems are crucial to achieve good performance. The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources were not utilized for alternative purposes. [2.5.3]

Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropland. Stimulating increased productivity in all forms of land use reduces the LUC pressure. [2.2.4.2, 2.5.2]

The assessment of available iLUC literature indicates that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation. While a 2008 study claimed an iLUC factor of 0.8 (losing 0.8 ha of forest land for each hectare of land used for bioenergy) later (2010) studies that coupled macro-economic to biophysical models reported a reduction to 0.15 to 0.3. Major factors are the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. The results from increased model sophistication and improved data on the actual dynamics of land distribution in the major biofuel producing countries are leading to lower overall LUC impacts, but still with wide uncertainties. All studies acknowledge that land use management at large is a key. Research to improve LUC assessment methods and increase the availability and quality of information on current land use, bioenergy-derived products and other potential LUC drivers can facilitate evaluation and provide tools to mitigate the risk of bioenergy-induced LUC. [2.5.3, 9.3.4.1]

Air pollution effects of bioenergy depend on both the bioenergy technology (including pollution control technologies) and the displaced energy technology. Improved biomass cookstoves for traditional biomass use can provide large and cost-effective mitigation of GHG emissions with substantial co-benefits for the 2.7 billion people that rely on traditional biomass for cooking and heating in terms of health and quality of life. [2.5.4, 2.5.5]

Without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable. Water is a critical issue that needs to be better analyzed at a regional level to understand the full impact of changes in vegetation and land use management. Recent studies indicate that considerable improvements can be made in water use efficiency in conventional



*CCS=Carbon Capture and Storage

Figure TS.2.5 | Ranges of GHG emissions per unit energy output (MJ) from major modern bioenergy chains compared to current and selected advanced fossil fuel energy systems (land use-related net changes in carbon stocks and land management impacts are excluded). Commercial and developing (e.g., algae biofuels, Fischer-Tropsch) systems for biomass and fossil technologies are illustrated. When CCS technologies are developed, capture and sequestration of biomass carbon emissions can compensate fossil fuel-based energy production emissions. [Figure 2.10]

agriculture, bioenergy crops and, depending on location and climate, perennial cropping systems by improving water retention and lowering direct evaporation from soils. [2.5.5, 2.5.5.1]

Similar remarks can be made with respect to biodiversity, although more scientific uncertainty exists due to ongoing debates on methods of biodiversity impact assessment. Clearly, development of large-scale monocultures at the expense of natural areas is detrimental for biodiversity, as highlighted in the 2007 Convention on Biological Diversity. However, integrating different perennial grasses and woody crops into agricultural landscapes can also increase soil carbon and productivity, reduce shallow landslides and local ‘flash floods’, provide ecological corridors, reduce wind and water erosion and reduce sediment and nutrients transported into river systems. Forest biomass harvesting can improve conditions for replanting, improve productivity and growth of the remaining stand and reduce wildfire risk. [2.5.5.3]

Social impacts associated with large expansions in bioenergy production are very complex and difficult to quantify. The demand for biofuels represents one driver of demand growth in the agricultural and forestry sectors and therefore contributes to global food price increases. Even considering the benefit of increased prices to poor farmers, higher food prices adversely affect poverty levels, food security, and malnourishment of children. On the other hand, biofuels can also provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable. In addition, expenditures on imported fossil fuels can be reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed. [2.5.7.4–2.5.7.6, 9.3.4]

The development of sustainability frameworks and standards can reduce potential negative impacts associated with bioenergy production and lead to higher efficiency than today’s systems. Bioenergy can contribute to climate change mitigation, a secure and diverse energy supply, and economic development in developed and developing countries alike, but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, and how projects are designed and implemented, among many other factors. [2.4.5.2, 2.8.3, 2.5.8, 2.2.5, 9.3.4]

2.6 Prospects for technology improvement and integration

Further improvements in biomass feedstock production and conversion technologies are quite possible and necessary if bioenergy is to contribute to global energy supply to the degree reflected in the high end of deployment levels shown in Figure TS.2.2. Increasing land productivity, whether for food or energy purposes, is a crucial prerequisite for realizing large-scale future deployment of biomass for energy since it would make more land available for growing biomass and reduce the associated demand for land. In addition, multi-functional land and water use systems could develop with bioenergy and biorefineries integrated into agricultural and forestry systems, contributing to biodiversity conservation and helping to restore/maintain soil productivity and healthy ecosystems. [2.6.1]

Lignocellulosic feedstocks offer significant promise because they 1) do not compete directly with food production, 2) can be bred specifically for energy purposes, enabling higher production per unit land area and a large market for energy products, 3) can be harvested as residues from crop production and other systems that increase land use efficiency, and 4) allow the integration of waste management operations with a variety of other industries offering prospects for industrial symbiosis at the local level. Literature on and investment trends in conversion technologies indicate that the industry is poised to increase product diversification, as did the petroleum industry, with increased interest in the high energy density fuels for air transport, an application for which other non-carbon fuels have not been identified. [2.6.4]

A new generation of aquatic feedstocks that produce algal lipids for diesel, jet fuels, or higher value products from CO_2 and water with sunlight can provide strategies for lower land use impacts, as algae can grow in brackish waters, lands inappropriate for cultivation, and industrial waste water. Algal organisms can operate in the dark and metabolize sugars for fuels and chemicals. Many microbes could become microscopic factories to produce specific products, fuels and materials that decrease society's dependence on fossil energy sources. [2.6.1.2, 2.7.3]

Although significant technical progress has been made, the more complex processing required by solid lignocellulosic biomass and the integration of a number of new steps takes time and support to bring development through the 'Valley of Death' in demonstration plants, first-of-a-kind plants and early commercialization. Projected costs of biofuels from a wide range of sources and process variables are very sensitive to feedstock cost and range from USD_{2005} 10 to 30/GJ. The US National Academies project a 40% reduction in operating costs for biochemical routes by 2035 to USD_{2005} 12 to 15/GJ. [2.6.3, 2.6.4]

Biomass gasification currently provides about 1.4 GW_{th} in industrial applications, thermal applications and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Many stakeholders have had a special interest in integrated gasification combined-cycle (IGCC) power plants that use bioenergy as a feedstock. These plants are projected to be more efficient than traditional steam turbine systems but have not yet reached full commercialization. However, they also have the potential to be integrated into CCS systems more effectively. In addition to providing power, syngas from gasification plants can be used to produce a wide range of fuels (methanol, ethanol, butanols and syndiesel) or can be used in a combined power and fuels approach. Technical and engineering challenges have so far prevented more rapid deployment of this technology option. Biomass to liquids conversion uses commercial technology developed for fossil fuels. Figure TS.2.5 illustrates projected emissions from coal to liquid fuels and the offsetting emissions that biomass could offer all the way to removal of GHG from the atmosphere when coupled with CCS technologies. Gaseous products (hydrogen, methane, synthetic natural gas) have lower estimated production costs and are in an early commercialization phase. [2.6.3, 2.6.4]

Pyrolysis and hydrothermal oils are low-cost transportable oils, used in heat or CHP applications and could become a feedstock for upgrading either in stand-alone facilities or coupled to a petrochemical refinery. [2.3.4, 2.6.3, 2.6.4, 2.7.1]

The production of biogas from a variety of waste streams and its upgrading to biomethane is already penetrating small markets for multiple applications, including transport in small networks in Sweden and for heat and power in Nordic and European countries. A key factor is the combination of waste streams, including agriculture residues. Improved upgrading and reducing costs is also needed. [2.6.3, 2.6.4]

Many bioenergy/biofuels routes enable CCS with significant opportunities for emissions reductions and sequestration. As CCS technologies are further developed and verified, coupling fermentation with concentrated CO_2 streams or IGCC offers opportunities to achieve carbon-neutral fuels, and in some cases negative net emissions. Achieving this goal will be facilitated by well-designed systems that span biomass selection, feedstock supply system, conversion to a secondary energy carrier and integration of this carrier into the existing and future energy systems. [2.6.3, 2.6.4, 9.3.4]

2.7 Current costs and trends

Biomass production, supply logistics, and conversion processes contribute to the cost of final products. [2.3, 2.6, 2.7]

The economics and yields of feedstocks vary widely across world regions and feedstock types with costs ranging from USD_{2005} 0.9 to 16/GJ (data from 2005 to 2007). Feedstock production for bioenergy competes with the forestry and food sectors, but integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services. Handling and transport of biomass from production sites to conversion plants may contribute 20 to up to 50% of the total costs of bioenergy production. Factors such as scale increase and technological innovations increase competition and contribute to a decrease in economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transportation distances over 50 km. [2.3.2, 2.6.2]

Several important bioenergy systems today, most notably sugarcane-based ethanol and heat and power generation from residues and waste biomass, can be deployed competitively. [Tables 2.6, 2.7]

Based on a standardized methodology outlined in Annex II, and the cost and performance data summarized in Annex III, the estimated production costs for commercial bioenergy systems at various scales and with some consideration of geographical regions are summarized in Figure TS.2.6. Values include production, supply logistics and conversion costs. [1.3.2, 2.7.2, 10.5.1, Annex II, Annex III]

Costs vary by world regions, feedstock types, feedstock supply costs, the scale of bioenergy production, and production time during the year, which is often seasonal. Examples of estimated commercial bioenergy levelized[10] cost ranges are roughly USD_{2005} 2 to 48/GJ for liquid and gaseous biofuels; roughly 3.5 to 25 US $cents_{2005}$/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feed stock costs of USD_{2005} 3/GJ feed and a heat value of USD_{2005} 5/GJ for steam or USD_{2005} 12/GJ for hot water); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are in expressed USD_{2005} at a 7% discount rate. The cost ranges for biofuels in Figure TS.2.6 cover the Americas, India, China and European countries. For heating systems, the costs are primarily European and the electricity and CHP costs come from primarily large user countries. [2.3.1–2.3.3, 2.7.2, Annex III]

In the medium term, the performance of existing bioenergy technologies can still be improved considerably, while new technologies offer the prospect of more efficient and competitive deployment of biomass for energy (and materials). Bioenergy systems, namely for ethanol and biopower production, show technological learning and related cost reductions with learning rates comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management for sugarcane and maize), supply systems and logistics (as observed in Nordic countries and international logistics) and in conversion (ethanol production, power generation and biogas) as shown in Table TS.2.2.

Although not all bioenergy options discussed in Chapter 2 have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance. However, they usually still require government subsidies provided for economic development (e.g., poverty reduction and a secure energy supply) and other country-specific reasons. For traditional biomass, charcoal made from biomass is a major fuel in developing countries, and should benefit from the adoption of higher-efficiency kilns. [2.3, 2.6.1, 2.6.2, 2.6.3, 2.7.2, 10.4, 10.5]

The competitive production of bio-electricity (through methane or biofuels) depends on the integration with the end-use systems, performance of alternatives such as wind and solar energy, developing CCS technologies coupled with coal conversion, and nuclear energy. The implications of successful deployment of CCS in combination with biomass conversion could result in removal of GHGs from the atmosphere and attractive mitigation cost levels but have so far received limited attention. [2.6.3.3, 8.2.1, 8.2.3, 8.2.4, 8.3, 9.3.4]

Table TS.2.3 illustrates that costs for some key bioenergy technology are expected to decline over the near- to mid-term. With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough for competition with oil at prices of USD_{2005} 60 to 80/barrel (USD_{2005} 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support is strong, technological progress could allow for their commercialization around 2020 (depending on oil and carbon prices). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, since competitive production would decouple deployment from policy targets (mandates) and demand for 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. [2.8.4, 2.4.3, 2.4.5]

Lignocellulosic ethanol development and demonstration continues in several countries. A key development step is the pretreatment to overcome the recalcitrance of the cell wall of woody, herbaceous or agricultural residues to make carbohydrate polymers accessible to hydrolysis (e.g., by enzymes) and fermentation of sugars to ethanol (or butanol) and lignin for process heat or electricity. Alternatively, multiple steps can be combined and bio-processed with multiple organisms simultaneously. A review of progress in the enzymatic area suggests that a 40% reduction in cost could be expected by 2030 from process improvements, which would bring down the estimated cost of production from USD_{2005} 18 to 22/GJ (pilot data) to USD 12 to 15/GJ, a competitive range. [2.6.3]

Biomass pyrolysis routes and hydrothermal concepts are also developing in conjunction with the oil industry and have demonstrated technically that upgrading of oils to blendstocks of gasoline or diesel and even jet fuel quality products is possible. [2.6.3]

Photosynthetic organisms such as algae biologically produce (using CO_2, water and sunlight) a variety of carbohydrates and lipids that can be used directly or for biofuels. These developments have significant long-term potential because algae photosynthetic efficiency is much higher

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[10] As in the electricity production in CHP systems in which calculations assumed a value for the co-produced heat, for biofuels systems, there are cases in which two co-products are obtained; for instance, sugarcane to sugar, ethanol, and electricity. Sugar co-product revenue could be about $US\$_{2005}$ 2.6/GJ and displace the ethanol cost by that amount.

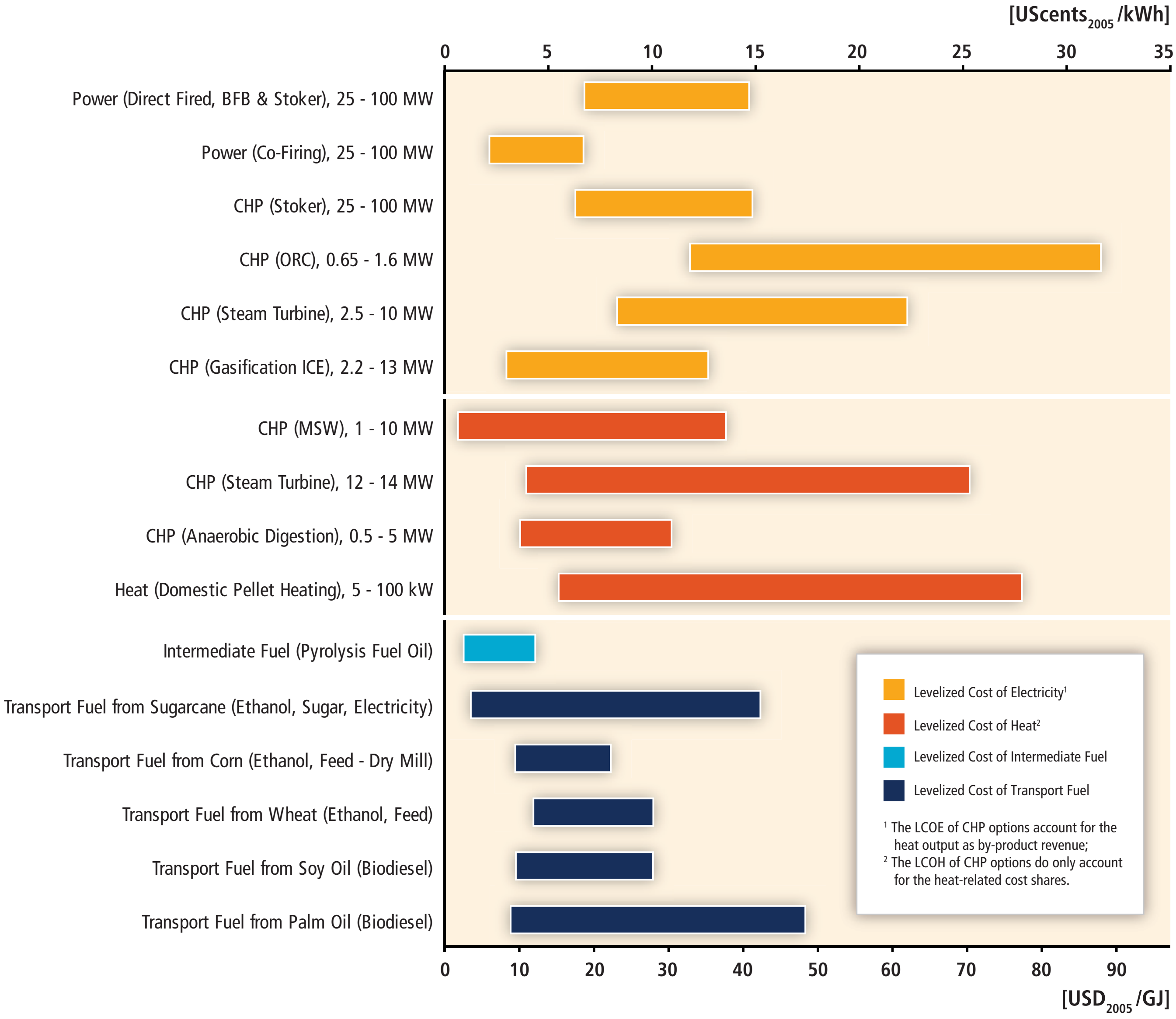


Figure TS.2.6 | Typical recent levelized cost of energy services from commercially available bioenergy systems at a 7% discount rate, calculated over a year of feedstock costs, which differ between technologies. These costs do not include interest, taxes, depreciation and amortization. [Figure 2.18] Levelized costs of electricity (LCOE), heat (LCOH), fuels (LCOF), intermediate fuel (LCOIF), BFB: Bubbling Fluidized Bed, ORC: Organic Rankine Cycle and ICE: Internal Combustion Engine. For biofuels, the range of LCOF represents production in a wide range of countries whereas LCOE and LCOH are given only for major user markets of the technologies for which data were available. Calculations are based on High Heating Value.

than that of oil crops. Potential bioenergy supplies from plants are very uncertain, but because their development can utilize brackish waters and heavily saline soils, their use is a strategy for low LUC impacts. [2.6.2, 3.3.5, 3.7.6]

Data availability is limited with respect to production of biomaterials, while cost estimates for chemicals from biomass are rare in peer-reviewed literature and future projections and learning rates even more so. This condition is linked, in part, to the fact that successful bio-based products are entering the market place either as partial components of otherwise fossil-derived products or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. In addition to producing biomaterials to replace fossil fuels, analyses indicate that cascaded use of biomaterials and subsequent use of waste material for energy can offer more effective and larger mitigation impacts per hectare or tonne of biomass used. [2.6.3.5]

2.8 Potential deployment levels

Between 1990 and 2008, bioenergy use increased at an average annual growth rate of 1.5% for solid biomass, while the more modern biomass use for secondary carriers such as liquid and gaseous forms increased at 12.1 and 15.4% respectively. As a result, the share of biofuels in global road transport was 2% in 2008. The production of ethanol and biodiesel increased by 10 and 9%, respectively, in 2009, to 90 billion litres, such that biofuels contributed nearly 3% of global road transport in 2009, as oil demand decreased for the first time since 1980. Government

Table TS.2.2 | Experience curves for major components of bioenergy systems and final energy carriers expressed as reduction (%) in cost (or price) per doubling of cumulative production, the Learning Rate (LR); N: number of doublings of cumulative production; R2 is the correlation coefficient of the statistical data; O&M: Operations and Maintenance. [Table 2.17]

Learning system	LR (%)	Time frame	Region	N	R^2
Feedstock production					
Sugarcane (tonnes sugarcane)	32±1	1975–2005	Brazil	2.9	0.81
Corn (tonnes corn)	45±1.6	1975–2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden)	15–12	1975–2003	Sweden/Finland	9	0.87–0.93
Investment and O&M costs					
CHP plants	19-25	1983–2002	Sweden	2.3	0.17–0.18
Biogas plants	12	1984–1998		6	0.69
Ethanol production from sugarcane	19±0.5	1975–2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs)	13±0.15	1983–2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane	7	1970–1985	Brazil		
	29	1985–2002		~6.1	N/A
Ethanol from sugarcane	20±0.5	1975–2003	Brazil	4.6	0.84
Ethanol from corn	18±0.2	1983–2005	USA	6.4	0.96
Electricity from biomass CHP	9-8	1990–2002	Sweden	~9	0.85–0.88
Electricity from biomass	15	Unknown	OECD	N/A	N/A
Biogas	0–15	1984–2001	Denmark	~10	0.97

Table TS.2.3 | Projected production cost ranges for developing technologies. [Table 2.18]

Selected Bioenergy Technologies	Energy Sector (Electricity, Thermal, Transport)[6]	2020-2030 Projected Production Costs (USD_{2005}/GJ)
Integrated gasification combined cycle [1]	Electricity and/or transport	12.8–19.1 (4.6–6.9 cents/kWh)
Oil plant-based renewable diesel and jet fuel	Transport and electricity	15–30
Lignocellulose sugar-based biofuels[2]	Transport	6–30
Lignocellulose syngas-based biofuels[3]		12–25
Lignocellulose pyrolysis-based biofuels[4]		14–24 (fuel blend components)
Gaseous biofuels[5]	Thermal and transport	6–12
Aquatic plant-derived fuels, chemicals	Transport	30–140

Notes: 1. Feed cost USD_{2005} 3.1/GJ, IGCC (future) 30 to 300 MW, 20-yr life, 10% discount rate. 2. Ethanol, butanols, microbial hydrocarbons and microbial hydrocarbons from sugar or starch crops or lignocellulose sugars. 3. Syndiesel, methanol and gasoline, etc.; syngas fermentation routes to ethanol. 4. Biomass pyrolysis and catalytic upgrading to gasoline and diesel blend components or to jet fuels. 5. Synfuel to synthetic natural gas, methane, dimethyl ether, hydrogen from biomass thermochemical and anaerobic digestion (larger scale). 6. Several applications can be coupled with CCS when these technologies, including CCS, are mature and thus could remove GHG from the atmosphere.

policies in various countries led to a five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008 representing 1% of the world's electricity and a doubling since 1990 (from 131 TWh (0.47 EJ)). [2.4]

The expected continued deployment of biomass for energy in the 2020 to 2050 time frame varies considerably between studies. A key message from the review of available insights is that large-scale biomass deployment strongly depends on sustainable development of the resource base, governance of land use, development of infrastructure and cost reduction of key technologies, for example, efficient and complete use of primary biomass for energy from the most promising first-generation feedstocks and new-generation lignocellulosic biomass. [2.4.3, 2.8]

The scenario results summarized in Figure TS.2.7 derive from a diversity of modelling teams and a wide range of assumptions including energy demand growth, cost and availability of competing low-carbon technologies, and cost and availability of RE technologies. Traditional biomass use is projected to decline in most scenarios while the use of liquid biofuels, biogas and electricity and hydrogen produced from biomass tends to increase. Results for biomass deployment for energy under these scenarios for 2020, 2030 and 2050 are presented for three GHG stabilization ranges based on the AR4: Categories III and IV (440-600 ppm CO_2), Categories I and II (<440 ppm CO_2) and Baselines (>600 ppm CO_2) all by 2100. [10.1–10.3]

Global biomass deployment for energy is projected to increase with more ambitious GHG concentration stabilization levels indicating its long-term role in reducing global GHG emissions. Median levels are 75

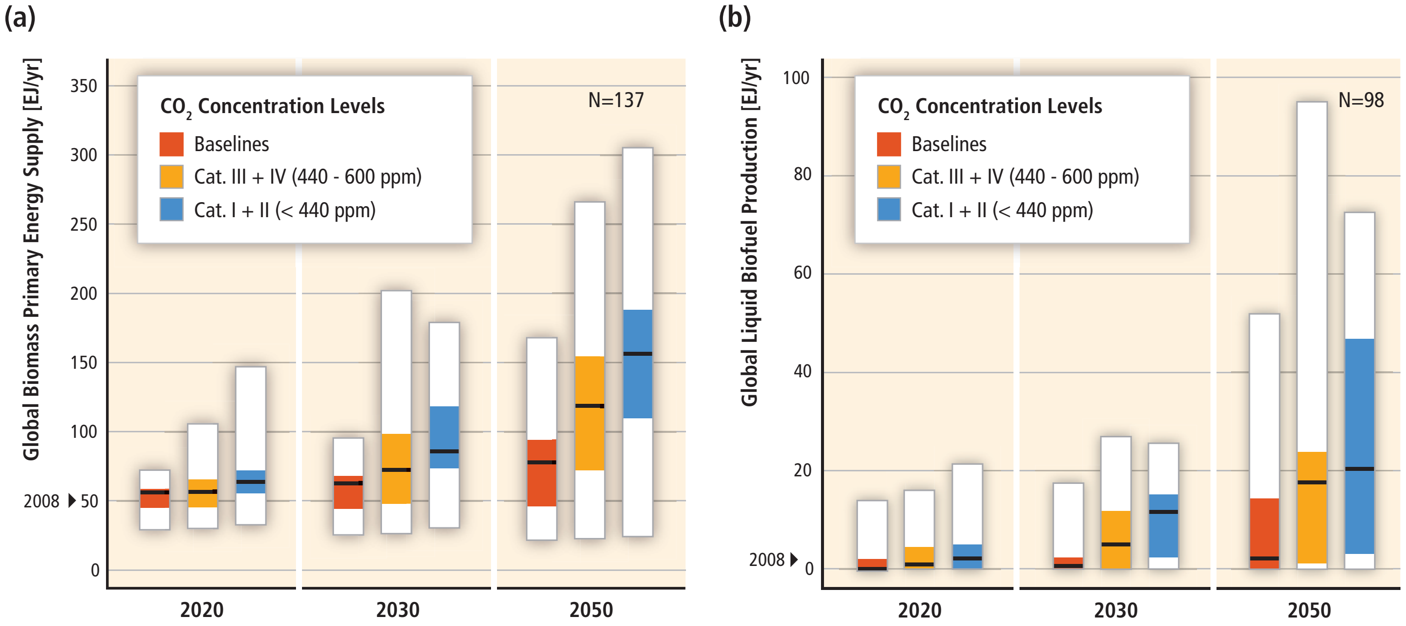


Figure TS.2.7 | (a) The global primary energy supply from biomass in long-term scenarios for electricity, heat and biofuels, all accounted for as primary energy; and (b) global biofuels production in long-term scenarios reported in secondary energy terms. For comparison, the historical levels in 2008 are indicated in the small black arrows on the left axis. [Figure 2.23]

to 85 EJ and 120 to 155 EJ for the two mitigation scenarios in 2030 and 2050, respectively, almost two and three times the 2008 deployment level of 50 EJ. These deployment levels are similar to the expert review mid-range levels for 2050. Global biofuels production shown in Figure TS.2.7(b) for 2020 and 2030 are at fairly low levels, but most models lack a detailed description of different conversion pathways and related learning potential. [2.7.3] For the <440 ppm mitigation scenario, biofuels production reaches six (2030) and ten (2050) times the 2008 actual value of 2 EJ. [2.2.5, 2.8.2, 2.5.8, 2.8.3]

The sector-level penetration of bioenergy is best explained using a single model with detailed transport sector representation such as the 2010 IEA World Energy Outlook (WEO) that also models both traditional and modern biomass applications and takes into account anticipated industrial and government investments and goals. This model projects very significant increases in modern bioenergy and a decrease in traditional biomass use. These projections are in qualitative agreement with the results from Chapter 10. In 2030, for the WEO 450-ppm mitigation scenario, the IEA projects that 11% of global transport fuels will be provided by biofuels with second-generation biofuels contributing 60% of the projected 12 EJ and half of this amount is projected to be supplied owing to continuation of current policies. Biomass and renewable wastes would supply 5% of the world's electricity generation or 1,380 TWh/yr (5 EJ/yr) of which 555 TWh/yr (2 EJ/yr) are a result of the stringent climate mitigation strategy. Biomass industrial heating applications for process steam and space and hot water heating for buildings (3.3 EJ in 2008) would each double in absolute terms from 2008 levels. However, the total heating demand is projected to decrease because of assumed traditional biomass decline. Heating is seen as a key area for continued modern bioenergy growth. Biofuels are projected to mitigate 17% of road and 3% of air transport emissions by 2030. [2.8.3]

2.8.1 Conclusions regarding deployment: Key messages about bioenergy

The long-term scenarios reviewed in Chapter 10 show increases in bioenergy supply with increasingly ambitious GHG concentration stabilization levels, indicating that bioenergy could play a significant long-term role in reducing global GHG emissions. [2.8.3]

Bioenergy is currently the largest RE source and is likely to remain one of the largest RE sources for the first half of this century. There is considerable growth potential, but it requires active development. [2.8.3]

- Assessments in the recent literature show that the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. However, large uncertainty exists about important factors such as market and policy conditions that affect this potential. [2.8.3]

- The expert assessment in Chapter 2 suggests potential deployment levels by 2050 in the range of 100 to 300 EJ/yr. Realizing this potential represents a major challenge but would make a substantial contribution to the world's primary energy demand in 2050—roughly equal to the equivalent heat content of today's worldwide biomass extraction in agriculture and forestry. [2.8.3]

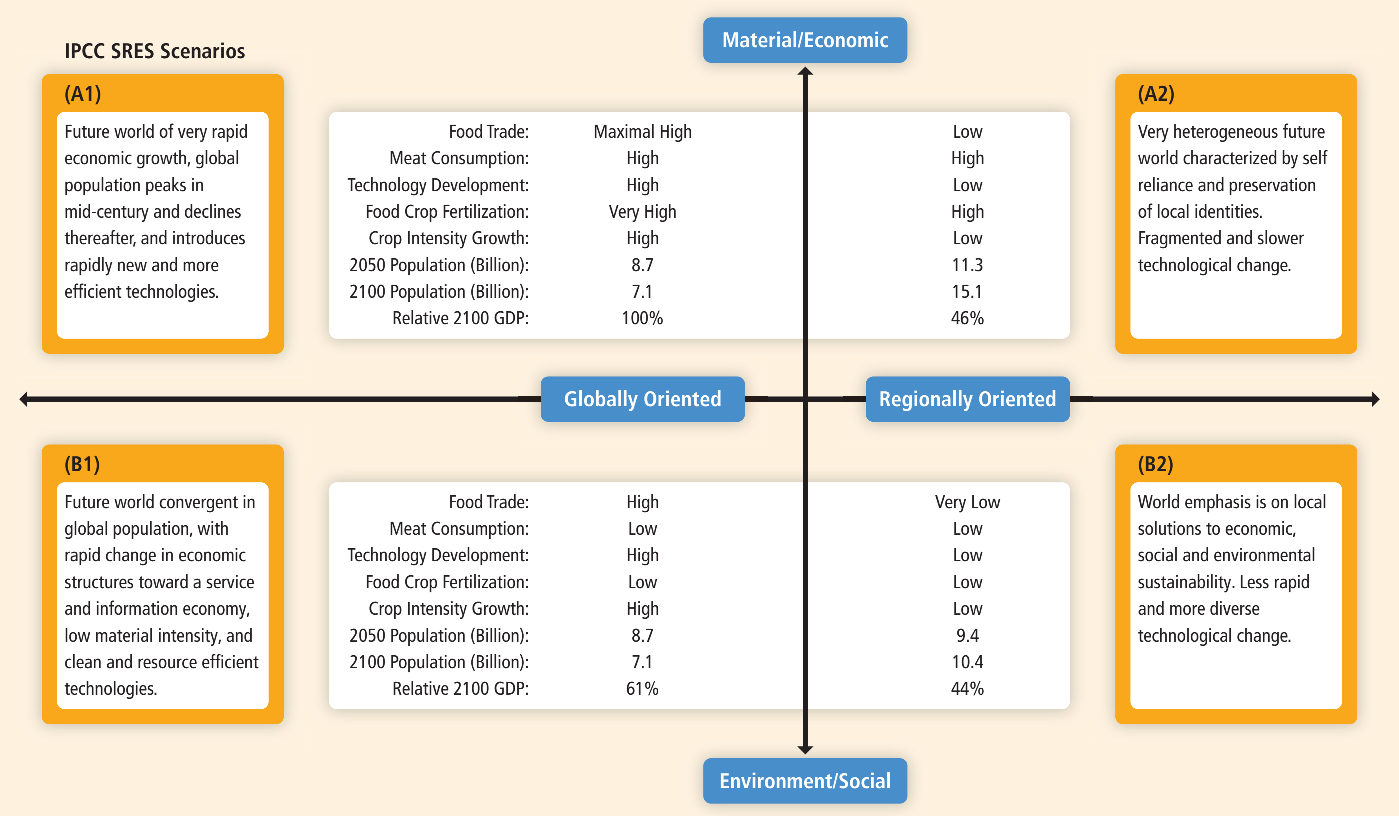
- Bioenergy has significant potential to mitigate GHGs if resources are sustainably developed and efficient technologies are applied.

Certain current systems and key future options, including perennial crops, forest products and biomass residues and wastes, and advanced conversion technologies, can deliver significant GHG mitigation performance—an 80 to 90% reduction compared to the fossil energy baseline. However, land conversion and forest management that lead to a large loss of carbon stocks and iLUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts. [2.8.3]

- In order to achieve the high potential deployment levels of biomas for energy, increases in competing food and fibre demand must be moderate, land must be properly managed and agricultural and forestry yields must increase substantially. Expansion of bioenergy in the absence of monitoring and good governance of land use carries the risk of significant conflicts with respect to food supplies, water resources and biodiversity, as well as a risk of low GHG benefits. Conversely, implementation that follows effective sustainability frameworks could mitigate such conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation, including opportunities to combine adaptation measures. [2.8.3]

- The impacts and performance of biomass production and use are region- and site-specific. Therefore, as part of good governance of land use and rural development, bioenergy policies need to consider regional conditions and priorities along with the agricultural (crops and livestock) and forestry sectors. Biomass resource potentials are influenced by and interact with climate change impacts but the specific 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. [2.8.3]

- Several important bioenergy options (i.e., sugarcane ethanol production in Brazil, select waste-to-energy systems, efficient biomass cookstoves, biomass-based CHP) are competitive today and can provide important synergies with longer-term options. Lignocellulosic biofuels to replace gasoline, diesel and jet fuels, advanced bioelectricity options, and biorefinery concepts can offer competitive deployment of bioenergy for the 2020 to 2030 timeframe. Combining biomass conversion with CCS raises the possibility of achieving GHG removal from the atmosphere in the long term—a necessity for substantial GHG emission reductions. Advanced biomaterials are promising as well for economics of bioenergy production and mitigation, though the potential is less well understood as is the potential role of aquatic biomass (algae), which is highly uncertain. [2.8.3]



(A1)

Future world of very rapid economic growth, global population peaks in mid-century and declines thereafter, and introduces rapidly new and more efficient technologies.

(A2)

Very heterogeneous future world characterized by self reliance and preservation of local identities. Fragmented and slower technological change.

	(A1)	(A2)
Food Trade:	Maximal High	Low
Meat Consumption:	High	High
Technology Development:	High	Low
Food Crop Fertilization:	Very High	High
Crop Intensity Growth:	High	Low
2050 Population (Billion):	8.7	11.3
2100 Population (Billion):	7.1	15.1
Relative 2100 GDP:	100%	46%

(B1)

Future world convergent in global population, with rapid change in economic structures toward a service and information economy, low material intensity, and clean and resource efficient technologies.

(B2)

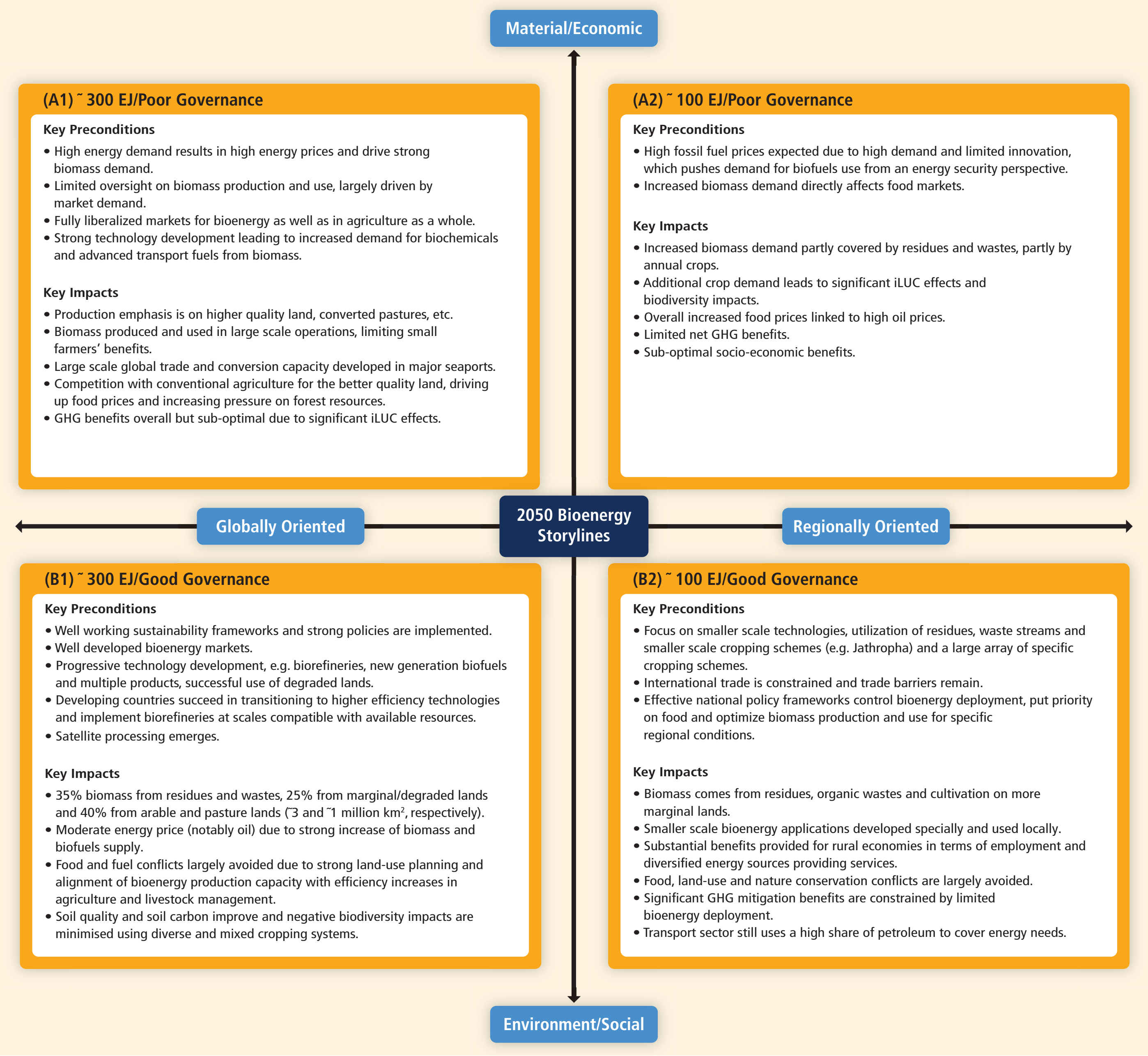
World emphasis is on local solutions to economic, social and environmental sustainability. Less rapid and more diverse technological change.

	(B1)	(B2)
Food Trade:	High	Very Low
Meat Consumption:	Low	Low
Technology Development:	High	Low
Food Crop Fertilization:	Low	Low
Crop Intensity Growth:	High	Low
2050 Population (Billion):	8.7	9.4
2100 Population (Billion):	7.1	10.4
Relative 2100 GDP:	61%	44%

Figure TS.2.8 | Storylines for the key SRES scenario variables used to model biomass and bioenergy, the basis for the 2050 sketches adapted to this report and used to derive the stacked bar showing the biomass technical potential in Figure TS.2.2. [Figure 2.26]

- Rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefineries and lignocellulosic biofuel options, and in particular the development of sustainability criteria and frameworks, all have the potential to drive bioenergy systems and their deployment in sustainable directions. Achieving this goal will require sustained investments that reduce costs of key technologies, improved biomass production and supply infrastructure, and implementation strategies that can gain public and political acceptance. [2.8.3]

In conclusion and for illustrating the interrelations between scenario variables (see Figure TS.2.8), key preconditions under which bioenergy production capacity is developed and what the resulting impacts may be, Figure TS.2.8 presents four different sketches for biomass deployment for energy at a global scale by 2050. The 100 to 300 EJ range that follows from the resource potential review delineates the lower and upper limit for deployment. The assumed storylines roughly follow the IPCC Special Report on Emissions Scenarios (SRES) definitions, applied to bioenergy and summarized in Figure TS.2.9 and which were also used



(A1) ~ 300 EJ/Poor Governance

Key Preconditions

- High energy demand results in high energy prices and drive strong biomass demand.
- Limited oversight on biomass production and use, largely driven by market demand.
- Fully liberalized markets for bioenergy as well as in agriculture as a whole.
- Strong technology development leading to increased demand for biochemicals and advanced transport fuels from biomass.

Key Impacts

- Production emphasis is on higher quality land, converted pastures, etc.
- Biomass produced and used in large scale operations, limiting small farmers' benefits.
- Large scale global trade and conversion capacity developed in major seaports.
- Competition with conventional agriculture for the better quality land, driving up food prices and increasing pressure on forest resources.
- GHG benefits overall but sub-optimal due to significant iLUC effects.

(A2) ~ 100 EJ/Poor Governance

Key Preconditions

- High fossil fuel prices expected due to high demand and limited innovation, which pushes demand for biofuels use from an energy security perspective.
- Increased biomass demand directly affects food markets.

Key Impacts

- Increased biomass demand partly covered by residues and wastes, partly by annual crops.
- Additional crop demand leads to significant iLUC effects and biodiversity impacts.
- Overall increased food prices linked to high oil prices.
- Limited net GHG benefits.
- Sub-optimal socio-economic benefits.

(B1) ~ 300 EJ/Good Governance

Key Preconditions

- Well working sustainability frameworks and strong policies are implemented.
- Well developed bioenergy markets.
- Progressive technology development, e.g. biorefineries, new generation biofuels and multiple products, successful use of degraded lands.
- Developing countries succeed in transitioning to higher efficiency technologies and implement biorefineries at scales compatible with available resources.
- Satellite processing emerges.

Key Impacts

- 35% biomass from residues and wastes, 25% from marginal/degraded lands and 40% from arable and pasture lands (~3 and ~1 million km^2, respectively).
- Moderate energy price (notably oil) due to strong increase of biomass and biofuels supply.
- Food and fuel conflicts largely avoided due to strong land-use planning and alignment of bioenergy production capacity with efficiency increases in agriculture and livestock management.
- Soil quality and soil carbon improve and negative biodiversity impacts are minimised using diverse and mixed cropping systems.

(B2) ~ 100 EJ/Good Governance

Key Preconditions

- Focus on smaller scale technologies, utilization of residues, waste streams and smaller scale cropping schemes (e.g. Jathropha) and a large array of specific cropping schemes.
- International trade is constrained and trade barriers remain.
- Effective national policy frameworks control bioenergy deployment, put priority on food and optimize biomass production and use for specific regional conditions.

Key Impacts

- Biomass comes from residues, organic wastes and cultivation on more marginal lands.
- Smaller scale bioenergy applications developed specially and used locally.
- Substantial benefits provided for rural economies in terms of employment and diversified energy sources providing services.
- Food, land-use and nature conservation conflicts are largely avoided.
- Significant GHG mitigation benefits are constrained by limited bioenergy deployment.
- Transport sector still uses a high share of petroleum to cover energy needs.

Figure TS.2.9 | Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines summarized in Figure TS.2.8. [Figure 2.27] to derive the technical potential shown on the stacked bar of Figure TS.2.2. [2.8.3]

Biomass and its multiple energy products can be developed alongside food, fodder, fibre and forest products in both sustainable and unsustainable ways. As viewed through IPCC scenario storylines and sketches, high and low penetration levels can be reached with and without taking into account sustainable development and climate change mitigation pathways. Insights into bioenergy technology developments and integrated systems can be gleaned from these storylines. [2.8.3]

3. Direct Solar

3.1 Introduction

Direct solar energy technologies are diverse in nature. Responding to the various ways that humans use energy—such as heating, electricity, and fuels—they constitute a family of technologies. This summary focuses on four major types: 1) solar thermal, which includes both active and passive heating of buildings, domestic and commercial solar water heating, swimming pool heating and process heat for industry; 2) photovoltaic (PV) electricity generation via direct conversion of sunlight to electricity by photovoltaic cells; 3) concentrating solar power (CSP) electricity generation by optical concentration of solar energy to obtain high-temperature fluids or materials to drive heat engines and electrical generators; and 4) solar fuels production methods, which use solar energy to produce useful fuels. [3.1]

The term ‘direct’ solar energy refers to the energy base for those RE technologies that draw on the Sun’s energy directly. Certain renewable technologies, such as wind and ocean thermal, use solar energy after it has been absorbed on the Earth and converted to other forms. (In the remainder of this section, the adjective ‘direct’ applied to solar energy will often be deleted as being understood.) [3.1]

3.2 Resource potential

Solar energy constitutes the thermal radiation emitted by the Sun’s outer layer. Just outside Earth’s atmosphere, this radiation, called solar irradiance, has a magnitude that averages 1,367 W/m^2 for a surface perpendicular to the Sun’s rays. At ground level (generally specified as sea level with the sun directly overhead), this irradiance is attenuated by the atmosphere to about 1,000 W/m^2 in clear sky conditions within a few hours of noon—a condition called ‘full sun’. Outside the atmosphere, the Sun’s energy is carried in electromagnetic waves with wavelengths ranging from about 0.25 to 3 μm. Part of the solar irradiance is contributed by rays arriving directly from the sun without being scattered in the atmosphere. This ‘beam’ irradiance, which is capable of being concentrated by mirrors and lenses, is most available in low cloud-cover areas. The remaining irradiance is called the diffuse irradiance. The sum of the beam and diffuse irradiance is called global solar irradiation. [3.2]

The theoretical solar energy potential, which indicates the amount of irradiance at the Earth’s surface (land and ocean) that is theoretically available for energy purposes, has been estimated at 3.9×10^6 EJ/yr. This number, clearly intended for illustrative purposes only, would require the full use of all available land and sea area at 100% conversion efficiency. A more useful metric is the technical potential; this requires assessing the fraction of land that is of practical use for conversion devices using a more realistic conversion efficiency. Estimates for solar energy’s technical potential range from 1,575 to 49,837 EJ/yr, that is, roughly 3 to 100 times the world’s primary energy consumption in 2008. [3.2, 3.2.2]

3.3 Technology and applications

Figure TS.3.1 illustrates the types of passive and active solar technologies currently in use to capture the Sun’s energy to provide both residential energy services and direct electricity. In this summary, only technologies for active heating and electricity are treated in depth. [3.3.1–3.3.4]

Solar thermal: The key component in active solar thermal systems is the solar collector. A flat-plate solar collector consists of a blackened plate with attached conduits, through which passes a fluid to be heated. Flat-plate collectors may be classified as follows: unglazed, which are suitable for delivering heat at temperatures a few degrees above ambient temperature; glazed, which have a sheet of glass or other transparent material placed parallel to the plate and spaced a few centimetres above it, making it suitable for delivering heat at temperatures of about 30°C to 60°C; or evacuated, which are similar to glazed, but the space between the plate and the glass cover is evacuated, making this type of collector suitable for delivering heat at temperatures of about 50°C to 120°C. To withstand the vacuum, the plates of an evacuated collector are usually put inside glass tubes, which constitute both the collector’s glazing and its container. In the evacuated type, a special black coating called a ‘selective surface’ is put on the plate to help prevent re-emission of the absorbed heat; such coatings are often used on the non-evacuated glazed type as well. Typical efficiencies of solar collectors used in their proper temperature range extend from about 40 to 70% at full sun. [3.3.2.1]

Flat-plate collectors are commonly used to heat water for domestic and commercial use, but they can also be used in active solar heating to provide comfort heat for buildings. Solar cooling can be obtained by using solar collectors to provide heat to drive an absorption refrigeration cycle. Other applications for solar-derived heat are industrial process heat, agricultural applications such as drying of crops, and for cooking. Water tanks are the most commonly used items to store heat during

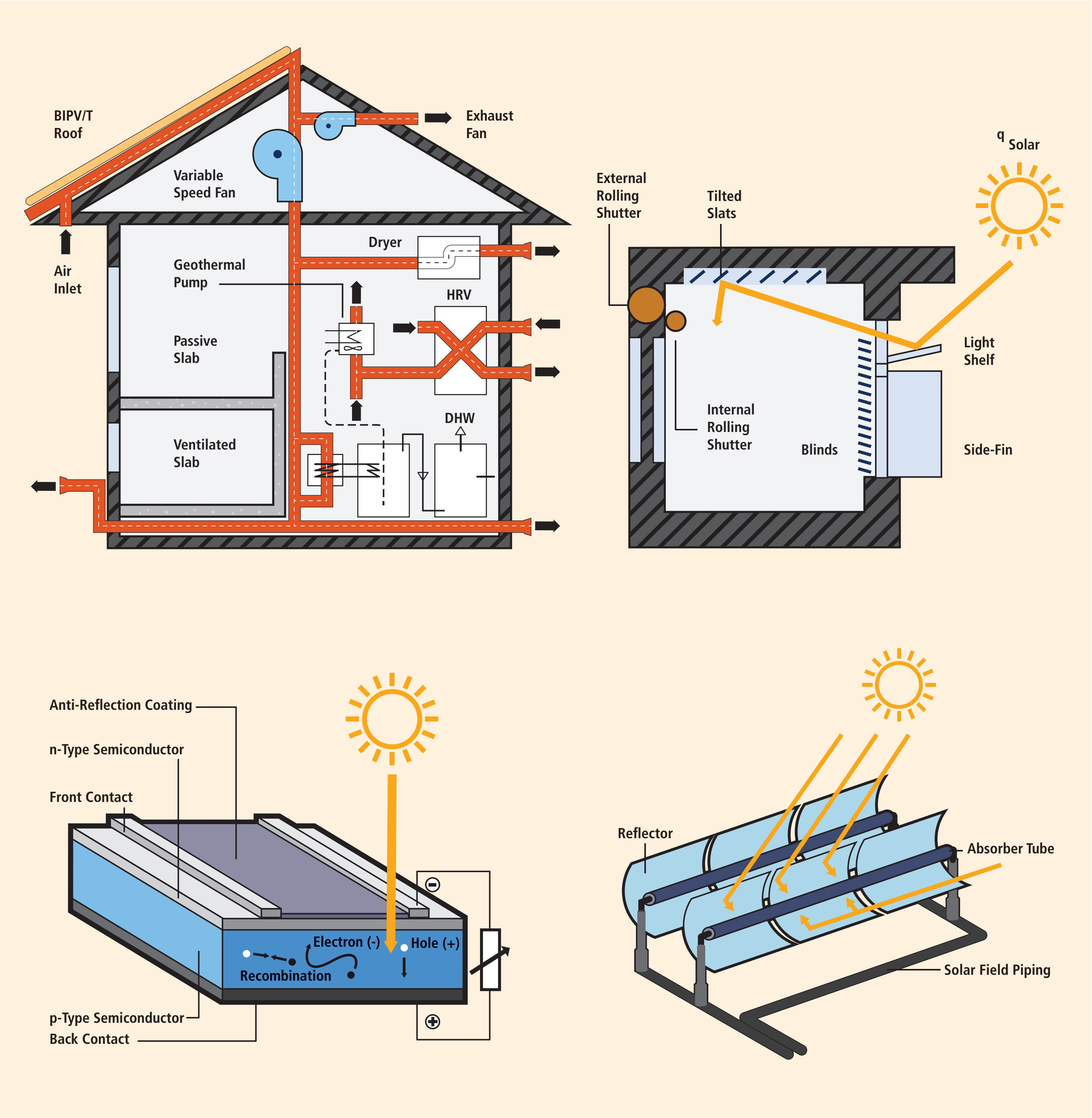


Figure TS.3.1 | Selected examples of (top) solar thermal, both passive and active integrated into a building; (bottom left) a photovoltaic device schematic for direct solar to electricity conversion; and (bottom right) one common type of concentrating solar power technology, a trough collector. [Derived from Figures 3.2, 3.5, 3.7]

the day/night period or short periods of cloudy weather. Supplemented by other energy sources, these systems typically provide 40 to 80% of the demand for heat energy of the target application. [3.3.2.2–3.3.2.4]

For passive solar heating, the building itself—particularly its windows—acts as the solar collector, and natural methods are used to distribute and store the heat. The basic elements of passive heating architecture are high-efficiency equatorial-facing windows and large internal thermal mass. The building must also be well insulated and incorporate methods such as shading devices to prevent it from overheating. Another feature of passive solar is 'daylighting', which incorporates special strategies to maximize the use of natural (solar) lighting in the building. Studies have shown that with current technology, using these strategies in new buildings in northern Europe or North America can reduce the building heating demands by as much as 40%. For existing, rather than new, buildings retrofitted with passive heating concepts, reductions of as much as 20% are achievable. [3.3.1]

Photovoltaic electricity generation: A detailed description of how PV conversion works is available in many textbooks. In the simplest terms, a thin sheet of semiconductor material such as silicon is placed in the Sun. The sheet, known as a cell, consists of two distinct layers formed by introducing impurities into the silicon resulting in an n-type layer and a p-type layer that form a junction at the interface. Solar photons striking the cell generate electron-hole pairs that are separated spatially by an internal electric field at the junction. This creates negative charges on one side of the interface and positive charges are on the other side. This resulting charge separation creates a voltage. When the two sides of the illuminated cell are connected to a load, current flows from one side of the device via the load to the other side of the cell generating electricity. [3.3.3]

Various PV technologies have been developed in parallel. Commercially available PV technologies include wafer-based crystalline silicon PV, as well as the thin-film technologies of copper indium/gallium disulfide/(di) selenide (CIGS), cadmium telluride (CdTe), thin-film silicon (amorphous and microcrystalline silicon), and dye-sensitized solar cells. In addition, there are commercially available concentrating PV concepts, in which very high efficiency cells (such as gallium arsenide (GaAs)-based materials) are placed at the focus of concentrating mirrors or other collectors such as Fresnel lenses. Mono- and multi- crystalline (sometimes called "polycrystalline") silicon wafer PV (including ribbon technologies) are the dominant technologies on the PV market, with a 2009 market share of about 80%. Peak efficiencies achieved by various cell types include more than 40% for GaAs-based concentrator cells, about 25% for monocrystalline, 20% for multicrystalline and CIGS, 17% for CdTe, and about 10% for amorphous silicon. Typically, groups of cells are mounted side by side under a transparent sheet (usually glass) and connected in series to form a 'module' with dimensions of up to 1 m by 1 m. In considering efficiencies, it is important to distinguish between cell efficiencies (quoted above) and module efficiencies; the latter are typically 50 to 80% of the former. Manufacturers continue to improve performance and reduce costs with automation, faster cell processing, and low-cost, high-throughput manufacturing. The performance of modules is typically guaranteed by manufacturers for 20 to 30 years. [3.3.3.1, 3.3.3.2]

The application of PV for useful power involves more than just the cells and modules; the PV system, for example, will often include an inverter to convert the DC power from the cells to AC power to be compatible with common networks and devices. For off-grid applications, the system may include storage devices such as batteries. Work is ongoing to make these devices more reliable, reduce their cost, and extend their lifetime to be comparable with that of the modules. [3.3.3.4]

PV power systems are classified as two major types: off-grid and grid-connected. Grid-connected systems are themselves classified into two types: distributed and centralized. The distributed system is made up of a large number of small local power plants, some of which supply the electricity mainly to an on-site customer, and the remaining electricity feeds the grid. The centralized system, on the other hand, works as one large power plant. Off-grid systems are typically dedicated to a single or small group of customers and generally require an electrical storage element or back-up power. These systems have significant potential in non-electrified areas. [3.3.3.5]

Concentrating solar power electricity generation: CSP technologies produce electricity by concentrating the Sun's rays to heat a medium that is then used (either directly or indirectly) in a heat engine process (e.g., a steam turbine) to drive an electrical generator. CSP uses only the beam component of solar irradiation, and so its maximum benefit tends to be restricted to a limited geographical range. The concentrator brings the solar rays to a point (point focus) when used in central-receiver or dish systems and to a line (line focus) when used in trough or linear Fresnel systems. (These same systems can also be used to drive thermochemical processes for fuel production, as described below.) In trough concentrators, long rows of parabolic reflectors that track the movement of the Sun concentrate the solar irradiation on the order of 70 to 100 times onto a heat-collection element (HCE) mounted along the reflector's focal line. The HCE comprises a blackened inner pipe (with a selective surface) and a glass outer tube, with an evacuated space between the two. In current commercial designs, a heat transfer oil is circulated through the steel pipe where it is heated (to nearly 400°C), but systems using other heat transfer materials such as circulating molten salt or direct steam are currently being demonstrated. [3.3.4]

The second kind of line-focus system, the linear Fresnel system, uses long parallel mirror strips as the concentrator, again with a fixed linear receiver. One of the two point-focus systems, the central-receiver (also called the 'power tower'), uses an array of mirrors (heliostats) on the ground, each tracking the Sun on two axes so as to focus the Sun's rays at a point on top of a tall tower. The focal point is directed onto a receiver, which comprises either a fixed inverted cavity and/or tubes in which the heat transfer fluid circulates. It can reach higher temperatures (up to 1,000°C) than the line-focus types, which allows the heat engine to convert (at least theoretically) more of the collected heat to power. In the second type of point-focus system, the dish concentrator, a single paraboloidal reflector (as opposed to an array of reflectors) tracking the sun on two axes is used for concentration. The dish focuses the solar rays onto a receiver that is not fixed, but moves with the dish, being only about one dish diameter away. Temperatures on the receiver engine can reach as high as 900°C. In one popular realization of this concept, a Stirling engine driving an electrical generator is mounted at the focus. Stirling dish units are relatively small, typically producing 10 to 25 kW, but they can be aggregated in field configuration to realize a larger central station-like power output. [3.3.4]

The four different types of CSP plants have relative advantages and disadvantages. [3.3.4] All four have been built and demonstrated. An important advantage of CSP technologies (except for dishes) is the ability to store thermal energy after it has been collected at the receiver and before going to the heat engine. Storage media considered include molten salt, pressurized air or steam accumulators (for short-term storage only), solid ceramic particles, high-temperature, phase-change materials, graphite, and high-temperature concrete. Commercial CSP plants are being built with thermal storage capacities reaching 15 hours, allowing CSP to offer dispatchable power. [3.3.4]

Solar fuel production: Solar fuel technologies convert solar energy into chemical fuels such as hydrogen, synthetic gas and liquids such as methanol and diesel. The three basic routes to solar fuels, which can work alone or in combination, are: (1) electrochemical; (2) photochemical/photo-biological; and (3) thermo-chemical. In the first route, hydrogen is produced by an electrolysis process driven by solar-derived electrical power that has been generated by a PV or CSP system. Electrolysis of water is an old and well-understood technology, typically achieving 70% conversion efficiency from electricity to hydrogen. In the second route, solar photons are used to drive photochemical or photobiological reactions, the products of which are fuels: that is, they mimic what plants and organisms do. Alternatively, semiconductor material can be used as a solar light-absorbing anode in photoelectrochemical cells, which also generate hydrogen by water decomposition. In the third route, high-temperature solar-derived heat (such as that obtained at the receiver of a central-receiver CSP plant) is used to drive an endothermic chemical reaction that produces fuel. Here, the reactants can include combinations of water, CO_2, coal, biomass and natural gas. The products, which constitute the solar fuels, can be any (or combinations) of the following: hydrogen, syngas, methanol, dimethyl ether and synthesis oil. When a fossil fuel is used as the reactant, overall calorific values of the products will exceed those of the reactants, so that less fossil fuel needs to be burned for the same energy release. Solar fuel can also be synthesized from solar hydrogen and CO_2 to produce hydrocarbons compatible with existing energy infrastructures. [3.3.5]

3.4 Global and regional status of market and industry deployment

3.4.1 Installed capacity and generated energy

Solar thermal: Active solar heating and cooling technologies for residential and commercial buildings represent a mature market. This market, which is distributed to various degrees in most countries of the world, grew by 34.9% from 2007 to 2009 and continues to grow at a rate of about 16% per year. At the end of 2009, the global installed capacity of thermal power from these devices was estimated to be 180 GW_{th}. The global market for sales of active solar thermal systems reached an estimated 29.1 GW_{th} in 2008 and 31 GW_{th} in 2009. Glazed collectors comprise the majority of the world market. China accounted for 79% of the installation of glazed collectors in 2008, and the EU accounted for about 14.5%. In the USA and Canada, swimming pool heating is still the dominant application, with an installed capacity of 12.9 GW_{th} of unglazed plastic collectors. Notably in 2008, China led the world in installed capacity of flat-plate and evacuated-tube collectors with 88.7 GW_{th}. Europe had 20.9 GW_{th} and Japan 4.4 GW_{th}. In Europe, the market size more than tripled between 2002 and 2008. Despite these gains, solar thermal still accounts for only a relatively small portion of the demand for hot water in Europe. For example, in Germany, with the largest market, about 5% of one- and two-family homes are using solar thermal energy. One measure of the market penetration is the per capita annual usage of solar energy. The lead country in this regard is Cyprus, where the figure is 527 kW_{th} per 1,000 people. Note that there is no available information on passive solar regarding the status of its market and its deployment by industry. Consequently, the preceding numbers refer only to active solar. [3.4.1]

Photovoltaic electricity generation: In 2009, about 7.5 GW of PV systems were installed. That brought the cumulative installed PV capacity worldwide in 2009 to about 22 GW—a capacity able to generate up to 26 TWh (93,600 TJ) per year. More than 90% of this capacity is installed in three leading markets: the EU with 73% of the total, Japan with 12% and the USA with 8%. Roughly 95% of the PV installed capacity in the OECD countries is grid connected, the remainder being off-grid. Growth in the top eight PV markets through 2009 is illustrated in Figure TS.3.2. Spain and Germany have seen, by far, the largest amounts of solar installed in recent years. [3.4.1]

Concentrating solar power: CSP has reached a cumulative installed capacity of about 0.7 GW, with another 1.5 GW under construction. The capacity factors for a number of these CSP plants are expected to range from 25 to 75%; these can be higher than for PV because CSP plants contain the opportunity to add thermal storage where there is a commensurate need to overbuild the collector field to charge the thermal storage. The lower end of the capacity factor range is for no thermal storage and the upper end is for up to 15 hours of thermal storage. [3.8.4] The earliest commercial CSP plants were the Solar Electric Generating Systems in California

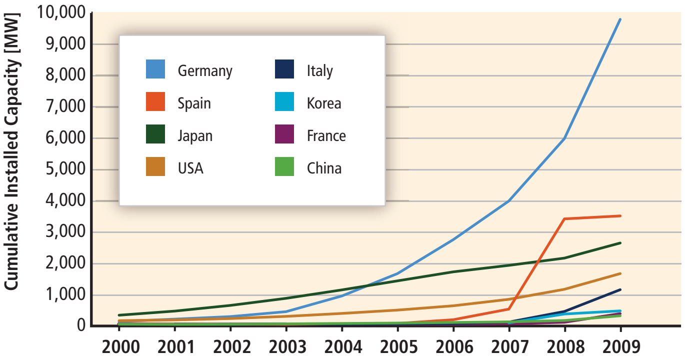


Figure TS.3.2 | Installed PV capacity for the years 2000 to 2009 in eight markets. [Figure 3.9] capable of producing 354 MW of power; installed between 1985 and 1991, they are still operating today. The period from 1991 to the early 2000s was slow for CSP, but since about 2004, there has been strong growth in planned generation. The bulk of the current operating CSP generation consists of trough technology, but central-receiver technology comprises a growing share, and there is strong proposed commercial activity in dish-Stirling. In early 2010, most of the planned global capacity was in the USA and Spain, but recently other countries announced commercial plans. Figure TS.3.3 shows the current and planned deployment of CSP capacity through the year 2015. [3.3.4, 3.4.1]

Solar fuel production: Currently, solar fuel production is in the pilot-plant phase. Pilot plants in the power range of 300 to 500 kW have been built for the carbo-thermic reduction of zinc oxide, steam methane reforming, and steam gasification of petcoke. A 250-kW steam-reforming reactor is operating in Australia. [3.3.4, 3.4.1]

3.4.2 Industry capacity and supply chain

Solar thermal: In 2008, manufacturers produced approximately 41.5 million m^2 of solar collectors, a scale large enough to adapt to mass production, even though production is spread among a large number of companies around the world. Indeed, large-scale industrial production levels have been attained in most parts of the industry. In the manufacturing process, a number of readily available materials—including copper, aluminium, stainless steel, and thermal insulation—are being applied and combined through different joining technologies to produce the absorber plate. This box is topped by the cover glass, which is almost always low-iron glass, now readily available. Most production is in China, where it is aimed at internal consumption. Evacuated collectors, suitable for mass production techniques, are starting to dominate that market. Other important production sites are in Europe, Turkey, Brazil and India. Much of the export market comprises total solar water heating systems rather than solar collectors per se. The largest exporters of solar water heating systems are Australia, Greece, the USA and France. Australian exports constitute about 50% of its production. [3.4.2]

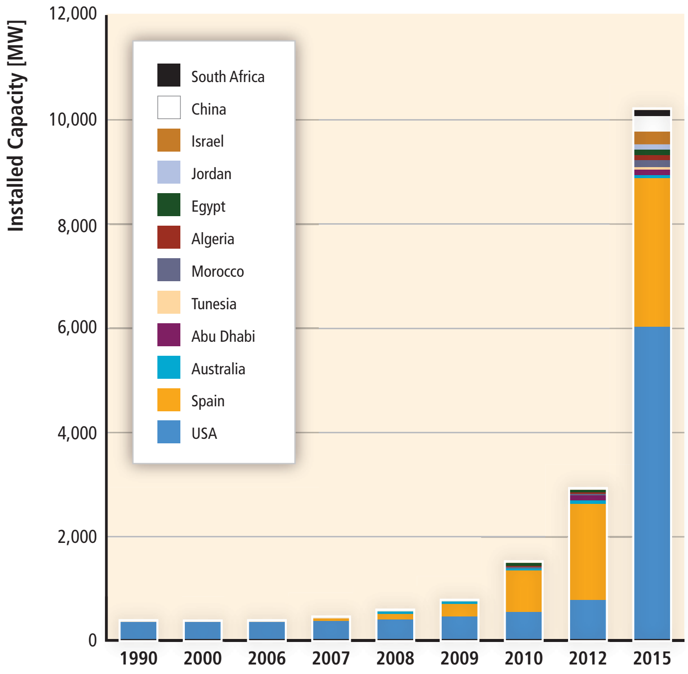


Figure TS.3.3 | Installed and planned concentrated solar power plants by country. [Figure 3.10]

For passive solar heating, part of the industry capacity and supply chain lies in people: namely, the engineers and architects who must systematically collaborate to produce a passively heated building. Close collaboration between the two disciplines has often been lacking in the past, but the dissemination of systematic design methodologies issued by different countries has improved the design capabilities. Windows and glazing are an important part of passively heated buildings, and the availability of a new generation of high-efficiency (low-emissivity, argon-filled) windows is having a major impact on solar energy's contribution to heating requirements in the buildings sector. These windows now constitute the bulk of new windows being installed in most northern-latitude countries. There do not appear to be any issues of industrial capacity or supply chains hindering the adoption of better windows. Another feature of passive design is adding internal mass to the building's structure. Concrete and bricks, the most commonly used storage materials, are readily available; phase-change materials (e.g., paraffin), considered to be the storage materials of the future, are not expected to have supply-chain issues. [3.4.2]

Photovoltaic electricity generation: The compound annual growth rate in PV manufacturing production from 2003 to 2009 exceeded 50%. In 2009, solar cell production reached about 11.5 GW per year (rated at peak capacity) split among several economies: China had about 51% of world production (including 14% from the Chinese province of Taiwan); Europe about 18%; Japan about 14%; and the USA about 5%. Worldwide, more than 300 factories produce solar cells and modules. In 2009, silicon-based solar cells and modules represented about 80% of the worldwide market. The remaining 20% mostly comprised cadmium telluride, amorphous silicon, and copper indium gallium diselenide. The total market is expected to increase significantly during the next few years, with thin-film module production gaining market share. Manufacturers are moving towards original design of manufacturing units and are also moving components of module production closer to the final market. Between 2004 and early 2008, the demand for crystalline silicon (or polysilicon) outstripped supply, which led to a price hike. With the new price, ample supplies have become available; the PV market is now driving its own supply of polysilicon. [3.4.2]

Concentrating solar power: In the past several years, the CSP industry has experienced a resurgence from a stagnant period to more than 2 GW being either commissioned or under construction. More than 10 different companies are now active in building or preparing for commercial-scale plants. They range from start-up companies to large organizations, including utilities, with international construction management expertise. None of the supply chains for construction of plants are limited by the availability of raw material. Expanded capacity can be introduced with a lead time of about 18 months. [3.4.2]

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

3.4.3 Impact of policies

Direct solar energy technologies face a range of potential barriers to achieving wide-scale deployment. Solar technologies differ in levels of maturity, and although some applications are already competitive in localized markets, they generally face one common barrier: the need to reduce costs. Utility-scale CSP and PV systems face different barriers than distributed PV and solar heating and cooling technologies. Important barriers include: siting, permitting, and financing challenges to develop land with favourable solar resources for utility-scale projects; lack of access to transmission lines for large projects far from electric load centres; complex access laws, permitting procedures, and fees for smaller-scale projects; lack of consistent interconnection standards and time-varying utility rate structures that capture the value of distributed generated electricity; inconsistent standards and certifications and enforcement of these issues; and lack of regulatory structures that capture environmental and risk-mitigation benefits across technologies. Through appropriate policy designs, governments have shown that they can support solar technologies by funding R&D and by providing incentives to overcome economic barriers. Price-driven incentive frameworks, for example, were popularized after FIT policies boosted levels of PV deployment in Germany and Spain. Quota-driven frameworks such as renewable portfolio standards and government bidding are common in the USA and China, respectively. In addition to these regulatory frameworks, fiscal policies and financing mechanisms (e.g., tax credits, soft loans and grants) are often employed to support the manufacturing of solar goods and to increase consumer demand. Most successful solar policies are tailored to the barriers imposed by specific applications, and the most successful policies are those that send clear, long-term and consistent signals to the market. [3.4.3]

3.5 Integration into the broader energy system

Solar technologies have a number of attributes that allow their advantageous integration into a broader energy system. In this section, only the integration features unique to solar technologies are summarized. These include low-capacity energy demand, district heating and other thermal loads, PV generation characteristics and smoothing effects, and CSP generation characteristics and grid stabilization. [3.5.1–3.5.4]

For applications that have low power consumption, such as lighting or solar-derived hot water, solar technologies sometimes have a comparative advantage relative to non-renewable fuel technologies. In addition, solar technologies allow small decentralized applications as well as larger centralized ones. In some regions of the world, integration of solar energy into district heating and other thermal loads has proven to be an effective strategy, especially because highly insulated buildings can be heated effectively with relatively low-temperature energy carriers. In some locations, a district cooling and heating system can provide additional advantages compared to decentralized cooling, including cost advantages for economies of scale, diversity of cooling demand of different buildings, reducing noise and structural load, and equipment space savings. Also, by combining biomass and low-temperature solar thermal energy, system capacity factor and emissions profiles can be improved. [3.5.1, 3.5.2]

For PV power generation at a specific location, electricity varies systematically during a day and a year, but also randomly according to weather conditions. This variation can, in some instances, have a large impact on voltage and power flow in the local transmission and distribution system from the early penetration stage, and the supply-demand balance in total power system operation in the high-penetration stage. This effect can potentially constrain PV system integration. However, modelling and system simulations suggest that numerous PV systems in a broad area should have less-random and slower variations, which are sometimes referred to as the 'smoothing effect'. Studies are underway to evaluate and quantify actual smoothing effects at a large scale (1,000 sites at distances from 2 to 200 km) and at time scales of 1 minute or less. [3.5.3]

In a CSP plant, even without storage, the inherent thermal mass in the collector system and spinning mass in the turbine tend to significantly reduce the impact of rapid solar transients on electrical output, and thus, lead to a reduced impact on the grid. By including integrated thermal storage systems, capacity factors typical of base-load operation could be achieved in the future. In addition, integrating CSP plants with fossil fuel generators, especially with gas-fired integrated solar combined-cycle systems (with storage), can offer better fuel efficiency and extended operating hours and ultimately be more cost effective than operating separate CSP and/or combined-cycle plants. [3.5.4]

3.6 Environmental and social impacts

3.6.1 Environmental impacts

Apart from its benefits in GHG reduction, the use of solar energy can reduce the release of pollutants—such as particulates and noxious gases—from the older fossil fuel plants that it replaces. Solar thermal and PV technologies do not generate any type of solid, liquid or gaseous by-products when producing electricity. The family of solar energy technologies may create other types of air, water, land and ecosystem impacts, depending on how they are managed. The PV industry uses some toxic, explosive gases as well as corrosive liquids in its production lines. 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. For other solar energy technologies, air and water pollution impacts are generally expected to be relatively minor. Furthermore, some solar technologies in certain regions may require water usage for cleaning to maintain performance. [3.6.1]

Lifecycle assessment estimates of the GHGs associated with various types of PV modules and CSP technologies are provided in Figure TS.3.4. The majority of estimates for PV modules cluster between 30 and 80 g of CO_2eq/kWh. Lifecycle GHG emissions for CSP-generated electricity have recently been estimated to range from about 14 to 32 g of CO_2eq/kWh. These emission levels are about an order of magnitude lower than those of natural gas-fired power plants. [3.6.1, 9.3.4]

Land use is another form of environmental impact. For roof-mounted solar thermal and PV systems, this is not an issue, but it can be an issue for central-station PV as well as for CSP. Environmentally sensitive lands may pose a special challenge for CSP permitting. One difference for CSP vis-à-vis PV is that it needs a method to cool the working fluid, and such cooling often involves the use of scarce water. Using local air as the coolant (dry cooling) is a viable option, but this can decrease plant efficiency by 2 to 10%. [3.6.1]

3.6.2 Social impacts

The positive benefits of solar energy in the developing world provide arguments for its expanded use. About 1.4 billion people do not have access to electricity. Solar home systems and local PV-powered community grids can provide electricity to many areas for which connection to a main grid is cost prohibitive. The impact of electricity and solar energy technologies on the local population is shown through a long list of important benefits: the replacement of indoor-polluting kerosene lamps and inefficient cook stoves; increased indoor reading; reduced time gathering firewood for cooking (allowing the women and children who normally gather it to focus on other priorities); street lighting for security; improved health by providing refrigeration for vaccines and food products; and, finally, communications devices (e.g., televisions, radios). All of these provide a myriad of benefits that improve the lives of people. [3.6.2]

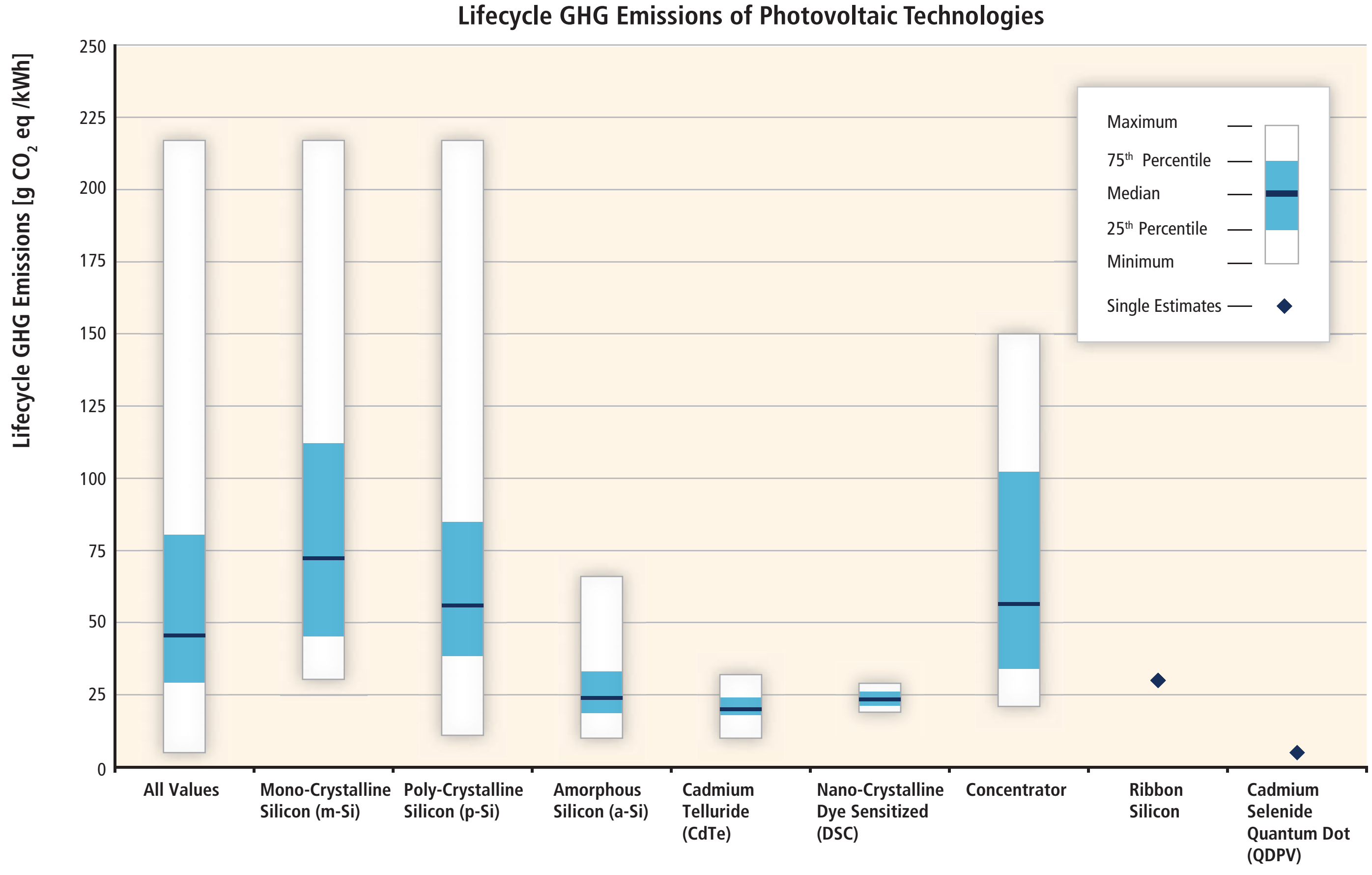
Job creation is an important social consideration associated with solar energy technology. Analysis indicates that solar PV has the highest job-generating potential among the family of solar technologies. Approximately 0.87 job-years per GWh are created through solar PV, followed by CSP with 0.23 job-years per GWh. When properly put forward, these job-related arguments can help accelerate social acceptance and increase public willingness to tolerate the perceived disadvantages of solar energy, such as visual impacts. [3.6.2]

3.7 Prospects for technology improvements and innovation

Solar thermal: If integrated at the earliest stages of planning, buildings of the future could have solar panels – including PV, thermal collector, and combined PV-thermal (hybrids) – making up almost all viewed components of the roof and façades. Such buildings could be established not just through the personal desires of individual builders/owners, but also as a result of public policy mandates, at least in some areas. For example, the vision of the European Solar Thermal Technology Platform is to establish the 'Active Solar Building' as a standard for new buildings by 2030, where an Active Solar Building, on average, covers all of its energy demand for water heating and space conditioning. [3.7.2]

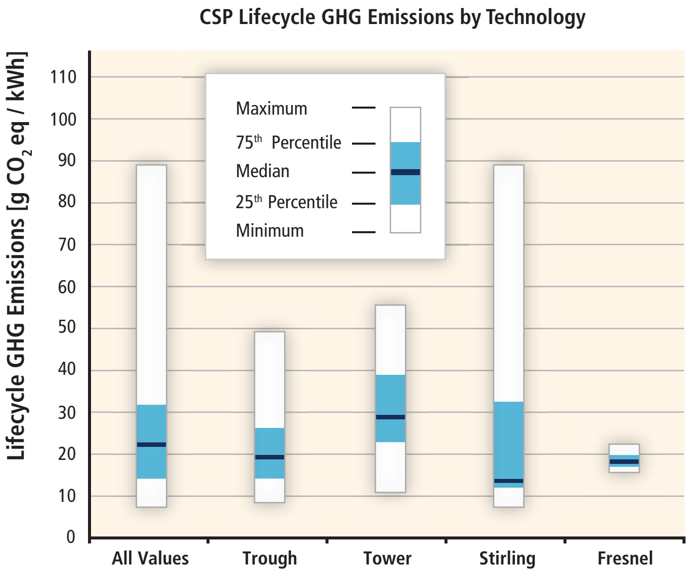
In highlighting the advances in passive solar, two climates can be distinguished between: those that are dominated by the demand for heating and those dominated by the demand for cooling. For the former, a wider-scale adoption of the following items can be foreseen: evacuated (as opposed to sealed) glazing, dynamic exterior night-time insulation, and translucent glazing systems that can automatically change solar/visible transmittance and that also offer improved insulation values. For the latter, there is the expectation for an increased use of cool roofs (i.e., light-coloured roofs that reflect solar energy); heat-dissipation techniques such as use of the ground and water as heat sinks; methods that improve the microclimate around the buildings; and solar control devices that allow penetration of the lighting, but not the thermal, component of solar energy. For both climates, improved thermal storage is expected to be embedded in building materials. Also anticipated are improved methods for distributing the absorbed solar heat around the building and/or to the outside air, perhaps using active methods such as fans. Finally, improved design tools are expected to facilitate these various improved methods. [3.7.1]

Photovoltaic electricity generation: Although now a relatively mature technology, PV is still experiencing rapid improvements in performance and cost, and a continuation of this steady progress is expected. The efforts required are being taken up in a framework of intergovernmental cooperation, complete with roadmaps. For the different PV technologies, four broad technological categories, each requiring specific R&D approaches, have been identified: 1) cell efficiency, stability, and lifetime; 2) module productivity and manufacturing; 3) environmental sustainability; and 4) applicability, all of which include standardization and harmonization. Looking to the future, PV technologies can by categorized in three major classes: current; emerging, which represent medium risk with a mid-term (10 to 20 year) time line; and the high-risk technologies aimed at 2030 and beyond, which have extraordinary potential but require technical breakthroughs. Examples of emerging cells are multiple-junction, polycrystalline thin films and crystalline silicon in the sub-100-μm thickness range. Examples of high-risk cells are organic solar cells, biomimetic devices and quantum dot designs that have the potential to substantially increase the maximum efficiency. Finally, there is important work to be done on the balance of systems (BOS), which comprises inverters, storage, charge controllers, system structures and the energy network. [3.7.3]



Estimates:	124	30	56	12	13	4	6	2*	1
References:	26	9	15	3	3	1	2	2	1

*same value



Estimates:	42	20	14	4	4
References:	13	7	5	3	1

Figure TS.3.4 | GHG emissions from the life cycles of (top) PV modules and (bottom) CSP technologies. See Annex II for details of literature search and citations of literature contributing to the estimates displayed. [Figures 3.14, 3.15]

CSP electricity generation: Although CSP is now a proven technology at the utility scale, technology advances are still taking place. As plants are built, both mass production and economies of scale are leading to cost reductions. There is scope for continuing improvement in solar-to-electricity efficiency, partly through higher collector temperatures. To increase temperature and efficiency, alternatives to the use of oil as the heat-transfer fluid—such as water (boiling in the receiver) or molten salts—are being developed, permitting higher operating temperatures. For central-receiver systems, the overall efficiencies can be higher because the operating temperatures are higher, and further improvements are expected to achieve peak efficiencies (solar to electricity) almost twice those of existing systems, up to 35%. Trough technology will benefit from continuing advances in solar-selective surfaces, and central receivers and dishes will benefit from improved receiver/absorber designs that afford high levels of solar irradiance at the focus. Capital cost reduction is expected to come from the benefits of mass production, economies of scale and learning from previous experience. [3.7.4]

Solar fuel production: Solar electrolysis using PV or CSP is available for niche applications, but it remains costly. Many paths are being pursued to develop a technology that will reduce the cost of solar fuels. These include solid-oxide electrolysis cells, the photoelectrochemical cell (which combines all the steps in solar electrolysis into a single unit), advanced thermo-chemical processes, and photochemical and photobiological processes—sometimes in combinations that integrate artificial photosynthesis in man-made biomimetic systems and photobiological hydrogen production in living organisms. [3.7.5]

Other potential future applications: Other methods under investigation for producing electricity using solar thermal technologies without an intermediate thermodynamic cycle include thermoelectric, thermionic, magnetohydrodynamic and alkali-metal methods. Space solar power, in which solar power collected in space is beamed via microwaves to receiving antennae on the ground, has also been proposed. [3.7.6]

3.8 Cost trends

Although the cost of solar energy varies widely by technology, application, location and other factors, costs have been reduced significantly during the past 30 years, and technical advances and supportive public policies continue to offer the potential for additional cost reductions. The degree of continued innovation will have a significant bearing on the level of solar deployment. [3.7.2–3.7.5, 3.8.2–3.8.5]

Solar thermal: The economics of solar heating applications depend on appropriate design of the system with regard to energy service needs, which often involves the use of auxiliary energy sources. In some regions, for example, in southern parts of China, solar water heating (SWH) systems are cost competitive with traditional options. SWH systems are generally more competitive in sunny regions, but this picture changes for space heating based on its usually higher overall heating load. In colder regions capital costs can be spread over a longer heating season, and solar thermal can then become more competitive. [3.8.2]

The investment costs for solar thermal heating systems vary widely depending on the complexity of the technology used as well as the market conditions in the country of operation. The costs for an installed system vary from as low as USD_{2005} 83/m² for SWH systems in China to more than USD_{2005} 1,200/m² for certain space-heating systems. The levelized cost of heat (LCOH) mirrors the wide variation in investment cost, and depends on an even larger number of variables, including the particular type of system, investment cost of the system, available solar irradiance in a particular location, conversion efficiency of the system, operating costs, utilization strategy of the system and the applied discount rate. Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOH for solar thermal systems over a large set and range of input parameters has been calculated to vary widely from USD_{2005} 9 to 200/GJ, but can be estimated for more specific settings with parametric analysis. Figure TS.3.5 shows the LCOH over a somewhat narrower set and range of input parameters. More specifically, the figure shows that for SWH systems with costs in the range of USD_{2005} 1,100 to 1,200/kW_{th} and conversion efficiencies of roughly 40%, LCOH is expected to range from slightly more than USD_{2005} 30/GJ to slightly less than USD_{2005} 50/GJ in regions comparable to Central and Southern European locations and up to almost USD_{2005} 90/GJ for regions with less solar irradiation. Not surprisingly, LCOH estimates are highly sensitive to all of the parameters shown in Figure TS.3.5, including investment costs and capacity factors. [3.8.2, Annex II, Annex III]

Over the last decade, for each 50% increase in installed capacity of solar water heaters, investment costs have fallen 20% in Europe. According to the IEA, further cost reductions in OECD countries will come from the use of cheaper materials, improved manufacturing processes, mass production, and the direct integration into buildings of collectors as multi-functional building components and modular, easy-to-install systems. Delivered energy costs in OECD countries are anticipated by the IEA to eventually decline by around 70 to 75%. [3.8.2]

PV electricity generation: PV prices have decreased by more than a factor of 10 during the last 30 years; however, the current levelized cost of electricity (LCOE) from solar PV is generally still higher than wholesale market prices for electricity. In some applications, PV systems are already competitive with other local alternatives (e.g., for electricity supply in certain rural areas in developing countries). [3.8.3, 8.2.5, 9.3.2]

The LCOE of PV highly depends on the cost of individual system components, with the highest cost share stemming from the PV module. The LCOE also includes BOS components, cost of labour for installation, operation and maintenance (O&M) cost, location and capacity factor, and the applied discount rate. [3.8.3]

The price for PV modules dropped from USD_{2005} 22/W in 1980 to less than USD_{2005} 1.50/W in 2010. The corresponding historical learning rate ranges from 11 to 26%, with a median learning rate of 20%. The price in USD/W for an entire system, including the module, BOS, and installation costs, has also decreased steadily, reaching numbers as low as USD_{2005} 2.72/W for some thin-film technologies by 2009. [3.8.3]

The LCOE for PV depends not only on the initial investment; it also takes into account operation costs and the lifetime of the system components, local solar irradiation levels and system performance. Based on the standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the recent LCOE for different types of PV systems has been calculated. It shows a wide variation from as low as USD_{2005} 0.074/kWh to as high as USD_{2005} 0.92/kWh, depending on a large set and range of input parameters. Narrowing the range of parameter variations, the LCOE in 2009 for utility-scale PV electricity generation in regions of high solar irradiance in Europe and the USA were in the range of about USD_{2005} 0.15/kWh to USD_{2005} 0.4/kWh at a

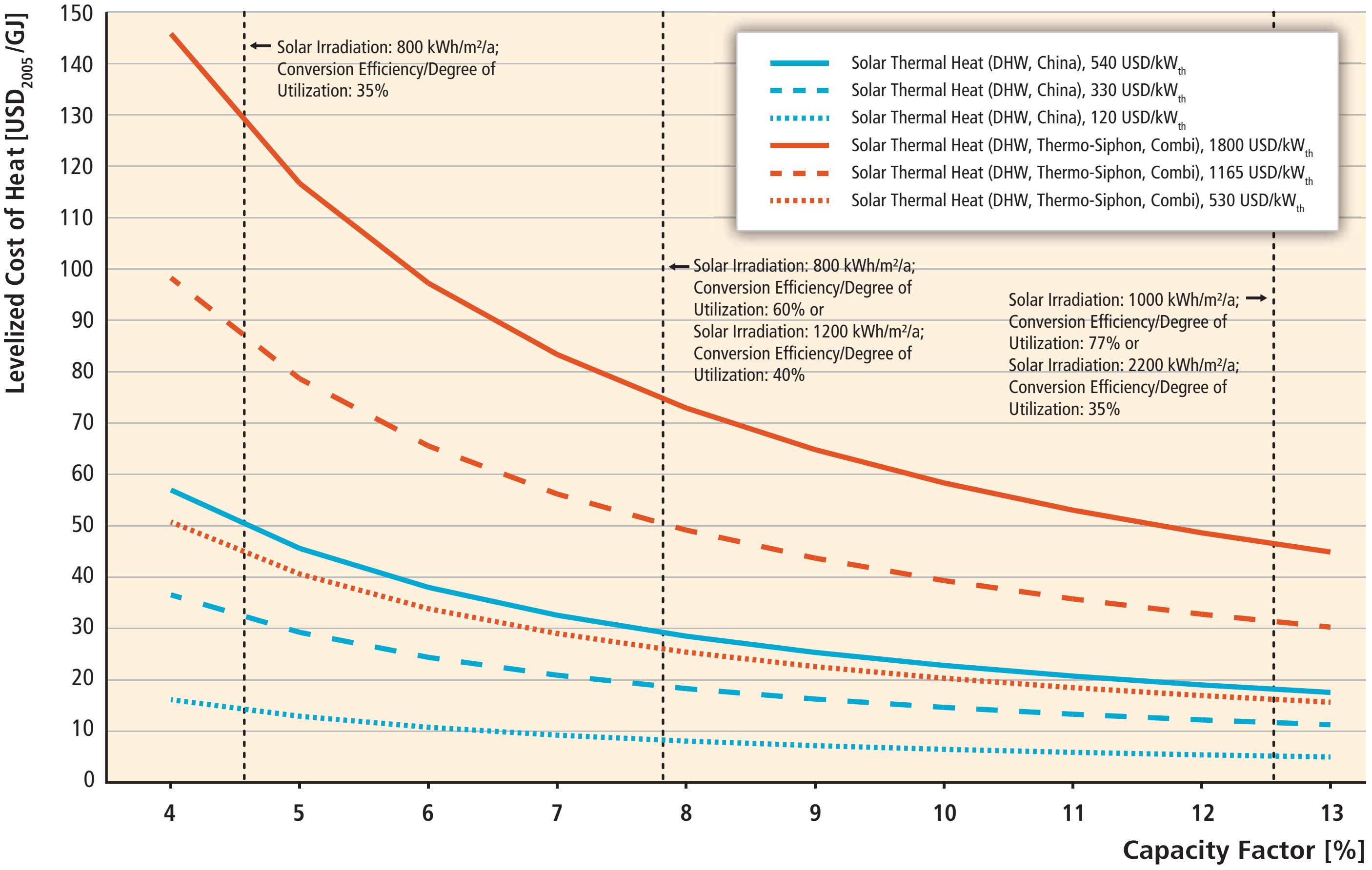


Figure TS.3.5 | Sensitivity of levelized cost of heat with respect to investment cost as a function of capacity factor. (Discount rate assumed to be 7%, annual operation and maintenance cost USD$_{2005}$ 5.6 and14/kW, and lifetimes set at 12.5 and 20 years for domestic hot water (DHW) systems in China and various types of systems in OECD countries, respectively.) [Figure 3.16]

7% discount rate, but may be lower or higher depending on the available resource and on other framework conditions. Figure TS.3.6 shows a wide variation of LCOE for PV depending on the type of system, investment cost, discount rates and capacity factors. [1.3.2, 3.8.3, 10.5.1, Annex II, Annex III]

Costs of electricity generation or LCOE are projected by the IEA to reach the following in 2020: US cent$_{2005}$ 14.5/kWh to US cent$_{2005}$ 28.6/kWh for the residential sector and US cent$_{2005}$ 9.5/kWh to US cent$_{2005}$ 19/kWh for the utility sector under favourable conditions of 2,000 kWh/kW (equivalent to a 22.8% capacity factor) and less favourable conditions of 1,000 kWh/kW (equivalent to a 11.4% capacity factor), respectively. The goal of the US Department of Energy is even more ambitious, with an LCOE goal of US cent$_{2005}$ 5/kWh to US cent$_{2005}$ 10/kWh, depending on the end user, by 2015. [3.8.3]

CSP electricity generation: CSP electricity systems are a complex technology operating in a complex resource and financial environment; so many factors affect the LCOE. The publicized investment costs of CSP plants are often confused when compared to other renewable sources, because varying levels of integrated thermal storage increase the investment, but also improve the annual output and capacity factor of the plant. For large, state-of-the-art trough plants, current investment costs are estimated to be USD$_{2005}$ 3.82/W (without storage) to USD$_{2005}$ 7.65/W (with storage) depending on labour and land costs, technologies, the amount and distribution of beam irradiance and, above all, the amount of storage and the size of the solar field. Performance data for modern CSP plants are limited, particularly for plants equipped with thermal storage, because new plants only became operational from 2007 onward. Capacity factors for early plants without storage were up to 28%. For modern plants without storage, capacity factors of roughly 20 to 30% are envisioned; for plants with thermal storage, capacity factors of 30 to 75% may be achieved. Based on the standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for a solar trough plant with six hours of thermal storage in 2009 over a large set and range of input parameters has been calculated to range from slightly more than US cent$_{2005}$ 10/kWh to about US cent$_{2005}$ 30/kWh. Restricting the range of discount rates to 10% results in a somewhat narrower range of about US cent$_{2005}$ 20/kWh to US cent$_{2005}$ 30/kWh, which is roughly in line with the range of US cent$_{2005}$ 18 to US cent$_{2005}$ 27/kWh available in the literature. Particular cost

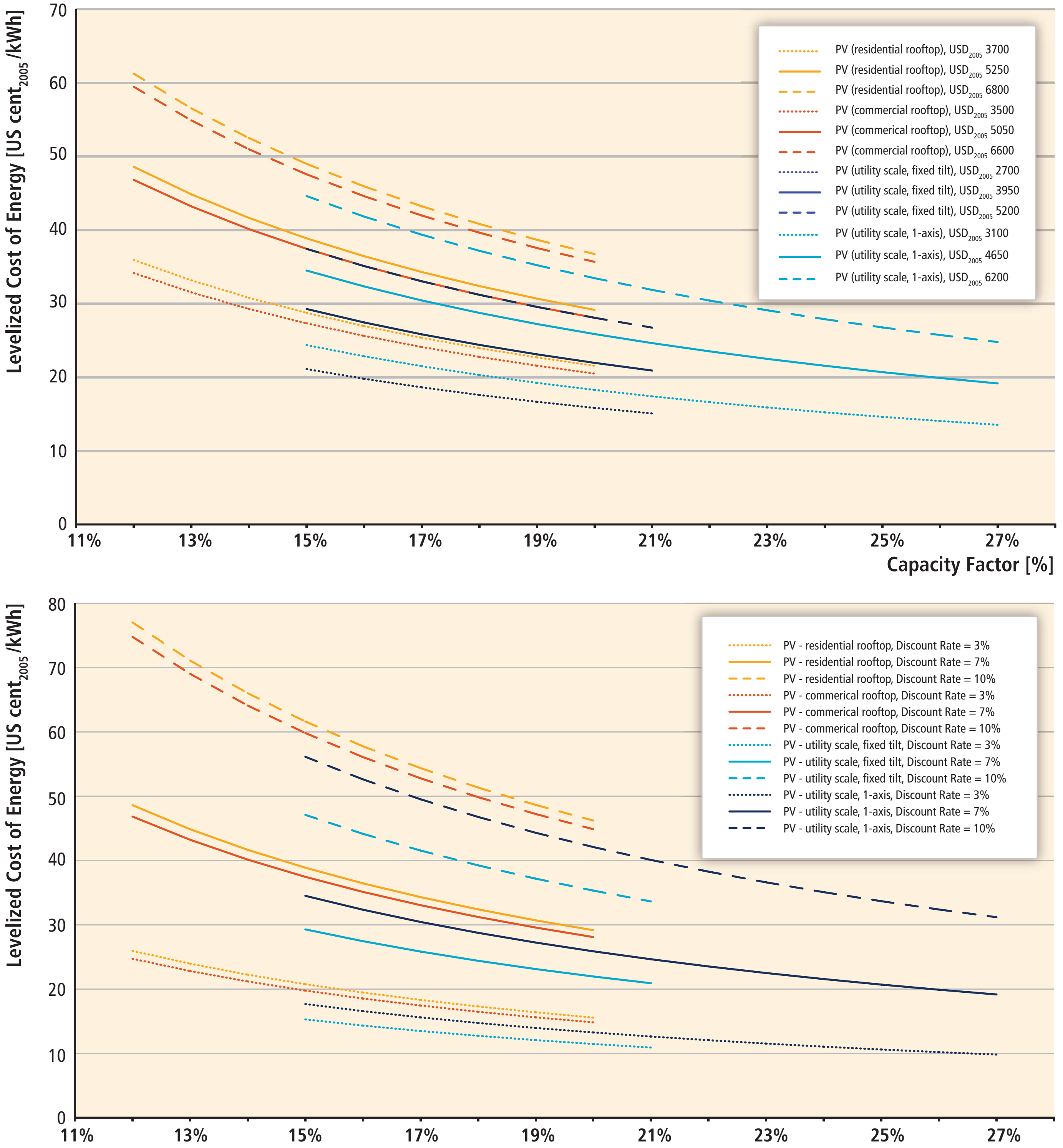


Figure TS.3.6 | Levelized cost of PV electricity generation, 2008–2009: (top) as a function of capacity factor and investment cost*,***; and (bottom) as a function of capacity factor and discount rate**,***. [Figure 3.19]

Notes: * Discount rate assumed to equal 7%. ** Investment cost for residential rooftop systems assumed at USD 5,500 US/kW, for commercial rooftop systems at USD 5,150, for utility-scale fixed tilt projects at USD 3,650/kW and for utility-scale one-axis projects at USD 4,050/kW. ***Annual O&M cost assumed at USD 41 to 64/kW, lifetime at 25 years.

and performance parameters, including the applied discount rate and capacity factor, affect the specific LCOE estimate, although the LCOE of different system configurations for otherwise identical conditions are expected to differ only marginally. [3.8.4]

The learning ratio for CSP, excluding the power block, has been estimated at 10 ± 5%. Specific LCOE goals for the USA are US cent_{2005} 6/kWh to US cent_{2005} 8/kWh with 6 hours storage by 2015 and US cent_{2005} 50/kWh to US cent_{2005} 60/kWh with 12 to 17 hours of storage by 2020. The EU is pursuing similar goals. [3.8.4]

3.9 Potential deployment

3.9.1 Near-term (2020) forecasts

Table TS.3.1 summarizes findings from the available studies on potential deployment up to 2020, as taken from the literature. Sources for the tabulated data are the following: European Renewable Energy Council (EREC) – Greenpeace (Energy [r]evolution, reference and advanced scenarios); and IEA (CSP and PV Technology Roadmaps). With regard to the solar thermal entries, note that passive solar contributions are not included in these data; although this technology reduces the demand for energy, it is not part of the supply chain considered in energy statistics. [3.9]

3.9.2 Long-term deployment in the context of carbon mitigation

Figure TS.3.7 presents the results of more than 150 long-term modelling scenarios described in Chapter 10. The potential deployment scenarios vary widely—from direct solar energy playing a marginal role in 2050 to it becoming one of the major sources of energy supply. Although direct solar energy today provides only a very small fraction of the world energy supply, it remains undisputed that this energy source has one of the largest potential futures.

Reducing cost is a key issue in making direct solar energy more commercially relevant and in position to claim a larger share of the worldwide energy market. This can only be achieved if solar technologies' costs are reduced as they move along their learning curves, which depend primarily on market volumes. In addition, continuous R&D efforts are required to ensure that the slopes of the learning curves do not flatten too early. The true costs of deploying solar energy are still unknown because the main deployment scenarios that exist today consider only a single technology. These scenarios do not take into account the co-benefits of a renewable/sustainable energy supply via a range of different RE sources and energy efficiency measures.

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

4. Geothermal Energy

4.1 Introduction

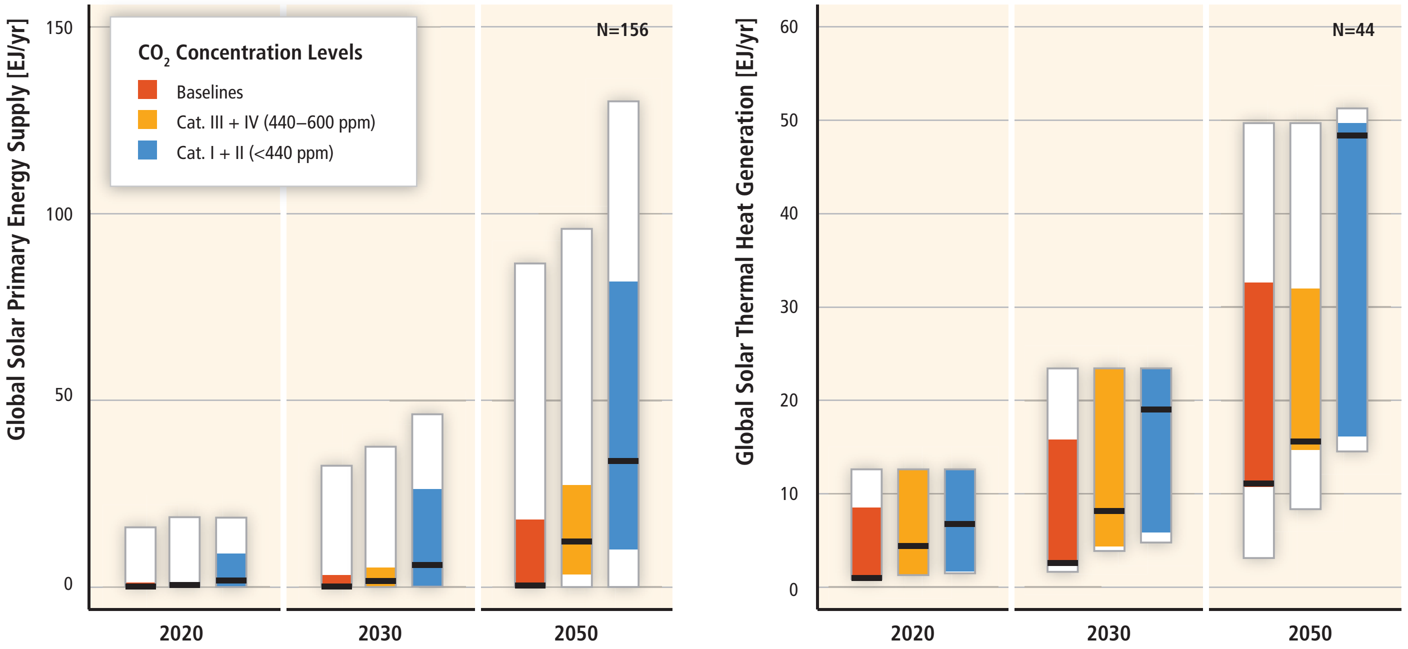
Geothermal resources consist of thermal energy from the Earth's interior stored in both rock and trapped steam or liquid water, and are used to generate electric energy in a thermal power plant or in other domestic and agro-industrial applications requiring heat as well as in CHP applications. Climate change has no significant impacts on the effectiveness of geothermal energy. [4.1]

Geothermal energy is a renewable resource as the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by reinjection of the cooled fluids. [4.1]

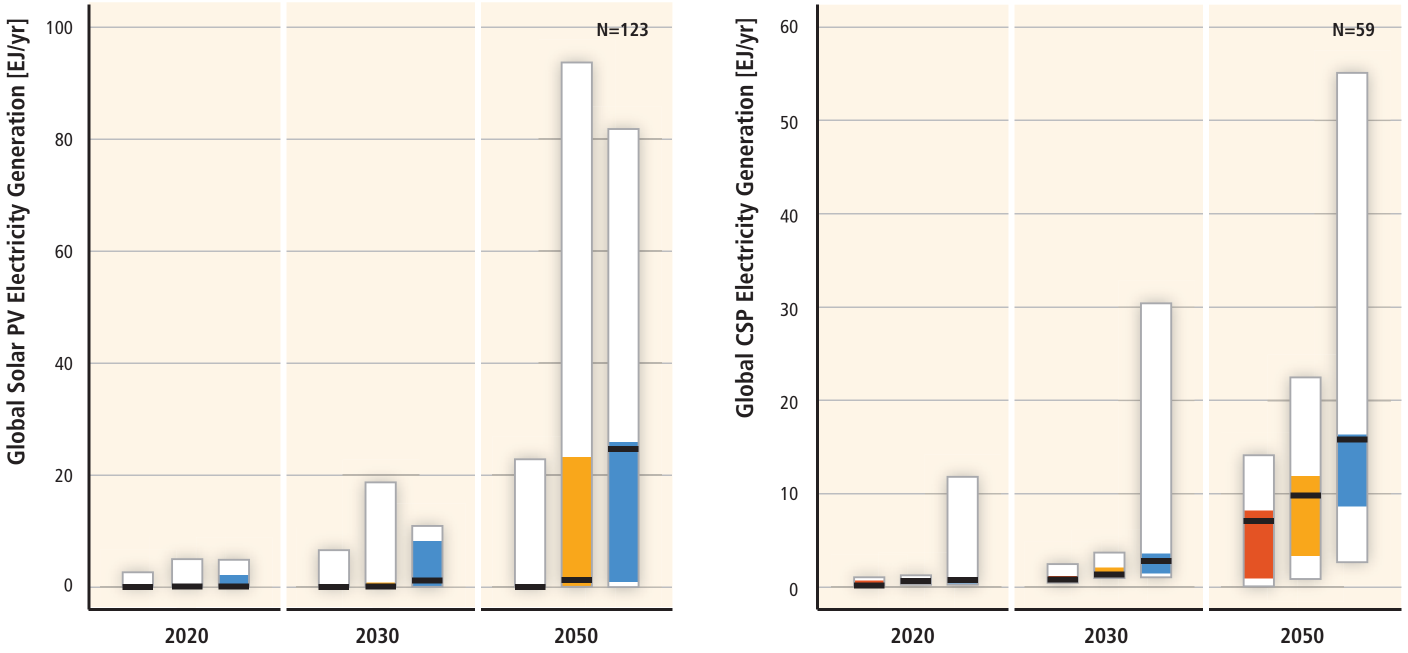
Table TS.3.1 | Evolution of cumulative solar capacities. [Table 3.7]

		Low-Temperature Solar Heat (GW_{th})			Solar PV Electricity (GW)			CSP Electricity (GW)		
	Year	2009	2015	2020	2009	2015	2020	2009	2015	2020
Name of Scenario	**Current cumulative installed capacity**	**180**			**22**			**0.7**		
	EREC – Greenpeace (reference scenario)		180	230		44	80		5	12
	EREC – Greenpeace ([r]evolution scenario)		715	1,875		98	335		25	105
	EREC – Greenpeace (advanced scenario)		780	2,210		108	439		30	225
	IEA Roadmaps		N/A			95[1]	210		N/A	148

Note: 1. Extrapolated from average 2010 to 2020 growth rate.


(a) Global Solar Primary Energy Supply

(b) Global Solar Thermal Heat Generation


(c) Global Solar PV Electricity Generation

(d) Global CSP Electricity Generation

Figure TS.3.7 | Global solar supply and generation in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the upper right-hand corner). (a) Global solar primary energy supply; (b) global solar thermal heat generation; (c) global solar PV electricity generation; and (d) global CSP electricity generation. [Figure 3.22]

4.2 Resource potential

The accessible stored heat from hot dry rocks in the Earth is estimated to range from 110 to 403 x 10^6 EJ down to 10 km depth, 56 to 140 x 10^6 EJ down to 5 km depth, and around 34 x 10^6 EJ down to 3 km depth. Using previous estimates for hydrothermal resources and calculations for enhanced (or engineered) geothermal systems derived from stored heat estimates at depth, geothermal technical potentials for electric generation range from 118 to 146 EJ/yr (at 3 km depth) to 318 to 1,109 EJ/yr (at 10 km depth), and for direct uses range from 10 to 312 EJ/yr (Figure TS.4.1). [4.2.1]

Technical potentials are presented on a regional basis in Table TS.4.1. The regional breakdown is based on the methodology applied by the Electric Power Research Institute to estimate theoretical geothermal

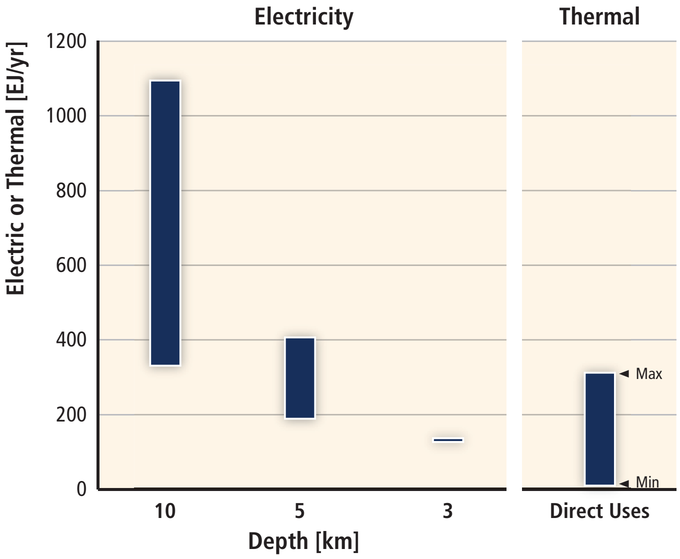


Figure TS.4.1 | Geothermal technical potentials for electricity and direct uses (heat). Direct uses usually do not require development to depths greater than about three km. [Figure 4.2]

potentials for each country, and then countries are grouped regionally. Thus, the present disaggregation of global technical potential is based on factors accounting for regional variations in the average geothermal gradient and the presence of either a diffuse geothermal anomaly or a high-temperature region associated with volcanism or plate boundaries. The separation into electric and thermal (direct uses) potentials is somewhat arbitrary in that most higher-temperature resources could be used for either, or both, in CHP applications depending on local market conditions. [4.2.2]

The heat extracted to achieve the technical potentials can be fully or partially replenished over the long term by the continental terrestrial heat flow of 315 EJ/yr at an average flux of 65 mW/m². [4.2.1]

4.3 Technology and applications

Geothermal energy is currently extracted using wells and other means that produce hot fluids from: (a) hydrothermal reservoirs with naturally high permeability, or (b) Enhanced or engineered geothermal systems (EGS) with artificial fluid pathways (Figure TS.4.2). Technology for electricity generation from hydrothermal reservoirs is mature and reliable, and has been operating for about 100 years. Technologies for direct heating using geothermal heat pumps (GHPs) for district heating and for other applications are also mature. Technologies for EGS are in the demonstration stage. [4.3]

Electric power from geothermal energy is especially suitable for supplying base-load power, but also can be dispatched and used to meet peak demand. Hence, geothermal electric power can complement variable electricity generation. [4.3]

Since geothermal resources are underground, exploration methods (including geological, geochemical and geophysical surveys) have been developed to locate and assess them. The objectives of geothermal exploration are to identify and rank prospective geothermal reservoirs prior to drilling. Today, geothermal wells are drilled over a range of depths up to 5 km using conventional rotary drilling methods similar to those for accessing oil and gas reservoirs. Advanced drilling technologies allow for high-temperature operation and provide directional capability. [4.3.1]

The basic types of geothermal power plants in use today are steam condensing turbines and binary cycle units. Condensing plants can be of the flash or dry-steam type (the latter do not require brine separation, resulting in simpler and cheaper plants) and are more common than binary units. They are installed in intermediate- and high-temperature resources (≥150°C) with capacities often between 20 and 110 MW_e.

Table TS.4.1 | Geothermal technical potentials on continents for the IEA regions. [Table 4.3]

REGION[1]	Electric technical potential (EJ/yr) at depths to:						Technical potentials (EJ/yr) for direct uses	
	3 km		5 km		10 km			
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
OECD North America	25.6	31.8	38.0	91.9	69.3	241.9	2.1	68.1
Latin America	15.5	19.3	23.0	55.7	42.0	146.5	1.3	41.3
OECD Europe	6.0	7.5	8.9	21.6	16.3	56.8	0.5	16.0
Africa	16.8	20.8	24.8	60.0	45.3	158.0	1.4	44.5
Transition Economies	19.5	24.3	29.0	70.0	52.8	184.4	1.6	51.9
Middle East	3.7	4.6	5.5	13.4	10.1	35.2	0.3	9.9
Developing Asia	22.9	28.5	34.2	82.4	62.1	216.9	1.8	61.0
OECD Pacific	7.3	9.1	10.8	26.2	19.7	68.9	0.6	19.4
Total	**117.5**	**145.9**	**174.3**	**421.0**	**317.5**	**1,108.6**	**9.5**	**312.2**

Note: 1. For regional definitions and country groupings see Annex II.

In binary cycle plants, the geothermal fluid passes through a heat exchanger heating another working fluid with a low boiling point, which vaporizes and drives a turbine. They allow for use of lower-temperature hydrothermal reservoirs and of EGS reservoirs (generally from 70°C to 170°C), and are often constructed as linked modular units of a few MW_e in capacity. Combined or hybrid plants comprise two or more of the above basic types to improve versatility, increase overall thermal efficiency, improve load-following capability, and efficiently cover a wide resource temperature range. Finally, cogeneration plants, or CHP plants, produce both electricity and hot water for direct use. [4.3.3]

EGS reservoirs require stimulation of subsurface regions where temperatures are high enough for effective utilization. A reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells. Heat is extracted by circulating water through the reservoir in a closed loop and can be used for power generation and for industrial or residential heating (see Figure TS.4.2). [4.3.4]

Direct use provides heating and cooling for buildings including district heating, fish ponds, greenhouses, bathing, wellness and swimming pools, water purification/desalination and industrial and process heat for agricultural products and mineral drying. Although it can be debated whether GHPs are a 'true' application of geothermal energy, they can be utilized almost anywhere in the world for heating and cooling, and take advantage of the relatively constant ground or groundwater temperature in the range of 4°C to 30°C. [4.3.5]

4.4 Global and regional status of market and industry development

For nearly a century, geothermal resources have been used to generate electricity. In 2009, the global geothermal electric market had a wide range of participants with 10.7 GW_e of installed capacity. Over 67 TWh_e (0.24 EJ) of electricity were generated in 2008 in 24 countries (Figure TS.4.3), and provided more than 10% of total electricity demand in 6 of them. There were also 50.6 GW_{th} of direct geothermal applications operating in 78 countries, which generated 121.7 TWh_{th} (0.44 EJ) of heat in 2008. GHPs contributed 70% (35.2 GW_{th}) of this installed capacity for direct use. [4.4.1, 4.4.3]

The global average annual growth rate of installed geothermal electric capacity over the last five years (2005-2010) was 3.7%, and over the last 40 years (1970-2010), 7.0%. For geothermal direct uses rates were 12.7% (2005-2010), and 11% between 1975 and 2010. [4.4.1]

EGS is still in the demonstration phase, with one small plant in operation in France and one pilot project in Germany. In Australia considerable investment has been made in EGS exploration and development in recent years, and the USA has recently increased support for EGS research, development and demonstration as part of a revived national geothermal programme. [4.4.2]

(a)

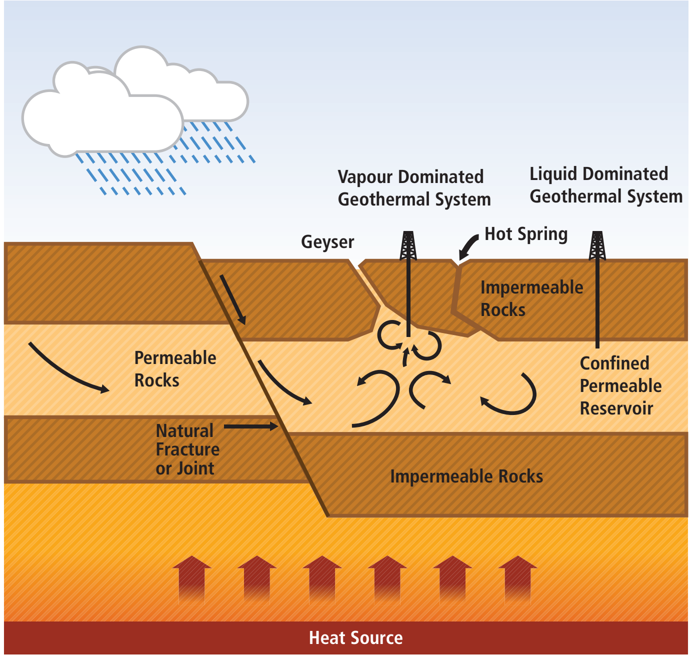


Figure TS.4.2a | Scheme showing convective (hydrothermal) resources. [Figure 4.1a]

In 2009, the main types (and relative percentages) of direct geothermal applications in annual energy use were: space heating of buildings (63%), bathing and balneology (25%), horticulture (greenhouses and soil heating) (5%), industrial process heat and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%). [4.4.3]

For geothermal to reach its full capacity in climate change mitigation it is necessary to overcome technical and non-technical barriers. Policy measures specific to geothermal technology can help overcome these barriers. [4.4.4]

4.5 Environmental and social impacts

Environmental and social impacts related to geothermal energy do exist, and are typically site- and technology-specific. Usually, these impacts are manageable, and the negative environmental impacts are minor. The main GHG emission from geothermal operations is CO_2, although it is not created through combustion, but emitted from naturally occurring sources. A field survey of geothermal power plants operating in 2001 found a wide spread in the direct CO_2 emission rates, with values ranging from 4 to 740 g/kWh_e depending on technology design and composition of the geothermal fluid in the underground reservoir. Direct CO_2 emissions for direct use applications are negligible, while EGS power plants are likely to be designed as liquid-phase closed-loop circulation systems, with zero direct emissions. Lifecycle assessments anticipate that CO_2-equivalent emissions are less than 50 g/kWh_e for geothermal power plants; less than 80 g/kWh_e for projected EGS; and

(b)

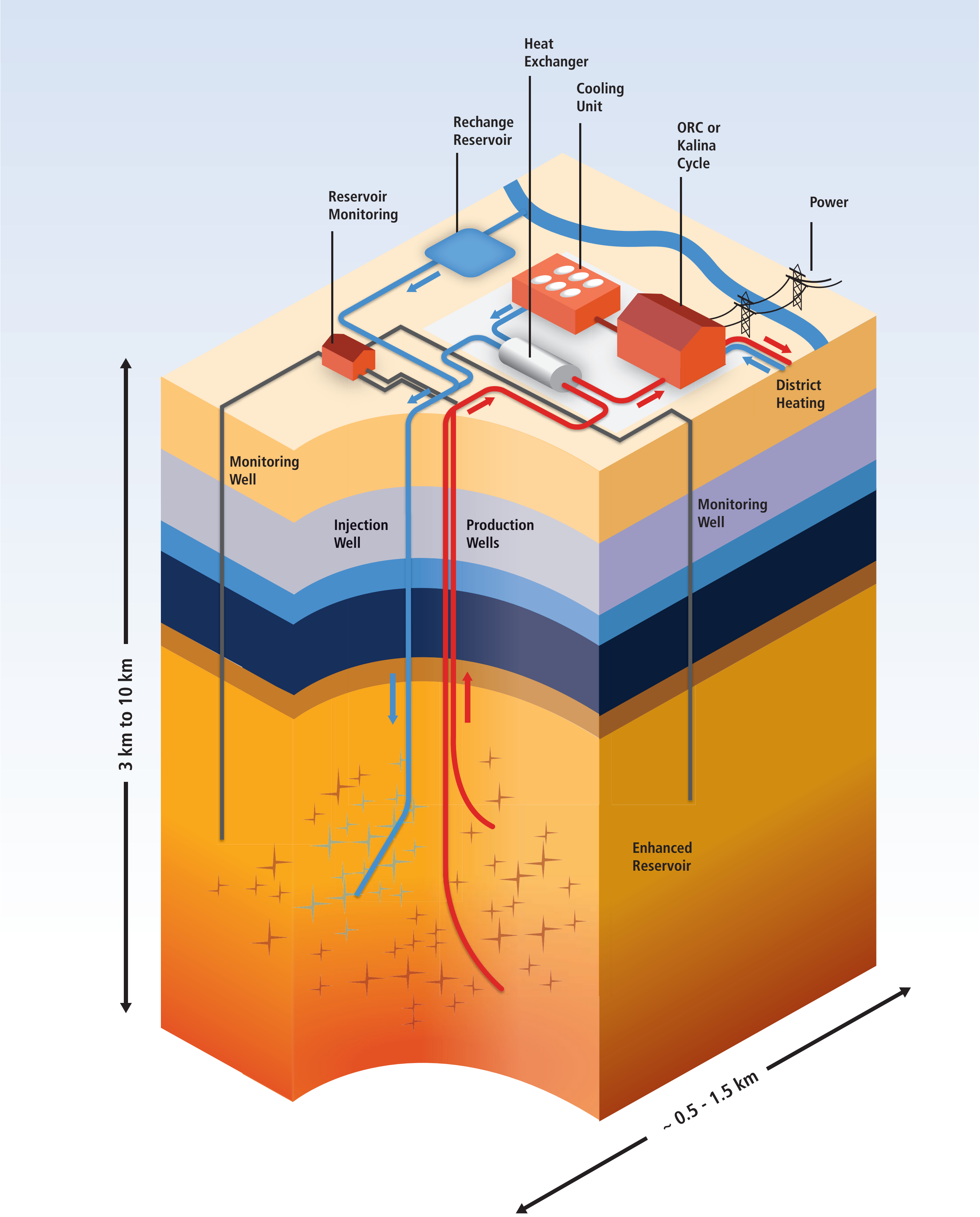


Figure TS.4.2b | Scheme showing conductive (EGS) resources. [Figure 4.1b]

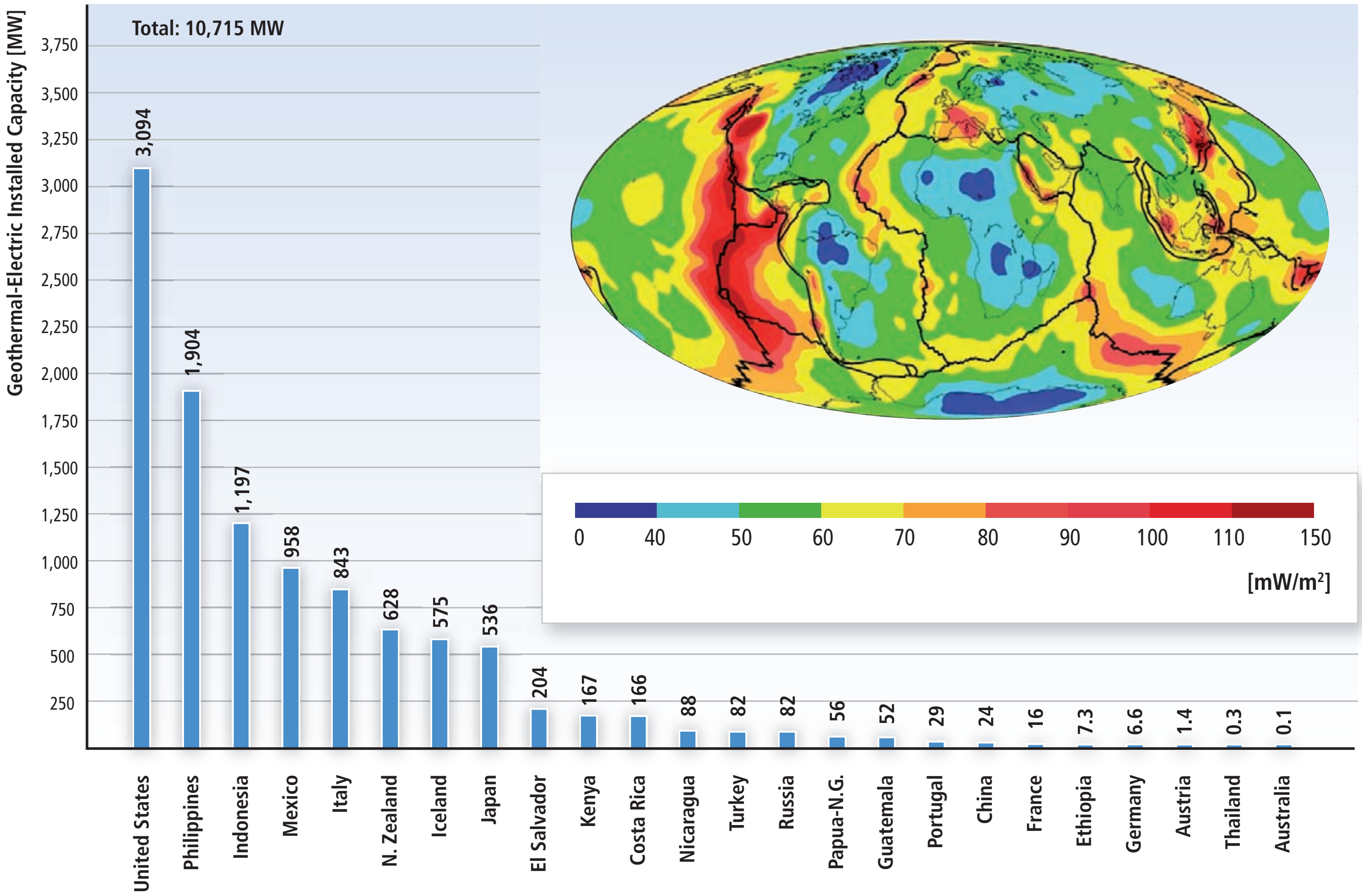


Figure TS.4.3 | Geothermal electric installed capacity by country in 2009. Figure shows worldwide average heat flow in mW/m² and tectonic plate boundaries. [Figure 4.5]

between 14 and 202 g/kWh_{th} for district heating systems and GHPs. [4.5, 4.5.1, 4.5.2]

Environmental impacts associated with geothermal projects involve consideration of a range of local air, land and water use impacts during both construction and operational phases that are common to most energy projects as well as specific to geothermal energy. Geothermal systems involve natural phenomena, and typically discharge gases mixed with steam from surface features, and minerals dissolved in water from hot springs. Some gases may be dangerous, but are typically either treated or monitored during production. In the past, surface disposal of separated water was more common, but today happens only in exceptional circumstances. Geothermal brine is usually injected back into the reservoir to support reservoir pressures and to avoid adverse environmental effects. Surface disposal, if significantly in excess of natural hot-spring flow rates, and if not strongly diluted, can have adverse effects on the ecology of rivers, lakes or marine environments. [4.5.3.1]

Local hazards arising from natural phenomena, such as micro-earthquakes, hydrothermal steam eruptions and ground subsidence may be influenced by the operation of geothermal fields. During 100 years of development, no buildings or structures within a geothermal operation or local community have been significantly damaged by shallow earthquakes originating from either geothermal production or injection activities. Some EGS demonstration projects, particularly in populated areas of Europe, have raised social opposition. The process of high-pressure injection of cold water into hot rock generates small seismic events. Induced seismic events have not been large enough to lead to human injury or significant property damage, but proper management of this issue will be an important step to facilitating significant expansion of future EGS projects. [4.5.3.2]

Land use requirements range from 160 to 290 $\text{m}^2/\text{GWh}_e/\text{yr}$ excluding wells, and up to 900 $\text{m}^2/\text{GWh/yr}$ including wells. Specific geothermal impacts on land use include effects on outstanding natural features such as springs, geysers and fumaroles. Land use issues in many settings (e.g., Japan, the USA and New Zealand) can be a serious impediment to further expansion of geothermal development. [4.5.3.3]

Geothermal resources may also have significant environmental advantages compared to the energy use they otherwise offset. [4.5.1]

4.6 Prospects for technology improvement, innovation and integration

Geothermal resources can be integrated into all types of electrical power supply systems, from large, interconnected continental transmission grids to onsite use in small, isolated villages or autonomous buildings. Since geothermal energy typically provides base-load electric generation, integration of new power plants into existing power systems does not present a major challenge. For geothermal direct uses, no integration problems have been observed, and for heating and cooling, geothermal energy (including GHPs) is already widespread at the domestic, community and district scales. Section 8 of this summary addresses integration issues in greater depth. [4.6]

Several prospects for technology improvement and innovation can reduce the cost of producing geothermal energy and lead to higher energy recovery, longer field and plant lifetimes, and better reliability. Advanced geophysical surveys, injection optimization, scaling/corrosion inhibition, and better reservoir simulation modelling will help reduce the resource risks by better matching installed capacity to sustainable generation capacity. [4.6]

In exploration, R&D is required to locate hidden geothermal systems (e.g., with no surface manifestations) and for EGS prospects. Refinement and wider usage of rapid reconnaissance geothermal tools such as satellite- and airborne-based hyper-spectral, thermal infrared, high-resolution panchromatic and radar sensors could make exploration efforts more effective. [4.6.1]

Special research in drilling and well construction technology is needed to improve the rate of penetration when drilling hard rock and to develop advanced slim-hole technologies, with the general objectives of reducing the cost and increasing the useful life of geothermal production facilities. [4.6.1]

The efficiency of the different system components of geothermal power plants and direct uses can still be improved, and it is important to develop conversion systems that more efficiently utilize the energy in the produced geothermal fluid. Another possibility is the use of suitable oil and gas wells potentially capable of supplying geothermal energy for power generation. [4.6.2]

EGS projects are currently at a demonstration and experimental stage. EGS require innovative methods to hydraulically stimulate reservoir connectivity between injection and production wells to attain sustained, commercial production rates while reducing the risk of seismic hazard, and to improve numerical simulators and assessment methods to enable reliable predictions of chemical interaction between geo-fluids and geothermal reservoirs rocks. The possibility of using CO_2 as a working fluid in geothermal reservoirs, particularly in EGS, is also under investigation since it could provide a means for enhancing the effect of geothermal energy deployment, lowering CO_2 emissions beyond just generating electricity with a carbon-free renewable resource. [4.6.3]

Currently there are no technologies in use to tap submarine geothermal resources, but in theory electrical energy could be produced directly from a hydrothermal vent. [4.6.4]

4.7 Cost trends

Geothermal projects typically have high upfront investment costs, due to the need to drill wells and construct power plants, and relatively low operational costs. Though costs vary by project, the LCOE of power plants using hydrothermal resources are often competitive in today's electricity markets; the same is true for direct uses of geothermal heat. EGS plants remain in the demonstration phase, but estimates of EGS costs are higher than those for hydrothermal reservoirs. [4.7]

The investment costs of a typical geothermal electric project are: (a) exploration and resource confirmation (10 to 15% of the total); (b) drilling of production and injection wells (20 to 35% of the total); (c) surface facilities and infrastructure (10 to 20% of the total); and (d) power plant (40 to 81% of the total). Current investment costs vary worldwide between USD_{2005} 1,800 and 5,200/kW_e. [4.7.1]

Geothermal electric O&M costs, including make-up wells (i.e., new wells to replace failed wells and restore lost production or injection capacity), have been calculated to be USD_{2005} 152 to 187/kW_e/yr, but in some countries can be significantly lower (e.g., USD_{2005} 83 to 117/kW_e/yr in New Zealand). [4.7.2]

Power plant longevity and capacity factor are also important economic parameters. The worldwide capacity factor average in 2008 for existing geothermal power plants was 74.5%, with newer installations above 90%. [4.7.3]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for hydrothermal geothermal projects over a large set and range of input parameters has been calculated to range from US $cents_{2005}$ 3.1/kWh to US $cents_{2005}$ 17/kWh, depending on the particular type of technology and project-specific conditions. Using a narrower set and range of parameters, Figure TS.4.4 shows that, at a 7% discount rate, recently installed green-field hydrothermal projects operating at the global average capacity factor of 74.5% (and under other conditions specified in [4.7.4]) have LCOE in the range from US $cents_{2005}$ 4.9/kWh to US $cents_{2005}$ 7.2/kWh for condensing flash plants and, for binary cycle plants, from US $cents_{2005}$ 5.3/kWh to US $cents_{2005}$ 9.2/kWh. The LCOE is shown to vary substantially with capacity factor, investment cost and discount rate. No LCOE data exist for EGS, but some projections have been made using different models for several cases with diverse temperatures and depths, for example, US $cents_{2005}$ 10/kWh to US $cents_{2005}$ 17.5/kWh for relatively high-grade EGS resources. [1.3.2, 4.7.4, 10.5.1, Annex II, Annex III]

Estimates of possible cost reductions from design changes and technical advances rely solely on expert knowledge of the geothermal process

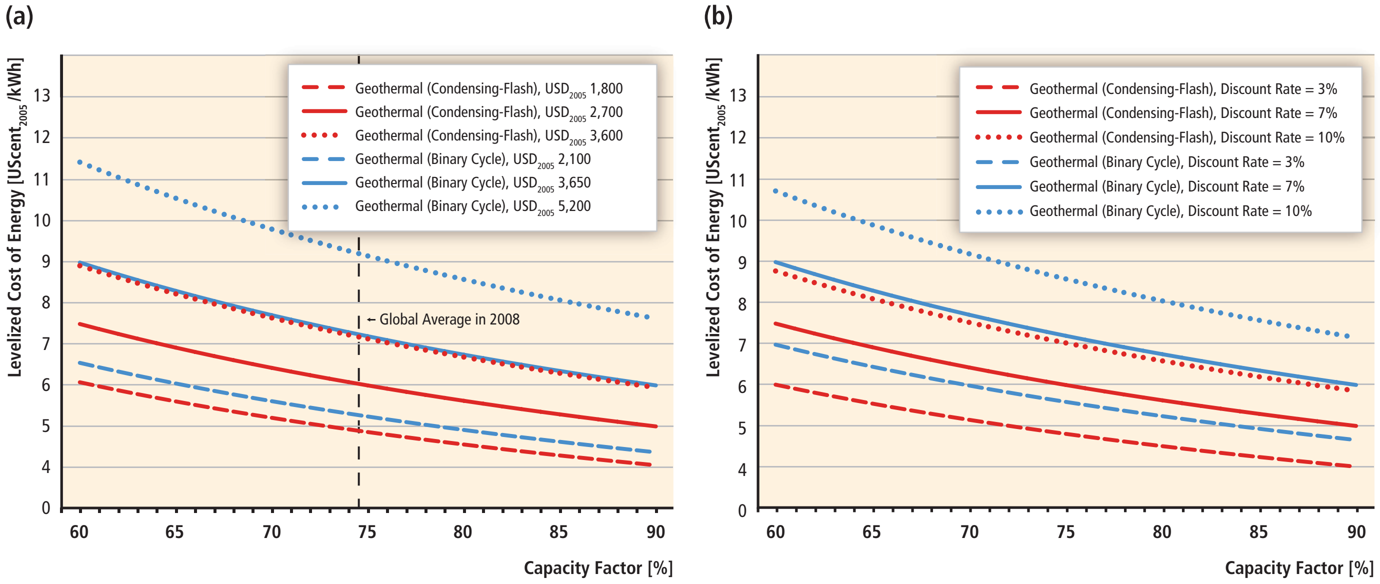


Figure TS.4.4 | Levelized cost of geothermal power, 2008: a) as a function of capacity factor and cost*,***; and b) as a function of capacity factor and discount rate**,***. [Figure 4.8]

Notes: * Discount rate assumed to equal 7%. ** Investment cost for condensing flash plants assumed at USD 2,700/kW and for binary-cycle plants at USD 3,650/kW. ***Annual O&M cost assumed to be USD 170/kW and lifetime 27.5 years.

value chain, as published learning curve studies are limited. Engineering improvements in design and stimulation of geothermal reservoirs, and improvements in materials, operation and maintenance are expected to have the greatest impact on LCOE in the near term, for example, leading to higher capacity factors and a lower contribution of drilling cost to overall investment costs. For green-field projects in 2020, the worldwide average projected LCOE is expected to range from US cents$_{2005}$ 4.5/kWh to US cents$_{2005}$ 6.6/kWh for condensing flash plants and from US cents$_{2005}$ 4.9/kWh to US cents$_{2005}$ 8.6/kWh for binary cycle plants ranges, given an average worldwide capacity factor of 80%, a 27.5-year lifetime and a discount rate of 7%. Therefore, a global average LCOE reduction of about 7% is expected for geothermal flash and binary plants by 2020. Future costs of EGS are expected to decline to lower levels as well. [4.7.5]

The LCOH for direct-use projects has a wide range, depending upon specific use, temperature and flow rate required, associated O&M and labour costs, and output of the produced product. In addition, costs for new construction are usually less than costs for retrofitting older structures. The cost figures given in Table TS.4.2 are based on a climate typical of the northern half of the USA or Europe. Heating loads would be higher for more northerly climates such as Iceland, Scandinavia and Russia. Most figures are based on cost in the USA, but would be similar in developed countries and lower in developing countries. [4.7.6]

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 (USA and New Zealand) to pulp and paper plants (New Zealand). [4.7.6]

4.8 Potential deployment

Geothermal energy can contribute to near- and long-term carbon emissions reduction. In 2008, global geothermal energy use represented only about 0.1% of the global primary energy supply. However, by 2050, geothermal could meet roughly 3% of the global electricity demand and 5% of the global demand for heating and cooling. [4.8]

Taking into account the geothermal electric projects under construction or planned in the world, installed geothermal capacity is expected to reach 18.5 GW$_e$ by 2015. Practically all the new power plants expected to be on line by 2015 will be flash-condensing and binary utilizing hydrothermal resources, with a small contribution from EGS projects. Geothermal direct uses (heat applications including GHP) are expected to grow at the same historic annual rate (11% between 1975 and 2010) to reach 85.2 GW$_{th}$. By 2015, total electric generation could reach 121.6 TWh/yr (0.44 EJ/yr) while direct generation of heat could reach 224 TWh$_{th}$/yr (0.8 EJ/yr), with the regional breakdown presented in Table TS.4.3. [4.8.1]

The long-term potential deployment of geothermal energy based on a comprehensive assessment of numerous model-based scenarios is mentioned in Section 10 of this summary and spans a broad range. The scenario medians for three GHG concentration stabilization ranges, based

Table TS.4.2 | Investment costs and calculated levelized cost of heat (LCOH) for several direct geothermal applications. [Table 4.8]

Heat application	Investment cost (USD$_{2005}$/kW$_{th}$)	LCOH (USD$_{2005}$/GJ) at discount rates of:		
		3%	7%	10%
Space heating (buildings)	1,600–3,940	20–50	24–65	28–77
Space heating (districts)	570–1,570	12–24	14–31	15–38
Greenhouses	500–1,000	7.7–13	8.6–14	9.3–16
Uncovered aquaculture ponds	50–100	8.5–11	8.6–12	8.6–12
GHP (residential and commercial)	940–3,750	14–42	17–56	19–68

Table TS.4.3 | Regional current and forecast installed capacity for geothermal power and direct uses (heat) and forecast generation of electricity and heat by 2015. [Table 4.9]

REGION[1]	Current capacity (2010)		Forecast capacity (2015)		Forecast generation (2015)	
	Direct (GW$_{th}$)	Electric (GW$_e$)	Direct (GW$_{th}$)	Electric (GW$_e$)	Direct (TW$_{th}$)	Electric (TWh$_e$)
OECD North America	13.9	4.1	27.5	6.5	72.3	43.1
Latin America	0.8	0.5	1.1	1.1	2.9	7.2
OECD Europe	20.4	1.6	32.8	2.1	86.1	13.9
Africa	0.1	0.2	2.2	0.6	5.8	3.8
Transition Economies	1.1	0.1	1.6	0.2	4.3	1.3
Middle East	2.4	0	2.8	0	7.3	0
Developing Asia	9.2	3.2	14.0	6.1	36.7	40.4
OECD Pacific	2.8	1.2	3.3	1.8	8.7	11.9
TOTAL	**50.6**	**10.7**	**85.2**	**18.5**	**224.0**	**121.6**

Notes: 1. For regional definitions and country groupings see Annex II. Estimated average annual growth rate for 2010 to 2015 is 11.5% for power and 11% for direct uses. Average worldwide capacity factors of 75% (for electric) and 30% (for direct use) were assumed by 2015.

Table TS.4.4 | Potential geothermal deployments for electricity and direct uses in 2020 through 2050. [Table 4.10]

Year	Use	Capacity[1] (GW)	Generation (TWh/yr)	Generation (EJ/yr)	Total (EJ/yr)
2020	Electricity	25.9	181.8	0.65	2.01
	Direct	143.6	377.5	1.36	
2030	Electricity	51.0	380.0	1.37	5.23
	Direct	407.8	1,071.7	3.86	
2050	Electricity	150.0	1,182.8	4.26	11.83
	Direct	800.0	2,102.3	7.57	

Notes: 1. Installed capacities for 2020 and 2030 are extrapolated from 2015 estimates using a 7% annual growth rate for electricity and 11% for direct uses, and for 2050 are the middle value between projections cited in Chapter 4. Generation was estimated with average worldwide capacity factors of 80% (2020), 85% (2030) and 90% (2050) for electricity and of 30% for direct uses.

on the AR4 baselines (>600 ppm CO_2), 440 to 600 ppm (Categories III and IV) and <440 ppm (Categories I and II), range from 0.39 to 0.71 EJ/yr for 2020, 0.22 to 1.28 EJ/yr for 2030 and 1.16 to 3.85 EJ/yr for 2050.

Carbon policy is likely to be one of the main driving factors for future geothermal development, and under the most favourable GHG concentration stabilization policy (<440 ppm), geothermal deployment by 2020, 2030 and 2050 could be significantly higher than the median values noted above. By projecting the historic average annual growth rates of geothermal power plants (7%) and direct uses (11%) from the estimates for 2015, the installed geothermal capacity in 2020 and 2030 for electricity and direct uses could be as shown in Table TS.4.4. By 2050, the geothermal-electric capacity would be as high as 150 GW$_e$ (with half of that comprised of EGS plants), and up to an additional 800 GW$_{th}$ of direct-use plants (Table TS.4.4). [4.8.2]

Even the highest estimates for the long-term contribution of geothermal energy to the global primary energy supply (52.5 EJ/yr by 2050) are within the technical potential ranges (118 to 1,109 EJ/yr for electricity and 10 to 312 EJ/yr for direct uses) and even within the upper range of hydrothermal resources (28.4 to 56.8 EJ/yr). Thus, technical potential is not likely to be a barrier to reaching more ambitious levels of geothermal deployment (electricity and direct uses), at least on a global basis. [4.8.2]

Evidence suggests that geothermal supply could meet the upper range of projections derived from a review of about 120 energy and GHG-reduction scenarios. With its natural thermal storage capacity, geothermal is especially suitable for supplying base-load power. Considering its technical potential and possible deployment, geothermal energy could meet roughly 3% of global electricity demand by 2050, and also has the potential to provide roughly 5% of the global demand for heating and cooling by 2050. [4.8.3]

5. Hydropower

5.1 Introduction

Hydropower is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable and cost-competitive technology. The mechanical power of falling water is an old tool used for various services from the time of the Greeks more than 2,000 years ago. The world's first hydroelectric station of 12.5 kW was commissioned on 30 September 1882 on Fox River at the Vulcan Street Plant in Appleton, Wisconsin, USA. Though the primary role of hydropower in global energy supply today is in providing centralized electricity generation, hydropower plants also operate in isolation and supply independent systems, often in rural and remote areas of the world. [5.1]

5.2 Resource potential

The annual global technical potential for hydropower generation is 14,576 TWh (52.47 EJ) with a corresponding estimated total capacity potential of 3,721 GW—four times the currently installed global hydropower capacity (Figure TS.5.1). Undeveloped capacity ranges from about 47% in Europe to 92% in Africa, indicating large and well-distributed opportunities for hydropower development worldwide (see Table TS.5.1). Asia and Latin America have the largest technical potentials and the largest undeveloped resources. Africa has highest portion of total potential that is still undeveloped. [5.2.1]

It is noteworthy that the total installed capacities of hydropower in North America, Latin America, Europe and Asia are of the same order of magnitude and, in Africa and Australasia/Oceania, an order of magnitude less; Africa due to underdevelopment and Australasia/Oceania because of size, climate and topography. The global average capacity factor for hydropower plants is 44%. Capacity factor can be indicative of how hydropower is employed in the energy mix (e.g., peaking versus base-load generation) or water availability, or can be an opportunity for increased generation through equipment upgrades and operational optimization. [5.2.1]

The resource potential for hydropower could change due to climate change. Based on a limited number of studies to date, the climate change impacts on existing global hydropower systems is expected to be slightly positive, even though individual countries and regions could have significant positive or negative changes in precipitation and runoff. Annual power production capacity in 2050 could increase by 2.7 TWh (9.72 PJ) in Asia under the SRES A1B scenario, and decrease by 0.8 TWh (2.88 PJ) in Europe. In other regions, changes are found to be even smaller. Globally, the changes caused by climate change in the existing hydropower production system are estimated to be less than 0.1%, although additional research is needed to lower the uncertainty of these projections. [5.2.2]

5.3 Technology and applications

Hydropower projects are usually designed to suit particular needs and specific site conditions, and are classified by project type, head (i.e., the vertical height of water above the turbine) or purpose (single- or multi-purpose). Size categories (installed capacity) are based on national definitions and differ worldwide due to varying policies. There is no immediate, direct link between installed capacity as a classification criterion and general properties common to all hydropower plants (HPPs) above or below that MW limit. All in all, classification according to size, while both common and administratively simple, is—to a degree—arbitrary: general concepts like 'small' or 'large' hydropower are not technically or scientifically rigorous indicators of impacts, economics or characteristics. It may be more useful to evaluate a hydropower project on its sustainability or economic performance thus setting out more realistic indicators. The cumulative relative environmental and social impacts of large versus small hydropower development remain unclear and context dependent. [5.3.1]

Hydropower plants come in three main project types: run-of-river (RoR), storage and pumped storage. RoR HPPs have small intake basins with no storage capacity. Power production therefore follows the hydrological cycle of the watershed. For RoR HPPs the generation varies as water availability changes and thus they may be operated as variable in small streams or as base-load power plants in large rivers. Large-scale RoR HPPs may have some limited ability to regulate water flow, and if they operate in cascades in unison with storage hydropower in upstream reaches, they may contribute to the overall regulating and balancing ability of a fleet of HPPs. A fourth category, in-stream (hydrokinetic) technology, is less mature and functions like RoR without any regulation. [5.3.2]

Hydropower projects with a reservoir (storage hydropower) deliver a broad range of energy services such as base load, peak, and energy storage, and act as a regulator for other sources. In addition they often deliver services that go beyond the energy sector, including flood control, water supply, navigation, tourism and irrigation. Pumped storage plants store water as a source for electricity generation. By reversing the

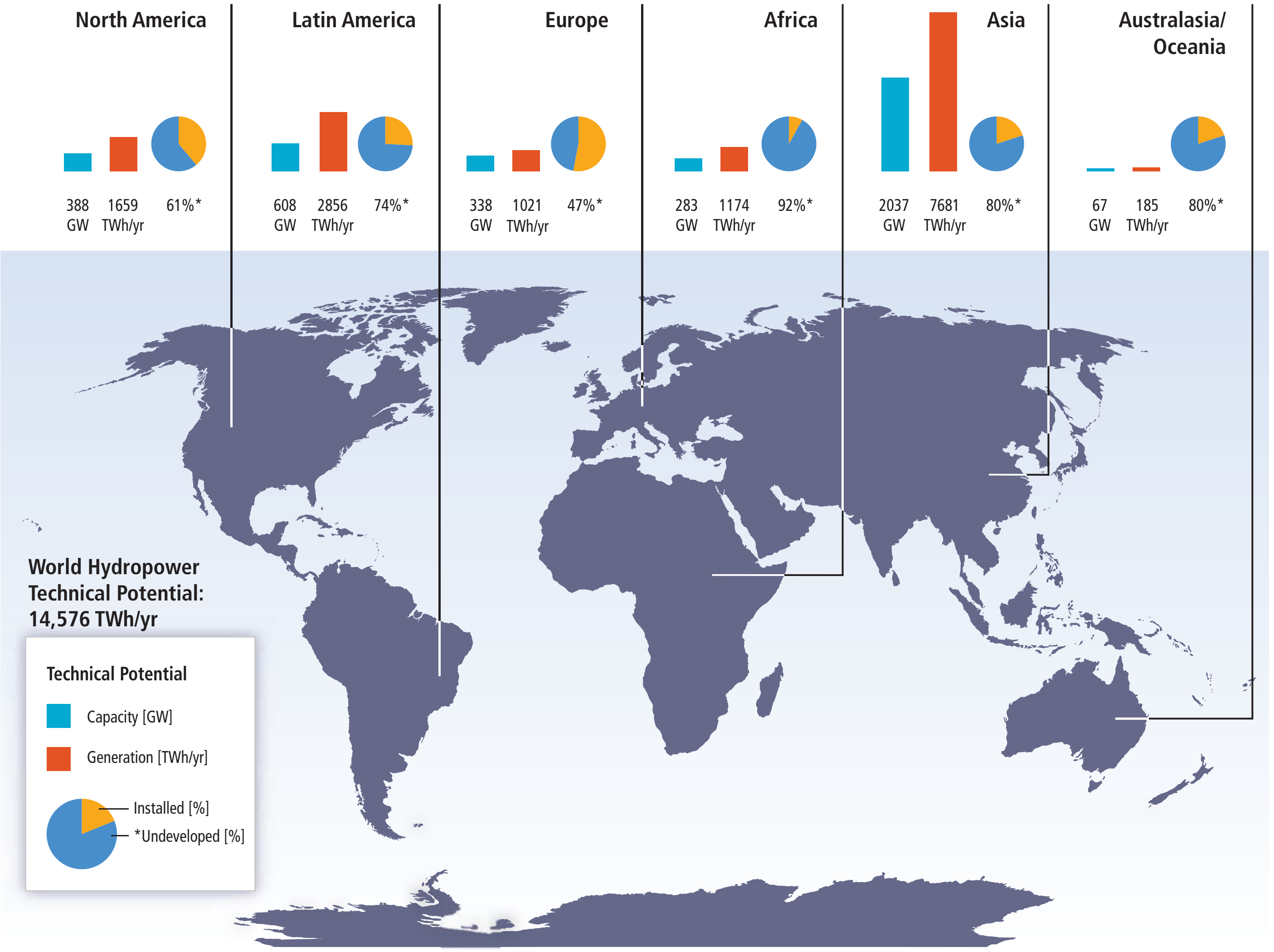


Figure TS.5.1 | Regional hydropower technical potential in terms of annual generation and installed capacity and the percentage of undeveloped technical potential in 2009. [Figure 5.2]

Table TS.5.1 | Regional hydro power technical potential in terms of annual generation and installed capacity (GW); and current generation, installed capacity, average capacity factors and resulting undeveloped potential as of 2009. [Table 5.1]

World region	Technical potential, annual generation TWh/yr (EJ/yr)	Technical potential, installed capacity (GW)	2009 Total generation TWh/yr (EJ/yr)	2009 Installed capacity (GW)	Undeveloped potential (%)	Average regional capacity factor (%)
North America	1,659 (5.971)	388	628 (2.261)	153	61	47
Latin America	2,856 (10.283)	608	732 (2.635)	156	74	54
Europe	1,021 (3.675)	338	542 (1.951)	179	47	35
Africa	1,174 (4.226)	283	98 (0.351)	23	92	47
Asia	7,681 (27.651)	2,037	1,514 (5.451)	402	80	43
Australasia/Oceania	185 (0.666)	67	37 (0.134)	13	80	32
World	**14,576 (52.470)**	**3,721**	**3,551 (12.783)**	**926**	**75**	**44**

flow of water, electrical energy can be produced on demand, with a very fast response time. Pumped storage is the largest-capacity form of grid energy storage now available. [5.3.2.2–5.3.2.3]

Sediment transport and reservoir sedimentation are problems that need to be understood as they have a number of negative effects on HPP performance: depletion of reservoir storage capacity over time; an increase in downstream degradation; increased flood risk upstream of reservoirs; generation losses due to reductions in turbine efficiency; increased frequency of repair and maintenance; and reductions in turbine lifetime and in regularity of power generation. The sedimentation problem may ultimately be controlled through land use policies and the protection of vegetation coverage. Hydropower has the best conversion efficiency of all known energy sources (about 90% efficiency, water to wire) and a very high energy payback ratio. [5.3.3]

Normally the life of a hydroelectric power plant is 40 to 80 years. Electrical and mechanical components and control equipment wear out early compared to civil structures, typically in 30 to 40 years, after which they require renovation. Upgrading/up-rating of HPPs calls for a systematic approach as there are a number of factors (hydraulic, mechanical, electrical and economic) that play a vital role in deciding the course of action. From a techno-economic viewpoint, up-rating should be considered along with renovation and modernization measures. Hydropower generating equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Most of the 926 GW of hydropower equipment in operation today (2010) will need to be modernized by 2030 to 2040. Refurbishment of existing hydropower plants often results in enhanced hydropower capacity, both where turbine capacity is being renovated/up-rated or where existing civil infrastructure (like barrages, weirs, dams, canal tunnels, etc.) is being reworked to add new hydropower facilities. [5.3.4]

5.4 Global and regional status of market and industry development

Hydropower is a mature, predictable and price-competitive technology. It currently provides approximately 16% of the world's total electricity production and 86% of all electricity from renewable sources. While hydropower contributes to some level of power generation in 159 countries, 5 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 differs widely, however. While Brazil and Canada are heavily dependent on hydropower to produce 84% and 59% of total generation, respectively, Russia and China produce only 19% and 16% of their total electricity from hydropower, respectively. Despite the significant growth of hydroelectric production around the globe, the percentage share of hydroelectricity has dropped during the last three decades (1973 to 2008) from 21 to 16%, because electricity load and other generation sources have grown more rapidly than has hydropower. [5.4.1]

Carbon credits benefit hydropower projects by helping to secure financing and to reduce risks. Financing is the most decisive step in the entire project development process. Hydropower projects are one of the largest contributors to the flexible mechanisms of the Kyoto Protocol and therefore to existing carbon credit markets. Out of the 2,062 projects registered by the Clean Development Mechanism (CDM) Executive Board by 1 March 2010, 562 are hydropower projects. With 27% of the total number of projects, hydropower is the CDM's leading deployed RE source. China, India, Brazil and Mexico represent roughly 75% of the hosted projects. [5.4.3.1]

Many economical hydropower projects are financially challenged. High up-front costs are a deterrent for investment. Also, hydropower tends to have lengthy lead times for planning, permitting and construction. In the evaluation of lifecycle costs, hydropower often has a very high performance, with annual O&M costs being a fraction of the capital investment. As hydropower and its industry are old and mature, it is expected that the hydropower industry will be able to meet the demand that will be created by the predicted deployment rate in the years to come. For example, in 2008 the hydropower industry managed to install more than 41 GW of new capacity worldwide. [5.4.3.2]

The development of more appropriate financing models is a major challenge for the hydropower sector, as is finding the optimum roles for the public and private sectors. The main challenges for hydropower relate to creating private-sector confidence and reducing risk, especially prior to project permitting. Green markets and trading in emissions reductions will undoubtedly provide 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. [5.4.3.2]

The concepts of classifying HPPs as 'small' or 'large', as defined by installed capacity (MW), can act as a barrier to the development of hydropower. For example, these classifications can impact the financing of new hydropower plants, determining how hydropower is treated in climate change and energy policies. Different incentives are used for small-scale hydropower (FITs, green certificates and bonuses) depending on the country, but no incentives are available for large-scale HPPs. The EU Linking Directive sets a limit for carbon credits issued from HPPs to 20 MW. The same limit is found in the UK Renewables Obligation, a green certificate market-based mechanism. Likewise, in several countries FITs do not apply to hydropower above a certain size limit (e.g., France 12 MW, Germany 5 MW, India 5 and 25 MW). [5.4.3.4]

The UNFCCC CDM Executive Board has decided that storage hydropower projects will have to follow the power density indicator (PDI: installed capacity/reservoir area in W/m^2) to be eligible for CDM credits. The PDI rule seems to presently exclude storage hydropower from qualifying for CDM (or Joint Implementation) credits and may lead to suboptimal development of hydropower resources as the non-storage RoR option will be favoured.

5.5 Integration into broader energy systems

Hydropower's large capacity range, its flexibility, storage capability (when coupled with a reservoir), and ability to operate in a stand-alone mode or in grids of all sizes enables it to deliver a broad range of services. [5.5]

Hydropower can be delivered through the national and regional electric grid, mini-grids and also in isolated mode. Realization has been growing in developing countries that small-scale hydropower schemes have an important role to play in the socioeconomic development of remote rural, especially hilly, areas as those can provide power for industrial, agricultural and domestic uses. In China, small-scale HPPs have been one of the most successful examples of rural electrification, where over 45,000 small HPPs totalling over 55,000 MW of capacity and producing 160 TWh (576 PJ) of generation annually benefit over 300 million people. [5.5.2]

With a very large reservoir relative to the size of the hydropower plant (or very consistent river flows), HPPs can generate power at a near-constant level throughout the year (i.e., operate as a base-load plant). Alternatively, in the case that the hydropower capacity far exceeds the amount of reservoir storage, the hydropower plant is sometimes referred to as energy-limited. An energy-limited hydro plant would exhaust its 'fuel supply' by consistently operating at its rated capacity throughout the year. In this case, the use of reservoir storage allows hydropower generation to occur at times that are most valuable from the perspective of the power system rather than at times dictated solely by river flows. Since electrical demand varies during the day and night, during the week and seasonally, storage hydropower generation can be timed to coincide with times where the power system needs are the greatest. In part, these times will occur during periods of peak electrical demand. Operating hydropower plants in a way to generate power during times of high demand is referred to as peaking operation (in contrast to base-load). Even with storage, however, hydropower generation will still be limited by the size of the storage, the rated electrical capacity of the hydropower plant, and downstream flow constraints for irrigation, recreation or environmental uses of the river flows. Hydropower peaking may, if the outlet is directed to a river, lead to rapid fluctuations in river flow, water-covered area, depth and velocity. In turn this may, depending on local conditions, lead to negative impacts in the river unless properly managed. [5.5.3]

In addition to hydropower supporting fossil and nuclear generation technologies, it can also help reduce the challenges with integrating variable renewable resources. In Denmark, for example, the high level of variable wind energy (>20% of the annual energy demand) is managed in part through strong interconnections (1 GW) to Norway, which has substantial storage hydropower. More interconnectors to Europe may further support increasing the share of wind power in Denmark and Germany. Increasing variable generation will also increase the amount of balancing services, including regulation and load following, required by the power system. In regions with new and existing hydropower facilities, providing these services from hydropower may avoid the need to rely on increased part-load and cycling of conventional thermal plants to provide these services. [5.5.4]

Though hydro has the potential to offer significant power system services in addition to energy and capacity, interconnecting and reliably utilizing HPPs may also require changes to power systems. The interconnection of hydropower to the power system requires adequate transmission capacity from HPPs to demand centres. Adding new HPPs has in the past required network investments to extend the transmission network. Without adequate transmission capacity, HPP operation can be constrained such that the services offered by the plant are less than what it could offer in an unconstrained system. [5.5.5]

5.6 Environmental and social impacts

Like all energy and water management options, hydropower projects have negative and positive environmental and social impacts. On the environmental side, hydropower may have a significant environmental footprint at local and regional levels but offers advantages at the macro-ecological level. With respect to social impacts, hydropower projects may entail the relocation of communities living within or nearby the reservoir or the construction sites, compensation for downstream communities, public health issues, and others. A properly designed hydropower project may, however, be a driving force for socioeconomic development, though a critical question remains about how these benefits are shared. [5.6]

All hydroelectric structures affect a river's ecology, mainly by inducing a change into its hydrologic characteristics and by disrupting the ecological continuity of sediment transport and fish migration through the building of dams, dikes and weirs. However, the extent to which a river's physical, chemical, biological and ecosystem characteristics are modified depends largely on the type of HPP. Whereas RoR hydropower projects do not alter a river's flow regime, the creation of a reservoir for storage hydropower entails a major environmental change by transforming a fast-running river ecosystem into a still-standing artificial lake. [5.6.1.1–5.6.1.6]

Similar to a hydropower project's ecological effects, the extent of its social impacts on the local and regional communities, land use, economy, health and safety or heritage varies according to project type and site-specific conditions. While RoR projects generally introduce little social change, the creation of a reservoir in a densely populated area can entail significant challenges related to resettlement and impacts on the livelihoods of the downstream populations. Restoration and improvement of living standards of affected communities is a long-term and challenging task that has been managed with variable success in the past. Whether HPPs can contribute to fostering socioeconomic development depends largely on how the generated services and revenues are shared and distributed among different stakeholders. HPPs can also have positive impacts on the living conditions of local communities and the regional economy, not only by generating electricity but also by facilitating through the creation 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. [5.6.1.7–5.6.1.11]

The assessment and management of environmental and social impacts associated with, especially, larger HPPs represent a key challenge for hydropower development. Emphasizing transparency and an open, participatory decision-making process, the stakeholder consultation approach is driving both present-day and future hydropower projects towards increasingly more environmentally friendly and sustainable solutions. In many countries, a national legal and regulatory framework has been put in place to determine how hydropower projects shall be developed and operated, while numerous multilateral financing agencies have developed their own guidelines and requirements to assess the economic, social and environmental performance of hydropower projects. [5.6.2]

One of hydropower's main environmental advantages is that it creates no atmospheric pollutants or waste associated with fuel combustion. However, all freshwater systems, whether they are natural or man-made, emit GHGs (e.g., CO_2, methane) due to decomposing organic material. Lifecycle assessments (LCAs) carried out on hydropower projects have so far demonstrated the difficulty of generalizing estimates of lifecycle GHG emissions for hydropower projects in all climatic conditions, pre-impoundment land cover types, ages, hydropower technologies, and other project-specific circumstances. The multipurpose nature of most hydropower projects makes allocation of total impacts to the several purposes challenging. Many LCAs to date allocate all impacts of hydropower projects to the electricity generation function, which in some cases may overstate the emissions for which they are 'responsible'. LCAs (Figure TS.5.2) that evaluate GHG emissions of HPPs during construction, operation and maintenance, and dismantling, show that the majority of lifecycle GHG emission estimates for hydropower cluster between about 4 and 14 g CO_2eq/kWh, but under certain scenarios there is potential to emit much larger quantities of GHGs, as shown by the outliers. [5.6.3.1]

While some natural water bodies and freshwater reservoirs may even absorb more GHGs than they emit, there is a definite need to properly assess the net change in GHG emissions induced by the creation of such reservoirs. All LCAs included in these assessments evaluated only gross GHG emissions from reservoirs. Whether reservoirs are net emitters of GHGs, considering emissions that would have occurred without the reservoir, is an area of active research. When considering net anthropogenic emissions as the difference in the overall carbon cycle between the situations with and without the reservoir, there is currently no consensus on whether reservoirs are net emitters or net sinks. Presently two international processes are investigating this issue: the UN Educational, Scientific and Cultural Organization/International Hydrological Programme research project and the IEA Hydropower Agreement Annex XII. [5.6.3.2]

5.7 Prospects for technology improvement and innovation

Though hydropower is a proven and well-advanced technology, there is still room for further improvement, for example, by optimizing operations, mitigating or reducing environmental impacts, adapting to new social and environmental requirements and implementing more robust and cost-effective technological solutions. Large hydropower turbines are now close to the theoretical limit for efficiency, with up to 96% efficiency when operated at the best efficiency point, but this is not always possible and continued research is needed to make more efficient operation possible over a broader range of flows. Older turbines can have lower efficiency by design or reduced efficiency due to corrosion and cavitation. There is therefore the potential to increase energy output by retrofitting with new higher efficiency equipment and usually also with increased capacity. Most of the existing electrical and mechanical equipment in operation today will need to be modernized during the next three decades, allowing for improved efficiency and higher power and energy output. Typically, generating equipment can be upgraded or replaced with more technologically advanced electro-mechanical equipment two or three times during the lifetime of the project, making more effective use of the same flow of water. [5.7]

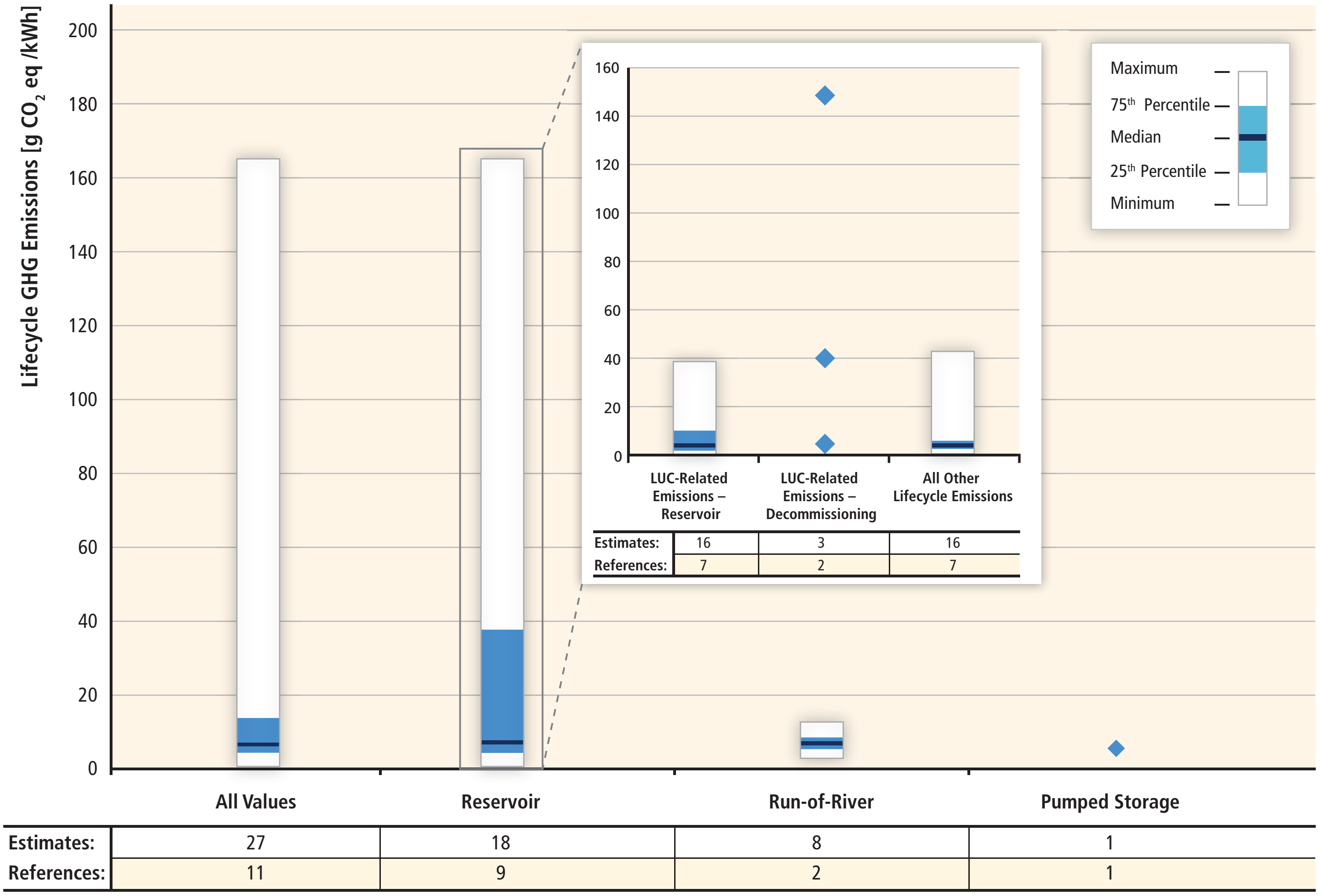
There is much ongoing technology innovation and material research aiming to extend the operational range in terms of head and discharge, and also to improve environmental performance, reliability and reduce costs. Some of the promising technologies under development are variable-speed and matrix technologies, fish-friendly turbines, hydrokinetic turbines, abrasive-resistant turbines, and new tunnelling and dam technologies. New technologies aiming at utilizing low (<15 m) or very low (<5 m) head may open up many sites for hydropower that have not been within reach of conventional technology. As most of the data available on hydropower potential are based on field work produced several decades ago, when low-head hydropower was not a high priority, existing data on low-head hydropower potential may not be complete. Finally, there is a significant potential for improving operation of HPPs by utilizing new methods for optimizing plant operation. [5.7.1–5.7.8]

5.8 Cost trends

Hydropower is often economically competitive with current market energy prices, though the cost of developing, deploying and operating new hydropower projects will vary from project to project. Hydropower projects often require a high initial investment, but have the advantage of very low O&M costs and a long lifespan. [5.8]

Investment costs for hydropower include costs of planning; licensing; plant construction; impact reductions for fish and wildlife, recreational, historical and archaeological sites; and water quality monitoring. Overall, there are two major cost groups: the civil construction costs, which normally are the greatest costs of the hydropower project; and electromechanical equipment costs. The civil construction costs follow the price trends in the country where the project is going to be developed. In the case of countries with economies in transition, the costs are likely to be relatively low due to the use of local labour and local materials. The costs of electromechanical equipment follow the tendency of prices at a global level. [5.8.1]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for hydropower projects over a large set and range of input parameters has been



	LUC-Related Emissions – Reservoir	LUC-Related Emissions – Decommissioning	All Other Lifecycle Emissions
Estimates:	16	3	16
References:	7	2	7

	All Values	Reservoir	Run-of-River	Pumped Storage
Estimates:	27	18	8	1
References:	11	9	2	1

Figure TS.5.2 | Life-cycle GHG emissions of hydropower technologies (unmodified literature values, after quality screen). See Annex I for details of literature search and citations of literature contributing to the estimates displayed. Surface emissions from reservoirs are referred to as gross GHG emissions. [Figure 5.15]

calculated to range from as low as US cent$_{2005}$ 1.1/kWh to US cent$_{2005}$ 15/kWh, depending on site-specific parameters for investment costs of each project and on assumptions regarding the discount rate, capacity factor, lifetime and O&M costs. [1.3.2, 5.8, 10.5.1, Annex II, Annex III]

Figure TS.5.3 presents the LCOE for hydropower projects over a somewhat different and more typical set and range of parameters consistent with the majority of hydropower projects, and does so as a function of capacity factor while applying different investment costs and discount rates.

Capacity factors will be determined by hydrological conditions, installed capacity and plant design, and the way the plant is operated. For power plant designs intended for maximum energy production (base-load) and/or with some regulation, capacity factors will often be from 30 to 60%, with average capacity factors for different world regions shown in the graph. For peaking-type power plants, the capacity factor can be even lower, whereas capacity factors for RoR systems vary across a wide range (20 to 95%) depending on the geographical and climatological conditions, technology, and operational characteristics. For an average capacity factor of 44% and investment costs between USD$_{2005}$ 1,000/kW and USD$_{2005}$ 3,000/kW, the LCOE ranges from US cent$_{2005}$ 2.5/kWh to US cent$_{2005}$ 7.5/kWh.

Most of the projects developed in the near-term future (up to 2020) are expected to have investment costs and LCOE in this range, though projects with both lower and higher costs are possible. Under good conditions, the LCOE of hydropower can be in the range of US cent$_{2005}$ 3/kWh to US cent$_{2005}$ 5/kWh. [5.8.3, 8.2.1.2, Annex III]

There is relatively little information on historical trends in hydropower costs in the literature. One reason for this—besides the fact that project costs are highly site-specific—may be the complex cost structure for hydropower plants, where some components may have decreasing cost trends (e.g., tunnelling costs), while others may have increasing cost trends (e.g., social and environmental mitigation costs). [5.8.4]

One complicating factor when considering the cost of hydropower is that, for multipurpose reservoirs, there is a need to share or allocate the cost of serving other water uses like irrigation, flood control, navigation, roads, drinking water supply, fish, and recreation. There are

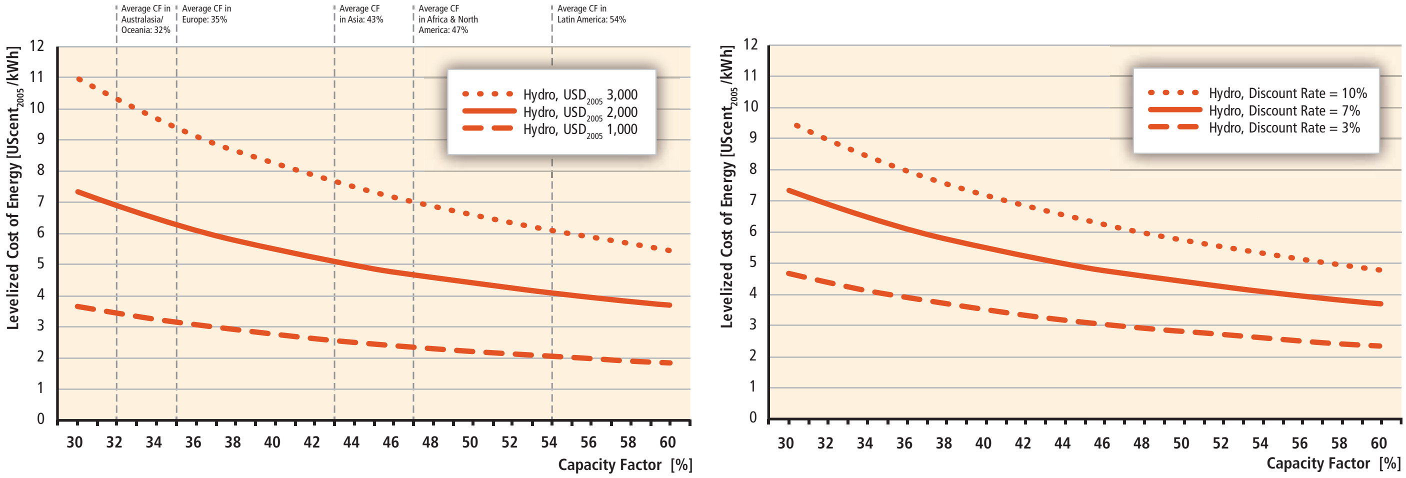


Figure TS.5.3 | Recent and near-term estimated levelized cost of hydropower (a) as a function of capacity factor and investment cost*, ***; and (b) as a function of capacity factor and discount rate**,***. [Figure 5.20]

Notes: * Discount rate is assumed to equal 7%. ** Investment cost is assumed to be USD 2,000/kW. *** Annual O&M cost is assumed at 2.5%/yr of investment cost and plant lifetime as 60 years.

different methods of allocating the cost to individual purposes, each of which has advantages and drawbacks. The basic rules are that the allocated cost to any purpose does not exceed that benefit of that purpose and each purpose will be carried out at its separable cost. Separable cost for any purpose is obtained by subtracting the cost of a multipurpose project without that purpose from the total cost of the project with the purpose included. Merging 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) is becoming a tool for consideration of cost sharing for multipurpose reservoirs. [5.8.5]

5.9 Potential deployment

Hydropower offers a significant potential for near- and long-term carbon emissions reduction. On a global basis, the hydropower resource is unlikely to constrain further development in the near to medium term, though environmental and social concerns may limit deployment opportunities if not carefully managed. [5.9]

So far, only 25% of the hydropower potential has been developed across the world (that is, 3,551 TWh out of 14,575 TWh) (12.78 EJ out of 52.47 EJ). The different long-term prospective scenarios propose a continuous increase for the next decades. The increase in hydropower capacity over the last 10 years is expected by several studies to continue in the near to medium term: from 926 GW in 2009 to between 1,047 and 1,119 GW by 2015; an annual addition ranging from 14 to 25 GW. [5.9, 5.9.1]

The reference-case projections presented in Chapter 10 (based on 164 analyzed longer-term scenarios) show hydropower's role in the global energy supply covering a broad range, with a median of roughly 13 EJ (3,600 TWh) in 2020, 16 EJ (4,450 TWh) in 2030 and 19 EJ (5,300 TWh) in 2050. 12.78 EJ was reached already in 2009 and thus the average estimate of 13 EJ for 2020 has probably been exceeded today. Also, some scenario results provide lower values than the current installed capacity for 2020, 2030 and 2050, which is counterintuitive given, for example, hydropower's long lifetimes, its significant market potential and other important services. These results could maybe be explained by model/scenario weaknesses (see discussions in Section 10.2.1.2 of this report). Growth of hydropower is therefore projected to occur even in the absence of GHG mitigation policies, even with hydropower's median contribution to global electricity supply dropping from about 16% today to less than 10% by 2050. As GHG mitigation policies are assumed to become more stringent in the alternative scenarios, the contribution of hydropower grows: by 2030, hydropower's median contribution equals roughly 16.5 EJ (4,600 TWh) in the 440 to 600 and <440 ppm CO_2 stabilization ranges (compared to the median of 15 EJ in the baseline cases), increasing to about 19 EJ by 2050 (compared to the median of 18 EJ in the baseline cases). [5.9.2]

Regional projections of hydropower generation in 2035 show a 98% increase in the Asia Pacific region compared to 2008 levels and a 104% increase in Africa. Brazil is the main driving force behind the projected 46% increase in hydropower generation in the South and Central America region over the same time period. North America and Europe/Eurasia expect more modest increases of 13 and 27%, respectively, over the period. [5.9.2]

Overall, evidence suggests that relatively high levels of deployment in the next 20 years are feasible. Even if hydropower's share in global electricity supply decreases by 2050, hydropower would remain an attractive RE source within the context of global carbon mitigation scenarios. Furthermore, increased development of storage hydropower may enable investment into water management infrastructure, which is needed in response to growing problems related to water resources. [5.9.3]

5.10 Integration into water management systems

Water, energy and climate change are inextricably linked. Water availability is crucial for many energy technologies, including hydropower, while energy is needed to secure water supply for agriculture, industries and households, in particular in water-scarce areas in developing countries. This close relationship has led to the understanding that the water-energy nexus must be addressed in a holistic way, in particular with regard to climate change and sustainable development. Providing energy and water for sustainable development may require improved regional and global water governance. As it is often associated with the creation of water storage facilities, hydropower is at the crossroads of these issues and can play an important role in enhancing both energy and water security. [5.10]

Today, about 700 million people live in countries experiencing water stress or scarcity. By 2035, it is projected that three 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 to climate change impacts will become very important in water management. [5.10.1]

In a context where multipurpose hydropower can be a tool to mitigate both climate change and water scarcity, these projects may have an enabling role beyond the electricity sector as a financing instrument for reservoirs, helping to secure freshwater availability. However, multiple uses may increase the potential for conflicts and reduce energy production during times of low water levels. As major watersheds are shared by several nations, regional and international cooperation is crucial. Both intergovernmental agreements and initiatives by international institutions are actively supporting these important processes. [5.10.2, 5.10.3]

6. Ocean Energy

6.1 Introduction

Ocean energy offers the potential for long-term carbon emissions reduction but is unlikely to make a significant short-term contribution before 2020 due to its nascent stage of development. The theoretical potential of 7,400 EJ/yr contained in the world's oceans easily exceeds present human energy requirements. Government policies are contributing to accelerate the deployment of ocean energy technologies, heightening expectations that rapid progress may be possible. The six main classes of ocean energy technology offer a diversity of potential development pathways, and most offer potentially low environmental impacts as currently understood. There are encouraging signs that the investment cost of ocean energy technologies and the levelized cost of electricity generated will decline from their present non-competitive levels as R&D and demonstrations proceed, and as deployment occurs. Whether these cost reductions are sufficient to enable broad-scale deployment of ocean energy is the most critical uncertainty in assessing the future role of ocean energy in mitigating climate change. [6 ES, 6.1]

6.2 Resource potential

Ocean energy can be defined as energy derived from technologies that utilize seawater as their motive power or harness the water's chemical or heat potential. The RE resource in the ocean comes from six distinct sources, each with different origins and each requiring different technologies for conversion. These sources are:

Wave energy derived from the transfer of the kinetic energy of the wind to the upper surface of the ocean. The total theoretical wave energy resource is 32,000 TWh/yr (115 EJ/yr), but the technical potential is likely to be substantially less and will depend on development of wave energy technologies. [6.2.1]

Tidal range (tidal rise and fall) derived from gravitational forces of the Earth-Moon-Sun system. The world's theoretical tidal power potential is in the range of 1 to 3 TW, located in relatively shallow waters. Again, technical potential is likely to be significantly less than theoretical potential. [6.2.2]

Tidal currents derived from water flow that results from the filling and emptying of coastal regions associated with tides. Current regional estimates of tidal current technical potential include 48 TWh/yr (0.17 EJ) for Europe and 30 TWh/yr (0.11EJ/yr) for China. Commercially attractive sites have also been identified in the Republic of Korea, Canada, Japan, the Philippines, New Zealand and South America. [6.2.3]

Ocean currents derived from wind-driven and thermohaline ocean circulation. The best-characterized system of ocean currents is the Gulf Stream in North America, where the Florida Current has a technical potential for 25 GW of electricity capacity. Other regions with potentially promising ocean circulation include the Agulhas/Mozambique Currents off South Africa, the Kuroshio Current off East Asia and the East Australian Current. [6.2.4]

Ocean thermal energy conversion (OTEC) derived from temperature differences arising from solar energy stored as heat in upper ocean layers and colder seawater, generally below 1,000 m. Although the energy density of OTEC is relatively low, the overall resource potential is much larger than for other forms of ocean energy. One 2007 study estimates that about 44,000 TWh/yr (159 EJ/yr) of steady-state power may be possible. [6.2.5]

Salinity gradients (osmotic power) derived from salinity differences between fresh and ocean water at river mouths. The theoretical potential of salinity gradients is estimated at 1,650 TWh/yr (6 EJ/yr). [6.2.6]

Figure TS.6.1 provides examples of how selected ocean energy resources are distributed across the globe. Some ocean energy resources, such as ocean currents or power from salinity gradients, are globally distributed. Ocean thermal energy is principally located in the Tropics around the equatorial latitudes (latitudes 0° to 35°), whilst the highest annual wave power occurs between latitudes of 30° to 60°. Wave power in the southern hemisphere undergoes smaller seasonal variation than in the northern hemisphere. Ocean currents, ocean thermal energy, salinity gradients and, to some extent, wave energy are consistent enough to generate base-load power. Given the early state of the available literature and the substantial uncertainty in ocean energy's technical potential, the estimates for technical ocean energy potential vary widely. [6.2.1–6.2.6]

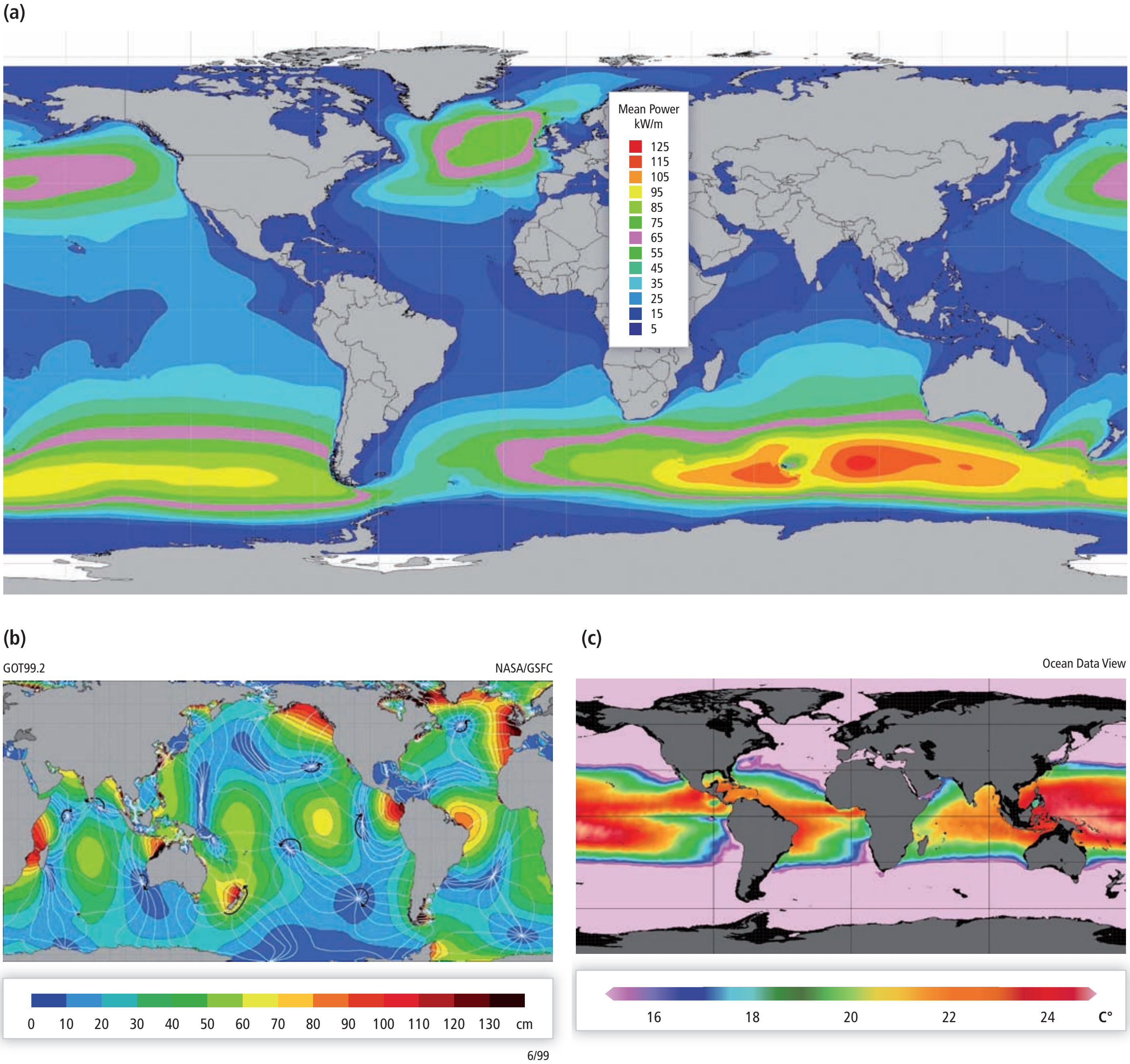


Figure TS.6.1a-c | Global distribution of various ocean energy resources: (a) Wave power; (b) Tidal range, (c) Ocean thermal energy. [Figures 6.1, 6.2, 6.4]

(d)

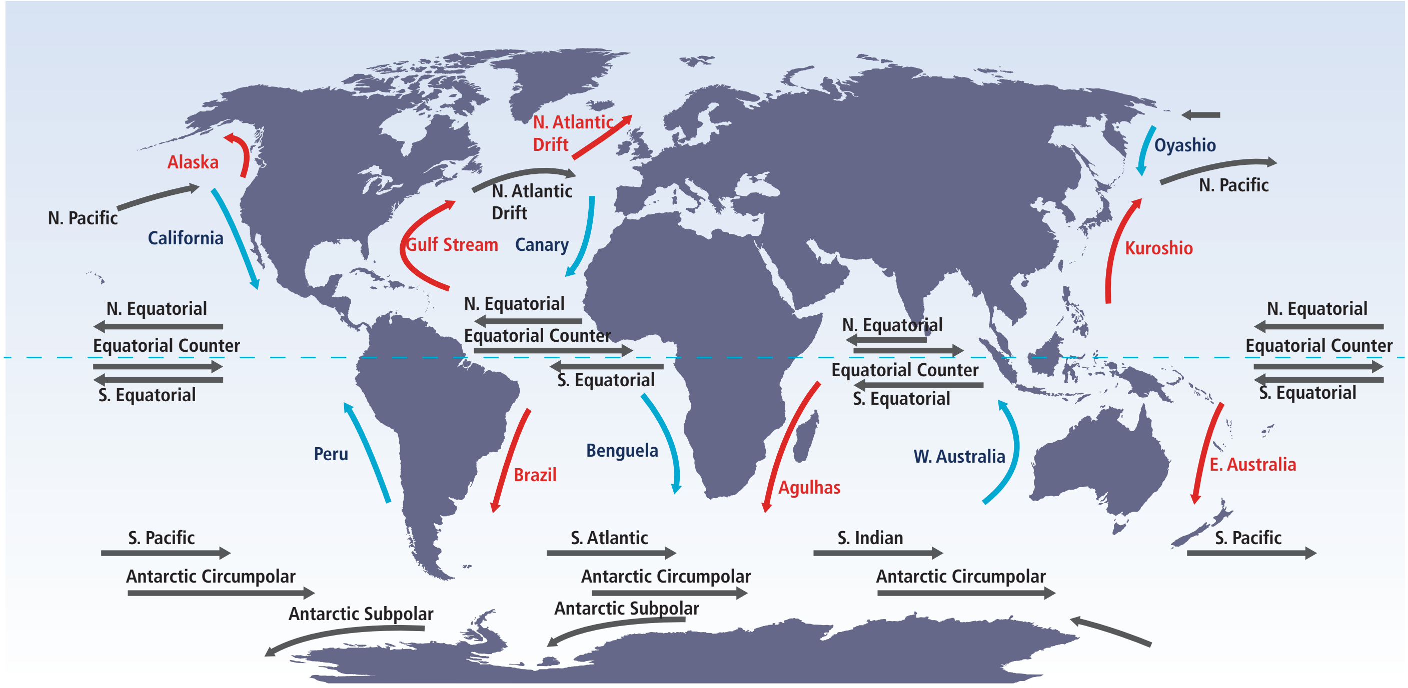


Figure TS.6.1d | Global distribution of various ocean energy resources: (d) Ocean currents. [Figure 6.3]

6.3 Technology and applications

The current development status of ocean energy technologies ranges from the conceptual and pure R&D stages to the prototype and demonstration stage, and only tidal range technology can be considered mature. Presently there are many technology options for each ocean energy source and, with the exception of tidal range barrages, technology convergence has not yet occurred. Over the past four decades, other marine industries (primarily offshore oil and gas) have made significant advances in the fields of materials, construction, corrosion, submarine cables and communications. Ocean energy is expected to directly benefit from these advances. [6.3.1]

Many wave energy technologies representing a range of operating principles have been conceived, and in many cases demonstrated, to convert energy from waves into a usable form of energy. Major variables include the method of wave interaction with respective motions (heaving, surging, pitching) as well as water depth (deep, intermediate, shallow) and distance from shore (shoreline, near-shore, offshore). Wave energy technologies can be classified into three groups: oscillating water columns (OWC: shore-based, floating), oscillating bodies (surface buoyant, submerged), and overtopping devices (shore-based, floating). [6.2.3] Principles of operation are presented in Figure TS.6.2.

Tidal range energy can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations, where a barrage encloses an estuary. The barrage may generate electricity on both the ebb and flood tides and some future barrages may have multiple basins to enable almost continuous generation. The most recent technical concepts are stand-alone offshore ‘tidal lagoons’. [6.3.3]

Technologies to harness power from tidal and ocean currents are also under development, but tidal energy turbines are more advanced. Some of the tidal/ocean current energy technologies are similar to mature wind turbine generators but submarine turbines must also account for reversing flow, cavitation at blade tips and harsh underwater marine conditions. Tidal currents tend to be bidirectional, varying with the tidal cycle, and relatively fast-flowing, compared with ocean currents, which are usually unidirectional and slow-moving but continuous. Converters are classified by their principle of operation into axial flow turbines, cross flow turbines and reciprocating devices as presented in Figure TS.6.3. [6.3.4]

Ocean thermal energy conversion (OTEC) plants use the temperature differences between warm seawater from the ocean surface and cool seawater from depth (1,000 m is often used as a reference level) to produce electricity. Open-cycle OTEC systems use seawater directly as the circulating fluid, whilst closed-cycle systems use heat exchangers and a secondary working fluid (most commonly ammonia) to drive a turbine. Hybrid systems use both open- and closed-cycle operation. Although there have been trials of OTEC technologies, problems have been encountered with maintenance of vacuums, heat exchanger biofouling and corrosion issues. Current research is focused on overcoming these problems. [6.3.5]

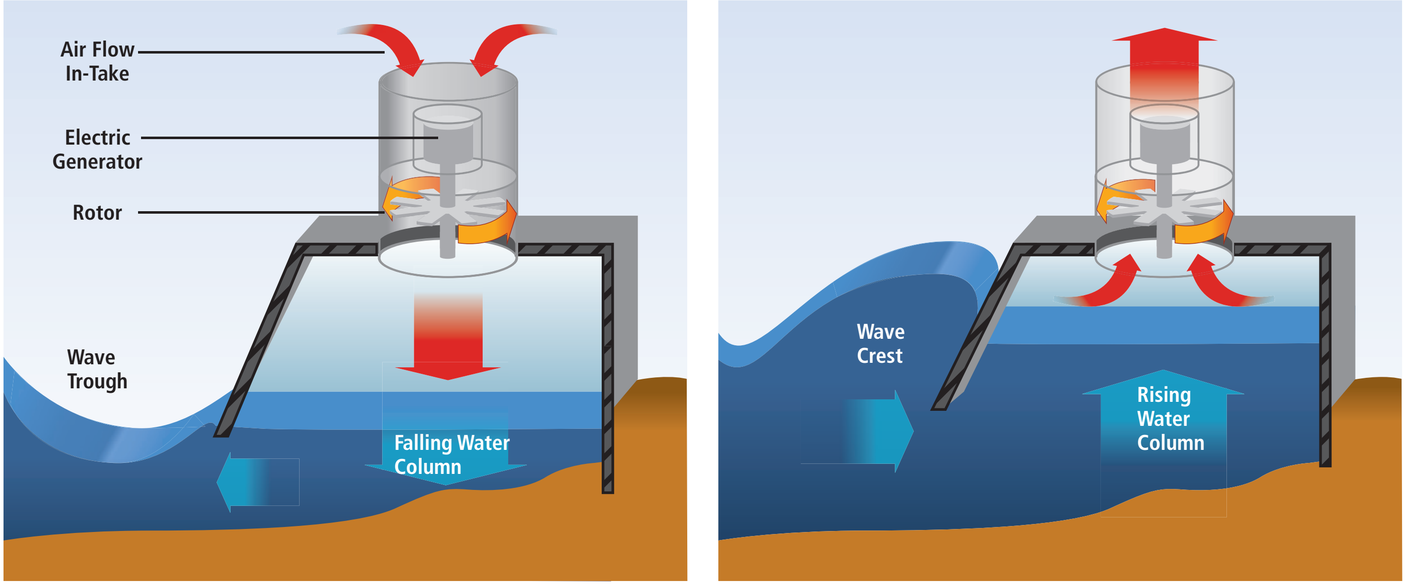


Figure TS.6.2a/b | Type of wave energy converter and its operation: oscillating water column device. [Figure 6.6] (design by the National Renewable Energy Laboratory (NREL))

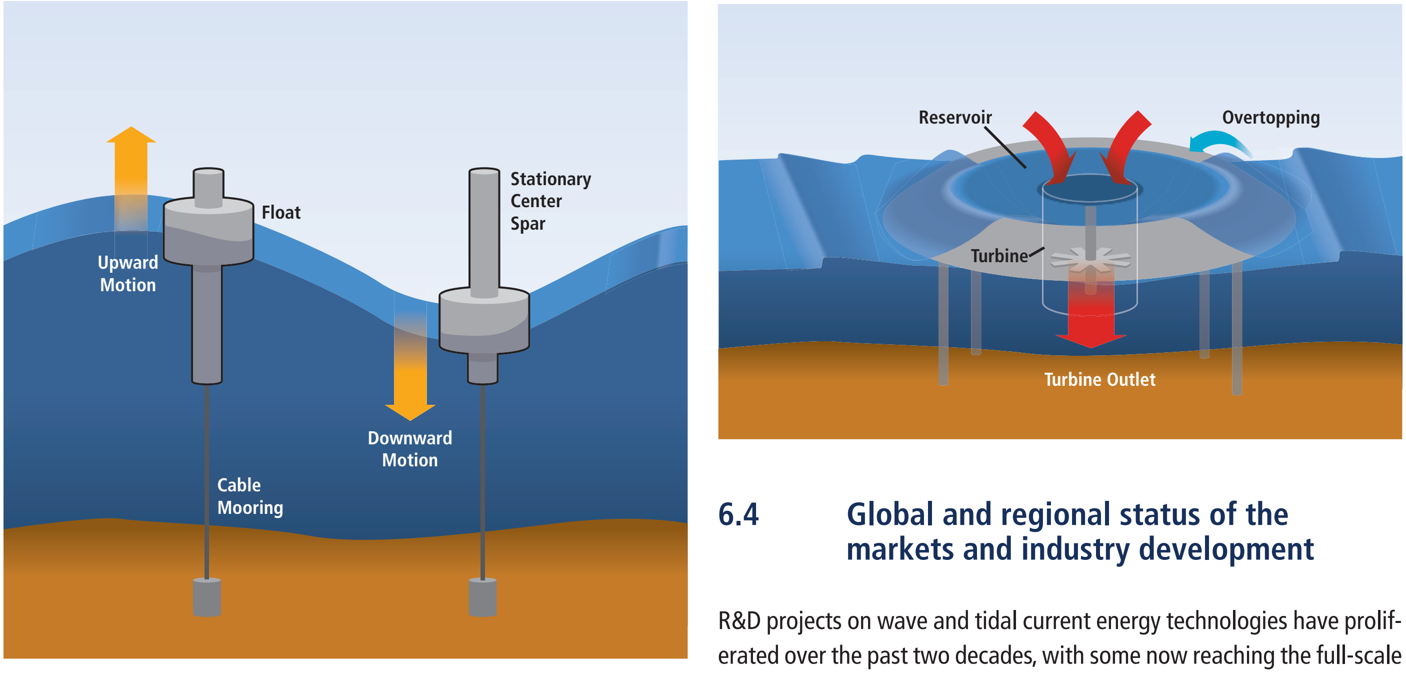


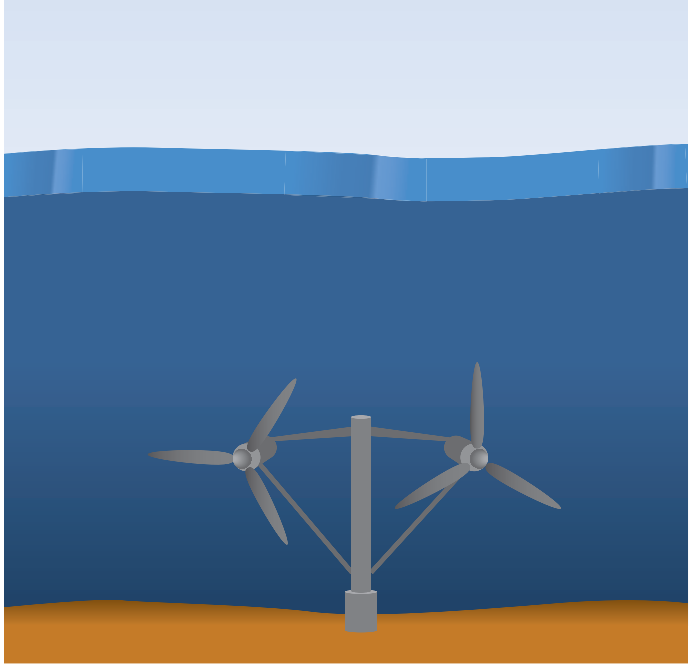
Figure TS.6.2c/d | Wave energy converters and their operation: (left) oscillating body device; and (right) overtopping device. [Figure 6.6] (design by the National Renewable Energy Laboratory (NREL))

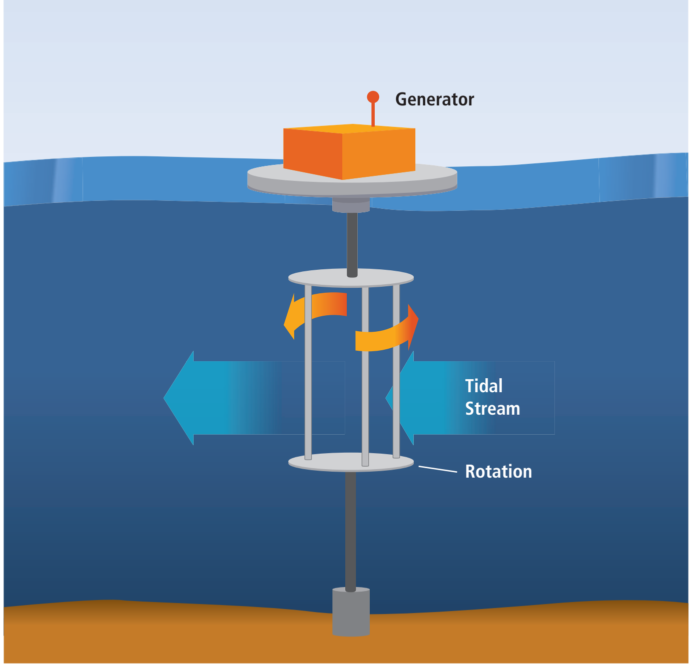
The salinity gradient between freshwater from rivers and seawater can be utilized as a source of power with at least two concepts under development. The reversed electro dialysis (RED) process is a concept in which the difference in chemical potential between the two solutions is the driving force (Figure TS.6.4). The pressure-retarded osmosis, or osmotic power process, utilizes the concept of naturally occurring osmosis, a hydraulic pressure potential, caused by the tendency of freshwater to mix with seawater due to the difference in salt concentration (Figure TS.6.5). [6.3.6]

6.4 Global and regional status of the markets and industry development

R&D projects on wave and tidal current energy technologies have proliferated over the past two decades, with some now reaching the full-scale pre-commercial prototype stage. Presently, the only full-size and operational ocean energy technology available is the tidal barrage, of which the best example is the 240 MW La Rance Barrage in north-western France, completed in 1966. The 254 MW Sihwa Barrage (South Korea) is due to become operational in 2011. Technologies to develop other ocean energy sources including OTEC, salinity gradients and ocean currents are still at the conceptual, R&D or early prototype stages. Currently, more than 100 different ocean energy technologies are under development in over 30 countries. [6.4.1]

The principal investors in ocean energy R&D and deployments are national, federal and state governments, followed by major energy utilities and investment companies. National and regional governments are





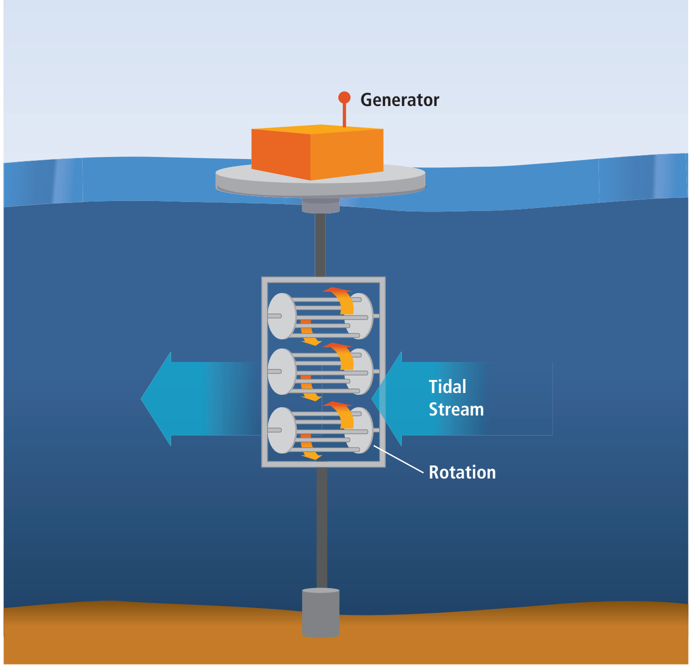


Figure TS.6.3 | Tidal current energy converters and their operation: (Top left) twin turbine horizontal axis device; (Bottom left) cross-flow device; and (Top right) vertical axis device. [Figure 6.8]

particularly supportive of ocean energy through a range of financial, regulatory and legislative initiatives to support developments. [6.4.7]

Industrial involvement in ocean energy is at a very early stage and there is no manufacturing industry for these technologies at present. The growth of interest may lead to the transfer of capacity, skills and capabilities from related industries, combined with new specific innovative aspects. One interesting feature of ocean energy is the development of a number of national marine energy testing centres and these are becoming foci for device testing, certification and advanced R&D. [6.4.1.2]

The status of industry development can be assessed by the current and recent deployments of ocean energy systems.

Wave energy: A number of shore-based wave energy prototypes are operating around the world. Two OWC devices have been operational in Portugal and Scotland for approximately a decade, while two other offshore OWC devices have been tested at prototype scale in Australia and Ireland. Another OWC was operational off the southern coast of India between 1990 and 2005. A number of companies in Australia, Brazil, Denmark, Finland, Ireland, Norway, Portugal, Spain, Sweden, New Zealand, the UK and the USA have been testing pilot scale or pre-commercial prototypes at sea, with the largest being 750 kW. [6.4.2]

Tidal range: The La Rance 240 MW plant in France has been operational since 1966. Other smaller projects have been commissioned since then in China, Canada and Russia. The Sihwa barrage 254 MW plant in Korea will be commissioned during 2011, and several other large projects are under consideration. [6.4.3]

Tidal and ocean currents: There are probably more than 50 tidal current devices at the proof-of-concept or prototype development stage, but large-scale deployment costs are yet to be demonstrated. The most advanced example is the SeaGen tidal turbine, which was installed near Northern Ireland and has delivered electricity into the electricity grid for more than one year. An Irish company has tested its open-ring turbine in Scotland, and more recently in Canada. Two companies have demonstrated horizontal-axis turbines at full scale in Norway and Scotland, whilst another has demonstrated a vertical-axis turbine in Italy. Lastly,

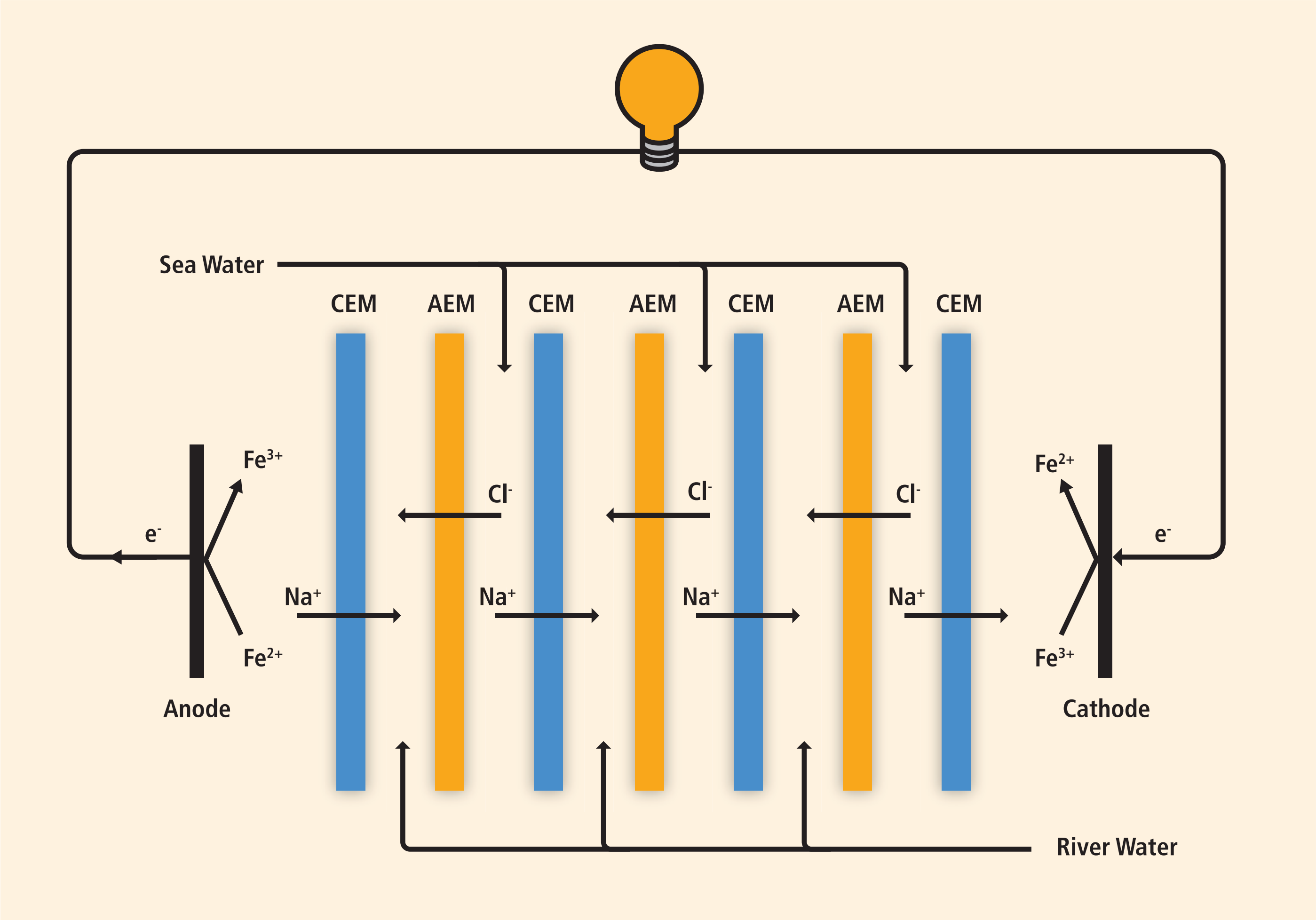


Figure TS.6.4 | Reversed electro dialysis (RED) system. [Figure 6.9]

Notes: CEM = cation exchange membrane; AEM = anion exchange membrane, Na = sodium, Cl = Chlorine, Fe = iron.

a reciprocating device was demonstrated in the UK in 2009. No pilot or demonstration plants have been deployed for ocean currents to date, although much larger scales are envisioned if technologies are able to capture the slower-velocity currents. [6.4.4]

OTEC: Japan, India, the USA and several other countries have tested pilot OTEC projects. Many have experienced engineering challenges related to pumping, vacuum retention and piping. Larger-scale OTEC developments could have significant markets in tropical maritime nations, including the Pacific Islands, Caribbean Islands, and Central American and African nations if the technology develops to the point of being a cost-effective energy supply option. [6.4.5]

Salinity gradients: Research into osmotic power is being pursued in Norway, with a prototype in operation since 2009 as part of a drive to deliver a commercial osmotic power plant. At the same time, the RED technology has been proposed for retrofitting the 75-year-old Afsluitdijk dike in The Netherlands. [6.4.6]

6.5 Environmental and social impacts

Ocean energy does not directly emit CO_2 during operation; however, GHG emissions may arise from different aspects of the lifecycle of ocean energy systems, including raw material extraction, component manufacturing, construction, maintenance and decommissioning. A comprehensive review of lifecycle assessment studies published since 1980 suggests that lifecycle GHG emissions from wave and tidal energy systems are less than 23 g CO_2eq/kWh, with a median estimate of lifecycle GHG emissions of around 8 g CO_2eq/kWh for wave energy. Insufficient studies are available to estimate lifecycle emissions from the other classes of ocean energy technology. Regardless, in comparison to fossil energy generation technologies, the lifecycle GHG emissions from ocean energy devices appear low. [6.5.1]

The local social and environmental impacts of ocean energy projects are being evaluated as actual deployments multiply, but can be estimated based on the experience of other maritime and offshore

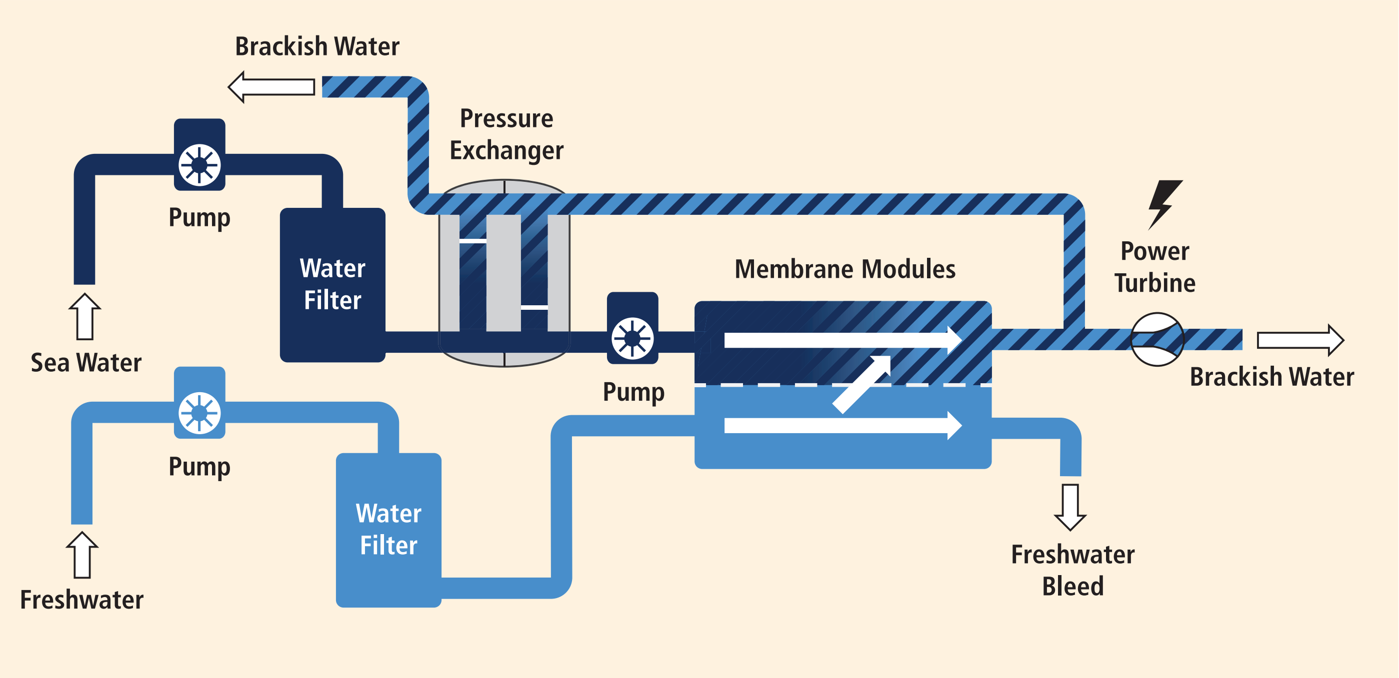


Figure TS.6.5 | Pressure-retarded osmosis (PRO) process. [Figure 6.10]

industries. Environmental risks from ocean energy technologies appear to be relatively low, but the early stage of ocean energy deployment creates uncertainty about the degree to which social and environmental concerns might eventually constrain development. [6 ES]

Each ocean power technology has its own specific set of environmental and social impacts. Possible positive effects from ocean energy may include avoidance of adverse effects on marine life by virtue of reducing other human activities in the area around the ocean devices, and the strengthening of energy supply and regional economic growth, employment and tourism. Negative effects may include a reduction in visual amenity and loss of access to space for competing users, noise during construction, noise and vibration during operation, electromagnetic fields, disruption to biota and habitats, water quality changes and possible pollution, for instance from chemical or oil leaks, and other limited specific impacts on local ecosystems. [6.5.2]

6.6 Prospects for technology improvement, innovation and integration

As emerging technologies, ocean energy devices have the potential for significant technological advances. Not only will device-specific R&D and deployment be important to achieving these advances, but technology improvements and innovation in ocean energy converters are also likely to be influenced by developments in related fields. [6.6]

Integration of ocean energy into wider energy networks will need to recognize the widely varying generation characteristics arising from the different resources. For example, electricity generation from tidal stream resources shows very high variability over one to four hours, yet extremely limited variability over monthly or longer time horizons. [6.6]

6.7 Cost trends

Commercial markets are not yet driving marine energy technology development. Government-supported R&D and national policy incentives are the key motivations. Because none of the ocean energy technologies but tidal barrages are mature (experience with other technologies is only now becoming available for validation of demonstration/prototype devices), it is difficult to accurately assess the economic viability of most ocean energy technologies. [6.7.1]

Table TS.6.1 shows the best available data for some of the primary cost factors that affect the levelized cost of electricity by each of the ocean energy sub-types. In most cases, these cost and performance parameters are based on sparse information due to the lack of peer-reviewed reference data and actual operating experience, and in many cases therefore reflect estimated cost and performance assumptions based on engineering knowledge. Present-day investment costs were found in a few instances but are based on a small sample of projects and studies, which may not be representative of the entire industry. [6.7.1]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for tidal barrages (which is currently the only commercially available ocean energy technology) over a large set and range of input parameters has been

Table TS.6.1 | Summary of core available cost and performance parameters for all ocean energy technology sub-types. [Table 6.3]

Ocean Energy Technology	Investment Costs (USD_{2005}/kW)	Annual O&M Costs (USD_{2005}/kW)	Capacity Factor (CF) (%)	Design Life (years)
Wave	6,200–16,100	180	25–40	20
Tidal Range	4,500–5,000	100	22.5–28.5	40
Tidal Current	5,400–14,300	140	26–40	20
Ocean Current	N/A	N/A	N/A	20
Ocean Thermal	4,200–12,300[1]	N/A	N/A	20
Salinity Gradient	N/A	N/A	N/A	20

Note: 1. Cost figures for ocean thermal energy have not been converted to 2005 USD.

calculated to range from US $cent_{2005}$ 12/kWh to US $cent_{2005}$ 32/kWh. This range should, however, only be considered as indicative given the present state of deployment experience. [1.3.2, 6.7.1, 6.7.3, 10.5.1, Annex II, Annex III]

Because of the early stage of technology development, estimates of future costs for ocean energy should be considered speculative. Nonetheless, the cost of ocean energy is expected to decline over time as R&D, demonstrations, and deployments proceed. [6.7.1–6.7.5]

6.8 Potential deployment

Until about 2008, ocean energy was not considered in any of the major global energy scenario modelling activities and therefore its potential impact on future world energy supplies and climate change mitigation is just now beginning to be investigated. As such, the results of the published scenarios literature as they relate to ocean energy are sparse and preliminary, reflecting a wide range of possible outcomes. Specifically, scenarios for ocean energy deployment are considered in only three major sources here: Energy [R]evolution (E[R]) 2010, IEA World Energy Outlook (WEO) 2009 and Energy Technology Perspectives (ETP) 2010. Multiple scenarios were considered in the E[R] and the ETP reports and a single reference scenario was documented in the WEO report. Each scenario is summarized in Table TS.6.2.

This preliminary presentation of scenarios that describe alternative levels of ocean energy deployment is among the first attempts to review the potential role of ocean energy in the medium- to long-term scenarios literature with the intention of establishing the potential contribution of ocean energy to future energy supplies and climate change mitigation. As shown by the limited number of existing scenarios, ocean energy has the potential to help mitigate long-term climate change by offsetting GHG emissions with projected deployments resulting in energy delivery of up to 1,943 TWh/yr (~7 EJ/yr) by 2050. Other scenarios have been developed that indicate deployment as low as 25 TWh/yr (0.9 EJ/yr) from ocean energy. The wide range in results is based in part on uncertainty about the degree to which climate change mitigation will drive energy

Table TS.6.2 | Main characteristics of medium- to long-term scenarios from major published studies that include ocean energy. [Table 6.5]

	Deployment TWh/yr (PJ/yr)				GW	
Scenario	**2010**	**2020**	**2030**	**2050**	**2050**	**Notes**
Energy [R]evolution - Reference	N/A	3 (10.8)	11 (36.6)	25 (90)	N/A	No policy changes
Energy [R]evolution	N/A	53 (191)	128 (461)	678 (2,440)	303	Assumes 50% carbon reduction
Energy [R]evolution – Advanced	N/A	119 (428)	420 (1,512)	1,943 (6,994)	748	Assumes 80% carbon reduction
WEO 2009	N/A	3 (10.8)	13 (46.8)	N/A	N/A	Basis for E[R] reference case
ETP BLUE map 2050	N/A	N/A	N/A	133 (479)	N/A	Power sector is virtually decarbonized
ETP BLUE map no CCS 2050	N/A	N/A	N/A	274 (986)	N/A	BLUE Map Variant – Carbon capture and storage is found to not be possible
ETP BLUE map hi NUC 2050	N/A	N/A	N/A	99 (356)	N/A	BLUE Map Variant – Nuclear share is increased to 2,000 GW
ETP BLUE Map hi REN 2050	N/A	N/A	N/A	552 (1,987)	N/A	BLUE Map Variant – Renewable share is increased to 75%
ETP BLUE map 3%	N/A	N/A	N/A	401 (1,444)	N/A	BLUE Map Variant – Discount rates are set to 3% for energy generation projects.

sector transformation, but for ocean energy, is also based on inherent uncertainty as to when and if various ocean energy technologies become commercially available at attractive costs. To better understand the possible role of ocean energy in climate change mitigation, not only will continued technical advances be necessary, but the scenarios modelling process will need to increasingly incorporate the range of potential ocean energy technology sub-types, with better data for resource potential, present and future investment costs, O&M costs, and anticipated capacity factors. Improving the availability of the data at global and regional scales will be an important ingredient to improving coverage of ocean energy in the scenarios literature. [6.8.4]

7. Wind Energy

7.1 Introduction

Wind energy has been used for millennia in a wide range of applications. The use of wind energy to generate electricity on a commercial scale, however, became viable only in the 1970s as a result of technical advances and government support. A number of different wind energy technologies are available across a range of applications, but the primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either on land ('onshore') or in sea- or freshwater ('offshore').[11] [7.1]

Wind energy offers significant potential for near-term (2020) and long-term (2050) GHG emissions reductions. The wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050 if ambitious efforts are made to reduce GHG emissions and to address other impediments to increased wind energy deployment. Onshore wind energy is already being deployed at a rapid pace in many countries, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. Moreover, though average wind speeds vary considerably by location, ample technical potential exists in most regions of the world to enable significant wind energy deployment. In some areas with good wind resources, the cost of wind energy is already competitive with current energy market prices, even without considering relative environmental impacts. Nonetheless, in most regions of the world, policy measures are still required to ensure rapid deployment. Continued advancements in on- and offshore wind energy technology are expected, however, further reducing the cost of wind energy and improving wind energy's GHG emissions reduction potential. [7.9]

7.2 Resource potential

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

No standardized approach has been developed to estimate the global technical potential of wind energy: the diversity in data, methods, assumptions, and even definitions for technical potential complicate comparisons. The AR4 identified the technical potential for onshore wind energy as 180 EJ/yr (50,000 TWh/yr). Other estimates of the global technical potential for wind energy that consider relatively more development constraints range from a low of 70 EJ/yr (19,400 TWh/yr) (onshore only) to a high of 450 EJ/yr (125,000 TWh/yr) (on- and near-shore). This range corresponds to roughly one to six times global electricity production in 2008, and may understate the technical potential due to several of the studies relying on outdated assumptions, the exclusion or only partial inclusion of offshore wind energy in some of the studies, and methodological and computing limitations. Estimates of the technical potential for offshore wind energy alone range from 15 EJ/yr to 130 EJ/yr (4,000 to 37,000 TWh/yr) when only considering relatively shallower and near-shore applications; greater technical potential is available if also considering deeper-water applications that might rely on floating wind turbine designs. [7.2.1]

Regardless of whether existing estimates under- or overstate the technical potential for wind energy, and although further advances in wind resource assessment methods are needed, it is evident that the technical potential of the resource itself is unlikely to be a limiting factor for global wind energy deployment. Instead, economic constraints associated with the cost of wind energy, institutional constraints and costs associated with transmission access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute limit to the global technical potential is encountered. [7.2.1]

In addition, ample technical potential exists in most regions of the world to enable significant wind energy deployment. The wind resource is not evenly distributed across the globe nor uniformly located near population centres, however, and wind energy will therefore not contribute equally in meeting the needs of every country. The technical potentials for onshore wind energy in OECD North America and Eastern Europe/Eurasia are found to be particularly sizable, whereas some areas of non-OECD Asia and OECD Europe appear to have more limited onshore technical potential. Figure TS.7.1, a global wind resource map, also shows limited technical potential in certain areas of Latin America and Africa, though other portions of those continents have significant

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[11] Smaller wind turbines, higher-altitude wind electricity, and the use of wind energy in mechanical and propulsion applications are only briefly discussed in Chapter 7.

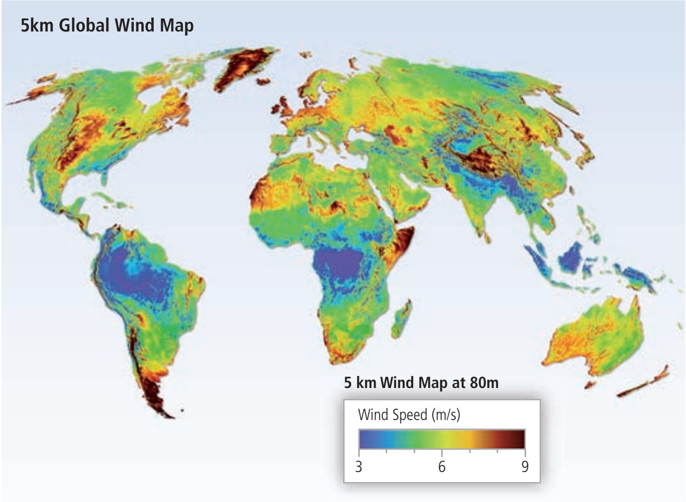

Figure TS.7.1 | Example global wind resource map with 5 km x 5 km resolution. [Figure 7.1]

technical potential. Recent, detailed regional assessments have generally found the size of the wind resource to be greater than estimated in previous assessments. [7.2.2]

Global climate change may alter the geographic distribution and/or the inter- and intra-annual variability of the wind resource, and/or the quality of the wind resource, and/or the prevalence of extreme weather events that may impact wind turbine design and operation. Research to date suggests that it is unlikely that multi-year annual mean wind speeds will change by more than a maximum of ±25% over most of Europe and North America during the present century, while research covering northern Europe suggests that multi-year annual mean wind power densities will likely remain within ±50% of current values. Fewer studies have been conducted for other regions of the world. Though research in this field is nascent and additional study is warranted, research to date suggests that global climate change may alter the geographic distribution of the wind resource, but that those effects are unlikely to be of a magnitude to greatly impact the global potential for wind energy deployment. [7.2.3]

7.3 Technology and applications

Modern, commercial grid-connected wind turbines have evolved from small, simple machines to large, highly sophisticated devices. Scientific and engineering expertise and advances, as well as improved computational tools, design standards, manufacturing methods and O&M procedures, have all supported these technology developments. [7.3]

Generating electricity from the wind requires that the kinetic energy of moving air be converted to electrical energy, and the engineering challenge for the wind energy industry is to design cost-effective wind turbines and power plants to perform this conversion. Though a variety of turbine configurations have been investigated, commercially available turbines are primarily horizontal-axis machines with three blades positioned upwind of the tower. In order to reduce the levelized cost of wind energy, typical wind turbine sizes have grown significantly (Figure TS.7.2), with the largest fraction of onshore wind turbines installed globally in 2009 having a rated capacity of 1.5 to 2.5 MW. As of 2010, onshore wind turbines typically stand on 50- to 100-m towers, with rotors that are often 50 to 100 m in diameter; commercial machines

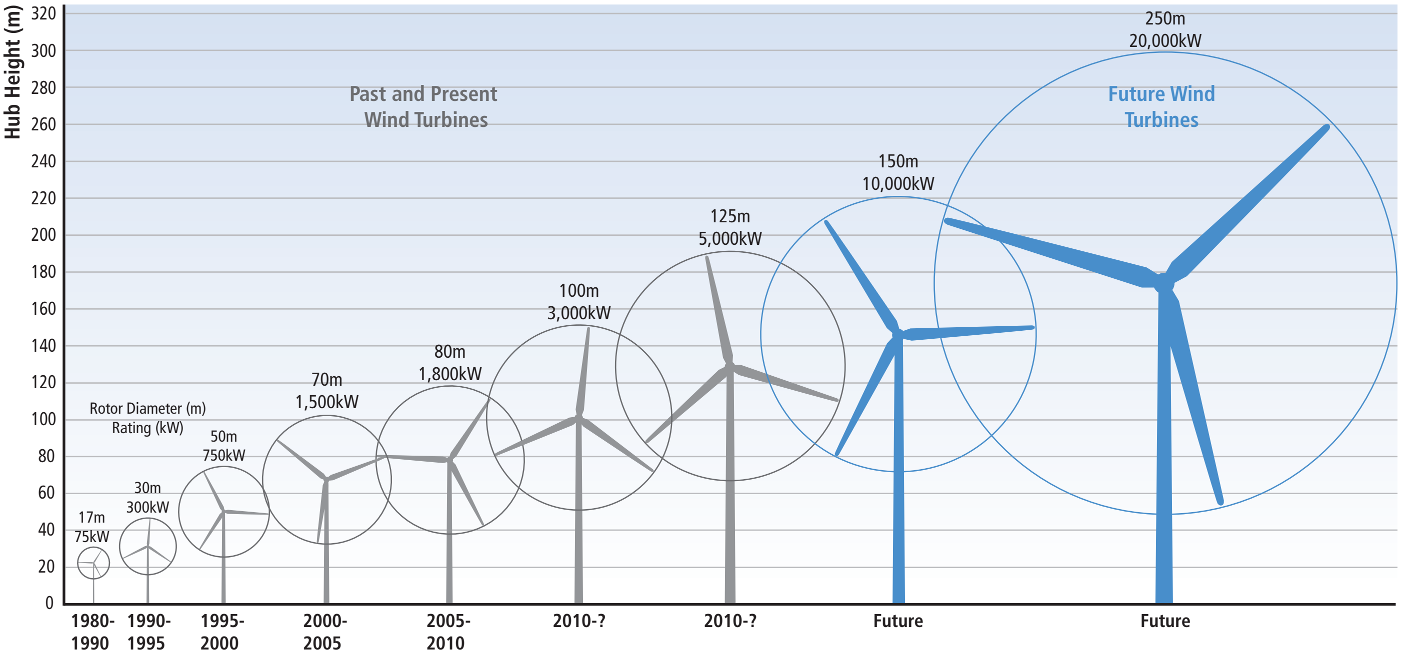

Figure TS.7.2 | Growth in size of typical commercial wind turbines. [Figure 7.6] with rotor diameters and tower heights in excess of 125 m are operating, and even larger machines are under development. Onshore wind energy technology is already being commercially manufactured and deployed at a large scale. [7.3.1]

Offshore wind energy technology is less mature than onshore, with higher investment costs. Lower power plant availabilities and higher O&M costs have also been common both because of the comparatively less mature state of the technology and because of the inherently greater logistical challenges of maintaining and servicing offshore turbines. Nonetheless, considerable interest in offshore wind energy exists in the EU and, increasingly, in other regions. The primary motivation to develop offshore wind energy is to provide access to additional wind resources in areas where onshore wind energy development is constrained by limited technical potential and/or by planning and siting conflicts with other land uses. Other motivations include the higher-quality wind resources located at sea; the ability to use even larger wind turbines and the potential to thereby gain additional economies of scale; the ability to build larger power plants than onshore, gaining plant-level economies of scale; and a potential reduction in the need for new, long-distance, land-based transmission infrastructure to access distant onshore wind energy. To date, offshore wind turbine technology has been very similar to onshore designs, with some modifications and with special foundations. As experience is gained, water depths are expected to increase and more exposed locations with higher winds will be utilized. Wind energy technology specifically tailored for offshore applications will become more prevalent as the offshore market expands, and it is expected that larger turbines in the 5 to 10 MW range may come to dominate this segment. [7.3.1.3]

Alongside the evolution of wind turbine design, improved design and testing methods have been codified in International Electrotechnical Commission standards. Certification agencies rely on accredited design and testing bodies to provide traceable documentation demonstrating conformity with the standards in order to certify that turbines, components or entire wind power plants meet common guidelines relating to safety, reliability, performance and testing. [7.3.2]

From an electric system reliability perspective, an important part of the wind turbine is the electrical conversion system. For modern turbines, variable-speed machines now dominate the market, allowing for the provision of real and reactive power as well as some fault ride-through capability, but no intrinsic inertial response (i.e., turbines do not increase or decrease power output in synchronism with system power imbalances); wind turbine manufacturers have recognized this latter limitation and are pursuing a variety of solutions. [7.3.3]

7.4 Global and regional status of market and industry development

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

Wind energy has quickly established itself as part of the mainstream electricity industry. From a cumulative capacity of 14 GW at the end of 1999, global installed capacity increased twelve-fold in 10 years to reach almost 160 GW by the end of 2009. The majority of the capacity has been installed onshore, with offshore installations primarily in Europe and totalling a cumulative 2.1 GW. The countries with the highest installed capacity by the end of 2009 were the USA (35 GW), China (26 GW), Germany (26 GW), Spain (19 GW) and India (11 GW). The total investment cost of new wind power plants installed in 2009 was USD$_{2005}$ 57 billion, while worldwide direct employment in the sector in 2009 has been estimated at approximately 500,000. [7.4.1, 7.4.2]

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

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

The deployment of wind energy must overcome a number of challenges, including: the relative cost of wind energy compared to energy market prices, at least if environmental impacts are not internalized and monetized; concerns about the impact of wind energy's variability; challenges of building new transmission; cumbersome and slow planning, siting and permitting procedures; the technical advancement needs and higher cost of offshore wind energy technology; and lack of institutional and technical knowledge in regions that have not yet experienced substantial wind energy deployment. As a result, growth is affected by a wide range of government policies. [7.4.4]

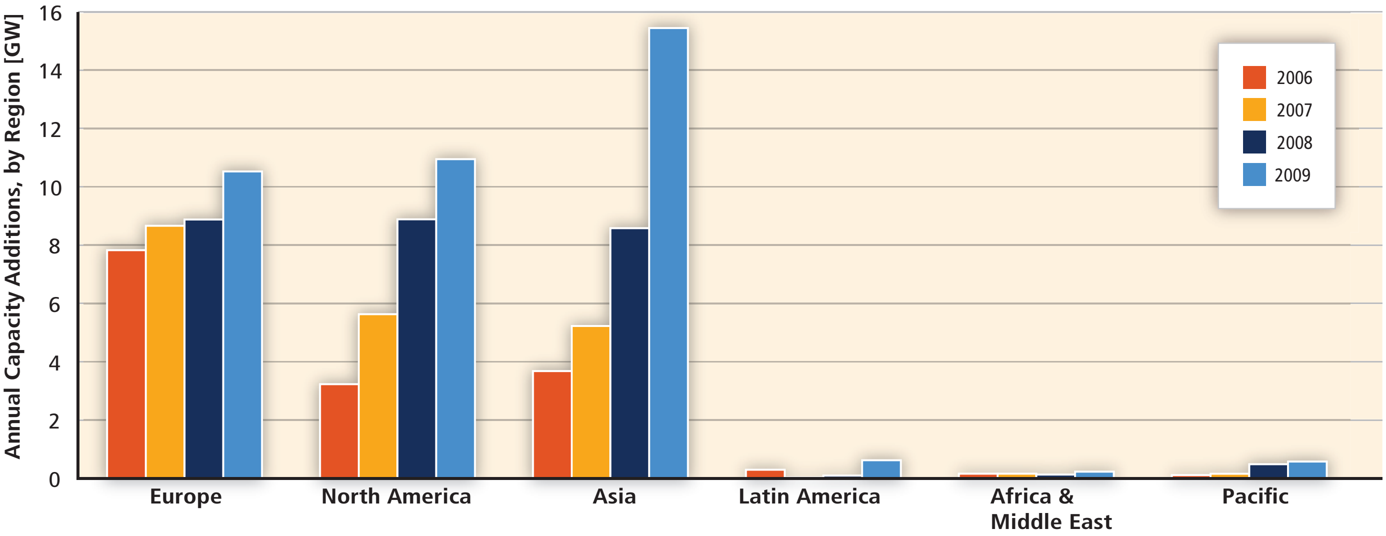

Figure TS.7.3 | Annual wind power capacity additions by region. [Figure 7.10]

Note: Regions shown in the figure are defined by the study.

7.5 Near-term grid integration issues

As wind energy deployment has increased, so have concerns about the integration of that energy into electric systems. The nature and magnitude of the integration challenge will depend on the characteristics of the existing electric system and the level of wind electricity penetration. Moreover, as discussed in Chapter 8, integration challenges are not unique to wind energy. Nevertheless, analysis and operating experience primarily from certain OECD countries suggests that, at low to medium levels of wind electricity penetration (defined here as up to 20% of total annual average electrical energy demand)[12], the integration of wind energy generally poses no insurmountable technical barriers and is economically manageable. At the same time, even at low to medium levels of wind electricity penetration, certain (and sometimes system-specific) technical and/or institutional challenges must be addressed. Concerns about (and the costs of) wind energy integration will grow with wind energy deployment, and even higher levels of penetration may depend on or benefit from the availability of additional technological and institutional options to increase flexibility and maintain a balance between supply and demand, as discussed further in Chapter 8 (Section 8.2). [7.5]

Wind energy has characteristics that present integration challenges, and that must be considered in electric system planning and operation to ensure the reliable and economical operation of the electric power system. These include: the localized nature of the wind resource with possible implications for new transmission for both on- and offshore wind energy; the variability of wind power output over multiple time scales; and the lower levels of predictability of wind power output than are common for many other types of power plants. The aggregate variability and uncertainty of wind power output depends, in part, on the degree of correlation between the output of different geographically dispersed wind power plants: generally, the outputs of wind power plants that are farther apart are less correlated with each other, and variability over shorter time periods (minutes) is less correlated than variability over longer time periods (multiple hours). Forecasts of wind power output are also more accurate over shorter time periods, and when multiple plants are considered together. [7.5.2]

Detailed system planning for new generation and transmission infrastructure is used to ensure that the electric system can be operated reliably and economically in the future. To do so, planners need computer-based simulation models that accurately characterize wind energy. Additionally, as wind power capacity has increased, so has the need for wind power plants to become more active participants in maintaining the operability and power quality of the electric system, and technical standards for grid connection have been implemented to help prevent wind power plants from adversely affecting the electric system during normal operation and contingencies. Transmission adequacy evaluations, meanwhile, must account for the location dependence of the wind resource, and consider any trade-offs between the costs of expanding the transmission system to access higher-quality wind resources in comparison to the costs of accessing lower-quality wind resources that require less transmission investment. Even at low to medium levels of wind electricity penetration, the addition of large quantities of on- or offshore wind energy in areas with higher-quality wind resources may require significant new additions or upgrades to the transmission system. Depending on the legal and regulatory framework in any particular region, the institutional challenges of transmission expansion can be substantial. Finally, planners need to account for wind

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[12] This level of penetration was chosen to loosely separate the integration needs for wind energy in the relatively near term from the broader, longer- term, and non-wind-specific discussion of power system changes provided in Chapter 8.

power output variability in assessing the contribution of wind energy to generation adequacy and therefore the long-term reliability of the electric system. Though methods and objectives vary from region to region, the contribution of wind energy to generation adequacy usually depends on the correlation of wind power output with the periods of time when there is a higher risk of a supply shortage, typically periods of high electricity demand. The marginal contribution of wind energy to generation adequacy typically declines as wind electricity penetration increases, but aggregating wind power plants over larger areas may slow this decline if adequate transmission capacity is available. The relatively low average contribution of wind energy to generation adequacy (compared to fossil units) suggests that electric systems with large amounts of wind energy will also tend to have significantly more total nameplate generation capacity to meet the same peak electricity demand than will electric systems without large amounts of wind energy. Some of this generation capacity will operate infrequently, however, and the mix of other generation will therefore tend (on economic grounds) to increasingly shift towards flexible 'peaking' and 'intermediate' resources and away from 'base-load' resources. [7.5.2]

The unique characteristics of wind energy also have important implications for electric system operations. Because wind energy is generated with a very low marginal operating cost, it is typically used to meet demand when it is available; other generators are then dispatched to meet demand minus any available wind energy (i.e., 'net demand'). As wind electricity penetration grows, the variability of wind energy results in an overall increase in the magnitude of changes in net demand, and also a decrease in the minimum net demand. As a result of these trends, wholesale electricity prices will tend to decline when wind power output is high and transmission interconnector capacity to other energy markets is constrained, and other generating units will be called upon to operate in a more flexible manner than required without wind energy. At low to medium levels of wind electricity penetration, the increase in minute-to-minute variability is expected to be relatively small. The more significant operational challenges relate to the need to manage changes in wind power output over one to six hours. Incorporating wind energy forecasts into electric system operations can reduce the need for flexibility from other generators, but even with high-quality forecasts, system operators will need a broad range of strategies to actively maintain the supply/demand balance, including the use of flexible power generation technologies, wind energy output curtailment, and increased coordination and interconnection between electric systems. Mass-market demand response, bulk energy storage technologies, large-scale deployment of electric vehicles and their associated contributions to system flexibility through controlled battery charging, diverting excess wind energy to fuel production or local heating, and geographic diversification of wind power plant siting will also become increasingly beneficial as wind electricity penetration rises. Despite the challenges, actual operating experience in different parts of the world demonstrates that electric systems can operate reliably with increased contributions of wind energy; in four countries (Denmark, Portugal, Spain, Ireland), wind energy in 2010 was already able to supply from 10 to roughly 20% of annual electricity demand. Experience is limited, in particular with regard to system faults at high instantaneous penetration levels, however, and as more wind energy is deployed in diverse regions and electric systems, additional knowledge about wind energy integration will be gained. [7.5.3]

In addition to actual operating experience, a number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed, primarily covering OECD countries. These studies employ a wide variety of methodologies and have diverse objectives, but the results demonstrate that the cost of integrating up to 20% wind energy into electric systems is, in most cases, modest but not insignificant. Specifically, at low to medium levels of wind electricity penetration, the available literature (again, primarily from a subset of OECD countries) suggests that the additional costs of managing electric system variability and uncertainty, ensuring generation adequacy, and adding new transmission to accommodate wind energy will be system specific but generally in the range of US cent$_{2005}$ 0.7/kWh to US cent$_{2005}$ 3/kWh. The technical challenges and costs of integration are found to increase with wind electricity penetration. [7.5.4]

7.6 Environmental and social impacts

Wind energy has significant potential to reduce (and is already reducing) GHG emissions. Moreover, attempts to measure the relative impacts of various electricity supply technologies suggest that wind energy generally has a comparatively small environmental footprint. [9.3.4, 10.6] As with other industrial activities, however, wind energy has the potential to produce some detrimental impacts on the environment and on human activities and well being, and many local and national governments have established planning and siting requirements to reduce those impacts. As wind energy deployment increases and as larger wind power plants are considered, existing concerns may become more acute and new concerns may arise. [7.6]

Although the major environmental benefits of wind energy result from displacing electricity generated from fossil fuel-based power plants, estimating those benefits is somewhat complicated by the operational characteristics of the electric system and the investment decisions that are made about new power plants. In the short run, increased wind energy will typically displace the operations of existing fossil fuel-fired plants. In the longer term, however, new generating plants may be needed, and the presence of wind energy can influence what types of power plants are built. The impacts arising from the manufacture, transport, installation, operation and decommissioning of wind turbines should also be considered, but a comprehensive review of available studies demonstrates that the energy used and GHG emissions produced during these steps are small compared to the energy generated and emissions avoided over the lifetime of wind power plants. The GHG emissions intensity of wind energy is estimated to range from 8 to 20 g CO_2/kWh in most instances, whereas energy payback times are between 3.4 and 8.5 months. In addition, managing the variability of wind power output has not been found to significantly degrade the GHG emissions benefits of wind energy. [7.6.1]

Other studies have considered the local ecological impacts of wind energy development. The construction and operation of both on- and offshore wind power plants impacts wildlife through bird and bat collisions and through habitat and ecosystem modifications, with the nature and magnitude of those impacts being site- and species-specific. For offshore wind energy, implications for benthic resources, fisheries and marine life more generally must be considered. Research is also underway on the potential impact of wind power plants on the local climate. Bird and bat fatalities through collisions with wind turbines are among the most publicized environmental concerns. Though much remains unknown about the nature and population-level implications of these impacts, avian fatality rates have been reported at between 0.95 and 11.67 per MW per year. Raptor fatalities, though much lower in absolute number, have raised special concerns in some cases, and as offshore wind energy has increased, concerns have also been raised about seabirds. Bat fatalities have not been researched as extensively, but fatality rates ranging from 0.2 to 53.3 per MW per year have been reported; the impact of wind power plants on bat populations is of particular contemporary concern. The magnitude and population-level consequences of bird and bat collision fatalities can also be viewed in the context of other fatalities caused by human activities. The number of bird fatalities at existing wind power plants appears to be orders of magnitude lower than other anthropogenic causes of bird deaths, it has been suggested that onshore wind power plants are not currently causing meaningful declines in bird population levels, and other energy supply options also impact birds and bats through collisions, habitat modifications and contributions to global climate change. Improved methods to assess species-specific population-level impacts and their possible mitigation are needed, as are robust comparisons between the impacts of wind energy and of other electricity supply options. [7.6.2]

Wind power plants can also impact habitats and ecosystems through avoidance of or displacement from an area, habitat destruction and reduced reproduction. Additionally, the impacts of wind power plants on marine life have moved into focus as offshore development has increased. The impacts of offshore wind energy on marine life vary between the installation, operation and decommissioning phases, depend greatly on site-specific conditions, and may be negative or positive. Potential negative impacts include underwater sounds and vibrations, electromagnetic fields, physical disruption and the establishment of invasive species. The physical structures may, however, create new breeding grounds or shelters and act as artificial reefs or fish aggregation devices. Additional research is warranted on these impacts and their long-term and population-level consequences, but they do not appear to be disproportionately large compared to onshore wind energy. [7.6.2]

Surveys have consistently found wind energy to be widely accepted by the general public. Translating this support into increased deployment, however, often requires the support of local host communities and/or decision makers. To that end, in addition to ecological concerns, a number of concerns are often raised about the impacts of wind power plants on local communities. Perhaps most importantly, modern wind energy technology involves large structures, so wind turbines are unavoidably visible in the landscape. Other impacts of concern include land and marine usage (including possible radar interference), proximal impacts such as noise and flicker, and property value impacts. Regardless of the type and degree of social and environmental concerns, addressing them is an essential part of any successful wind power planning and plant siting process, and engaging local residents is often an integral aspect of that process. Though some of the concerns can be readily mitigated, others—such as visual impacts—are more difficult to address. Efforts to better understand the nature and magnitude of the remaining impacts, together with efforts to minimize and mitigate those impacts, will need to be pursued in concert with increasing wind energy deployment. In practice, planning and siting regulations vary dramatically by jurisdiction, and planning and siting processes have been obstacles to wind energy development in some countries and contexts. [7.6.3]

7.7 Prospects for technology improvement and innovation

Over the past three decades, innovation in wind turbine design has led to significant cost reductions. Public and private R&D programmes have played a major role in these technical advances, leading to system- and component-level technology improvements, as well as improvements in resource assessment, technical standards, electric system integration, wind energy forecasting and other areas. From 1974 to 2006, government R&D budgets for wind energy in IEA countries totalled USD_{2005} 3.8 billion, representing 1% of total energy R&D expenditure. In 2008, OECD research funding for wind energy totalled USD_{2005} 180 million. [7.7, 7.7.1]

Though onshore wind energy technology is already commercially manufactured and deployed at a large scale, continued incremental advances are expected to yield improved turbine design procedures, more efficient materials usage, increased reliability and energy capture, reduced O&M costs and longer component lifetimes. In addition, as offshore wind energy gains more attention, new technology challenges arise and more radical technology innovations are possible. Wind power plants and turbines are complex systems that require integrated design approaches to optimize cost and performance. At the plant level, considerations include the selection of a wind turbine for a given wind resource regime; wind turbine siting, spacing and installation procedures; O&M methodologies; and electric system integration. Studies have identified a number of areas where technology advances could result in changes in the investment cost, annual energy production, reliability, O&M cost and electric system integration of wind energy. [7.3.1, 7.7.1, 7.7.2]

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

In addition, there are several areas of possible advancement that are more specific to offshore wind energy, including O&M procedures, installation and assembly schemes, support structure design, and the development of larger turbines, possibly including new turbine concepts. Foundation structure innovation, in particular, offers the potential to access deeper waters, thereby increasing the technical potential of wind energy. Offshore turbines have historically been installed primarily in relatively shallow water, up to 30 m deep, on a mono-pile structure that is essentially an extension of the tower, but gravity-based structures have become more common. These approaches, as well as other concepts that are more appropriate for deeper waters, including floating platforms, are depicted in Figure TS.7.4. Additionally, offshore turbine size is not restricted in the same way as onshore wind turbines, and the relatively higher cost of offshore foundations provides motivation for larger turbines. [7.7.3]

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

7.8 Cost trends

Though the cost of wind energy has declined significantly since the 1980s, policy measures are currently required to ensure rapid deployment in most regions of the world. In some areas with good wind resources, however, the cost of wind energy is competitive with current energy market prices, even without considering relative environmental impacts. Moreover, continued technology advancements are expected, supporting further cost reduction. [7.8]

The levelized cost of energy from on- and offshore wind power plants is affected by five primary factors: annual energy production; investment costs; O&M costs; financing costs; and the assumed economic life of

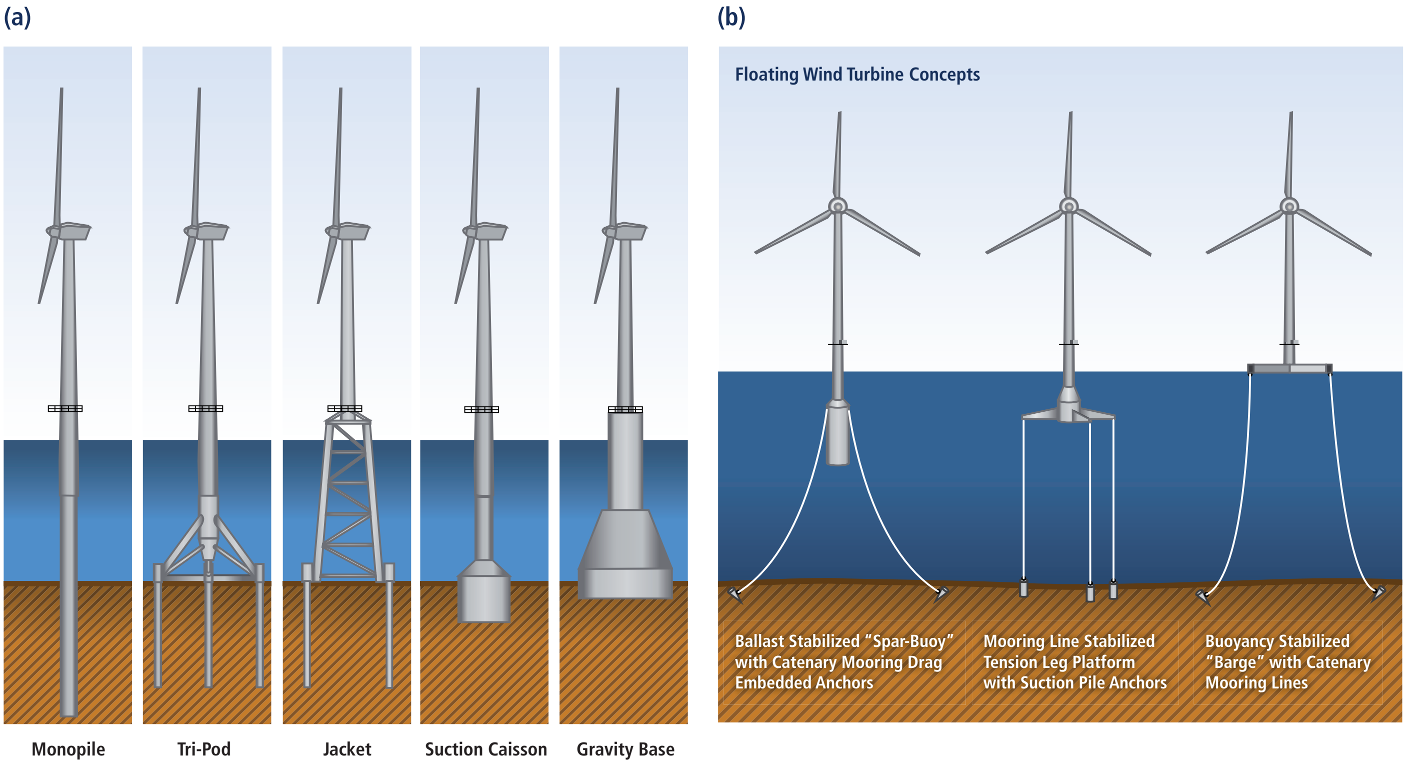

Figure TS.7.4 | Offshore wind turbine foundation designs: (a) near-term concepts and (b) floating offshore turbine concepts. [Figure 7.19] the power plant.[13] From the 1980s to roughly 2004, the investment cost of onshore wind power plants dropped. From 2004 to 2009, however, investment costs increased, the primary drivers of which were: escalation in the cost of labour and materials inputs; increasing profit margins among turbine manufacturers and their suppliers; the relative strength of the Euro currency; and the increased size of turbine rotors and hub heights. In 2009, the average investment cost for onshore wind power plants installed worldwide was approximately USD_{2005} 1,750/kW, with many plants falling in the range of USD_{2005} 1,400 to 2,100/kW; investment costs in China in 2008 and 2009 were around USD_{2005} 1,000 to 1,350/kW. There is far less experience with offshore wind power plants, and the investment costs of offshore plants are highly site-specific. Nonetheless, the investment costs of offshore plants have historically been 50 to more than 100% higher than for onshore plants; O&M costs are also greater for offshore plants. Offshore costs have also been influenced by some of the same factors that caused rising onshore costs from 2004 through 2009, as well as by several unique factors. The most recently installed or announced offshore plants have investment costs that are reported to range from roughly USD_{2005} 3,200/kW to USD_{2005} 5,000/kW. Notwithstanding the increased water depth of offshore plants over time, the majority of the operating plants have been built in relatively shallow water. The performance of wind power plants is highly site-specific, and is primarily governed by the characteristics of the local wind regime, but is also impacted by wind turbine design optimization, performance and availability, and by the effectiveness of O&M procedures. Performance therefore varies by location, but has also generally improved with time. Offshore wind power plants are often exposed to better wind resources. [7.8.1–7.8.3]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for on- and offshore wind power plants over a large set and range of input parameters has been calculated to range from US $cent_{2005}$ 3.5/kWh to US $cent_{2005}$ 17/kWh and from US $cent_{2005}$ 7.5/kWh to US $cent_{2005}$ 23/kWh, respectively. [1.3.2, 10.5.1, Annex II, Annex III]

Figure TS.7.5 presents the LCOE of on- and offshore wind energy over a somewhat different set and range of parameters, and shows that the LCOE varies substantially depending on assumed investment costs, energy production and discount rates. For onshore wind energy, estimates are provided for plants built in 2009; for offshore wind energy, estimates are provided for plants built from 2008 to 2009 as well as those plants that were planned for completion in the early 2010s. The LCOE for onshore wind energy in good to excellent wind resource regimes are estimated to average approximately US $cent_{2005}$ 5/kWh to US $cent_{2005}$ 10/kWh, and can reach more than US $cent_{2005}$ 15/kWh in lower-resource areas. Though

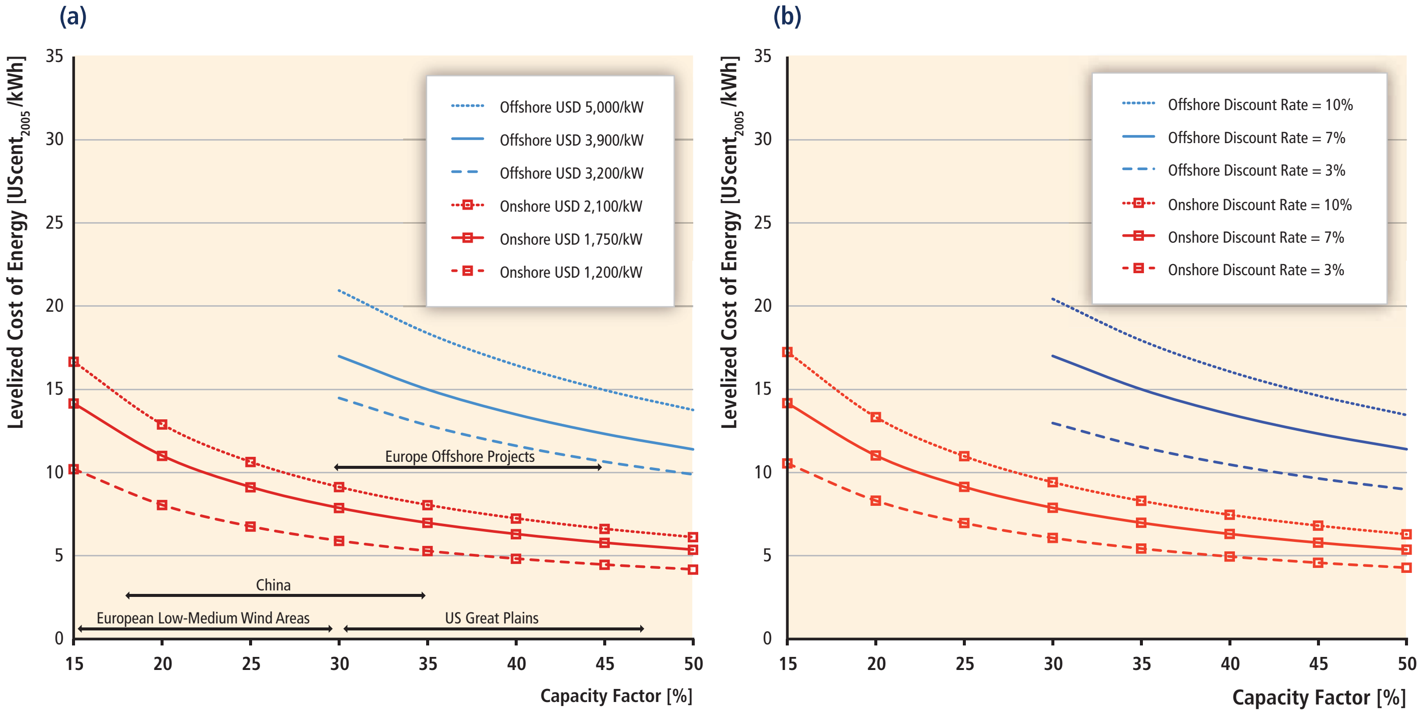

Figure TS.7.5 | Estimated levelized cost of on- and offshore wind energy, 2009: (a) as a function of capacity factor and investment cost* and (b) as a function of capacity factor and discount rate**. [Figure 7.23]

Notes: * Discount rate assumed to equal 7%. ** Onshore investment cost assumed at USD_{2005} 1,750/kW, and offshore at USD_{2005} 3,900/kW.

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[13] The economic competitiveness of wind energy in comparison to other energy sources, which necessarily must also include other factors such as subsidies and environmental externalities, is not covered in this section.

the offshore cost estimates are more uncertain, typical LCOE are estimated to range from US cent_{2005} 10/kWh to more than US cent_{2005} 20/kWh for recently built or planned plants located in relatively shallow water. Where the exploitable onshore wind resource is limited, offshore plants can sometimes compete with onshore plants. [7.8.3, Annex II, Annex III]

A number of studies have developed forecasted cost trajectories for on- and offshore wind energy based on differing combinations of learning curve estimates, engineering models and/or expert judgement. Among these studies, the starting year of the forecasts, the methodological approaches and the assumed wind energy deployment levels vary. Nonetheless, a review of this literature supports the idea that continued R&D, testing and experience could yield reductions in the levelized cost of onshore wind energy of 10 to 30% by 2020. Offshore wind energy is anticipated to experience somewhat deeper cost reductions of 10 to 40% by 2020, though some studies have identified scenarios in which market factors lead to cost increases in the near to medium term. [7.8.4]

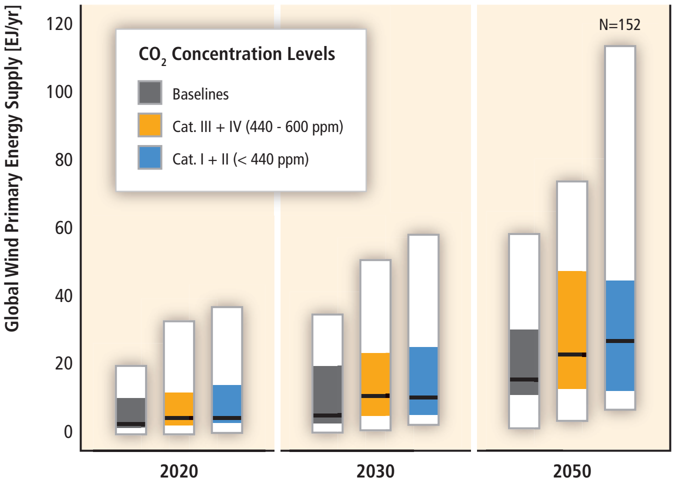

Figure TS.7.6 | Global primary energy supply of wind energy in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner). [Figure 7.24]

7.9 Potential deployment

Given the commercial maturity and cost of onshore wind energy technology, increased utilization of wind energy offers the potential for significant near-term GHG emission reductions: this potential is not conditioned on technology breakthroughs, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. As a result, in the near to medium term, the rapid increase in wind power capacity from 2000 to 2009 is expected by many studies to continue. [7.9, 7.9.1]

Moreover, a number of studies have assessed the longer-term potential of wind energy, often in the context of GHG concentration stabilization scenarios. [10.2, 10.3] Based on a review of this literature (including 164 different long-term scenarios), and as summarized in Figure TS.7.6, wind energy could play a significant long-term role in reducing global GHG emissions. By 2050, the median contribution of wind energy among the scenarios with GHG concentration stabilization ranges of 440 to 600 ppm CO_2 and <440 ppm CO_2 is 23 to 27 EJ/yr (6,500 to 7,600 TWh/yr), increasing to 45 to 47 EJ/yr at the 75th percentile of scenarios (12,400 to 12,900 TWh/yr), and to more than 100 EJ/yr in the highest study (31,500 TWh). Achieving this contribution would require wind energy to deliver around 13 to 14% of global electricity supply in the median scenario result by 2050, increasing to 21 to 25% at the 75th percentile of the reviewed scenarios. [7.9.2]

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

8. Integration of Renewable Energy into Present and Future Energy Systems

8.1 Introduction

In many countries, energy supply systems have evolved over decades, enabling the efficient and cost-effective distribution of electricity, gas, heat and transport energy carriers to provide useful energy services to end users. The transition to a low-carbon future that employs high shares of RE may require considerable investment in new RE technologies and infrastructure, including more flexible electricity grids, expansion of district heating and cooling schemes, distribution systems for RE-derived gases and liquid fuels, energy storage systems, novel methods of transport, and innovative distributed energy and control systems in buildings. Enhanced RE integration can lead to the provision of the full range of energy services for large and small communities in both developed and developing countries. Regardless of the energy supply system presently in place, whether in energy-rich or energy-poor communities, over the long term, and through measured system planning and integration, there are few, if any, technical limits to increasing the shares of RE at the national, regional and local scales as well as for individual buildings, although other barriers may need to be overcome. [8.1, 8.2]

Energy supply systems are continuously evolving, with the aim of increasing conversion technology efficiencies, reducing losses and lowering the costs of providing energy services to end users. To provide a greater share of RE heating, cooling, transport fuels and electricity may require modification of current policies, markets and existing energy supply systems over time so that they can accommodate higher rates of deployment leading to greater supplies of RE. [8.1]

All countries have access to some RE resources and in many parts of the world these are abundant. The characteristics of many of these resources distinguish them from fossil fuels and nuclear systems. Some resources, such as solar and ocean energy, are widely distributed, whereas others, such as large-scale hydropower, are constrained by geographic location and hence integration options are more centralized. Some RE resources are variable and have limited predictability. Others have lower energy densities and their technical specifications differ from solid, liquid and gaseous fossil fuels. Such RE resource characteristics can constrain the ease of integration and invoke additional system costs, particularly when reaching higher shares of RE. [8.1, 8.2]

Following the structural outline of Chapter 8, RE resources can be used through integration into energy supply networks delivering energy to consumers using energy carriers with varying shares of RE embedded or by direct integration into the transport, buildings, industry and agriculture end-use sectors (Figure TS.8.1). [8.2, 8.3]

The general and specific requirements for enhanced integration of RE into energy supply systems are reasonably well understood. However, since integration issues tend to be site-specific, analyses of typical additional costs for RE integration options are limited and future research is required for use in scenario modelling. For example, it is not clear how the possible trend towards more decentralized energy supply systems might affect the future costs for developing further centralized heat and power supplies and the possible avoidance of constructing new infrastructure. [8.2]

Centralized energy systems, based mainly on fossil fuels, have evolved to provide reasonably cost-effective energy services to end users using

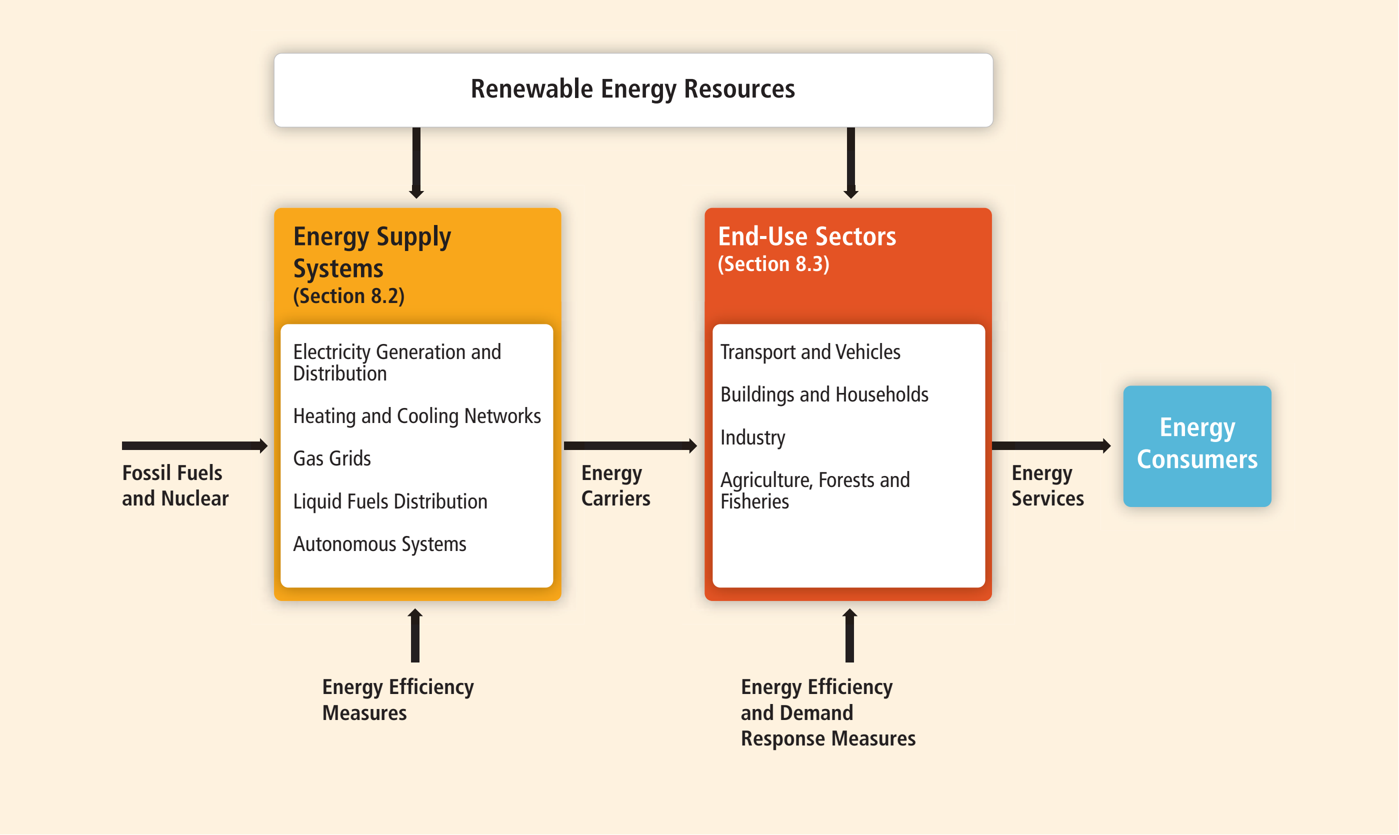

Figure TS.8.1 | Pathways for RE integration to provide energy services, either into energy supply systems or on-site for use by the end-use sectors. [Figure 8.1] a range of energy carriers including solid, liquid and gaseous fuels, electricity, and heat. Increasing the deployment of RE technologies requires their integration into these existing systems by overcoming the associated technical, economic, environmental and social barriers. The advent of decentralized energy systems could open up new deployment opportunities. [8.1, 8.2]

In some regions, RE electricity systems could become the dominant future energy supply, especially if heating and transport demands are also to be met by electricity. This could be driven by parallel developments in electric vehicles, increased heating and cooling using electricity (including heat pumps), flexible demand response services (including the use of smart meters), and other innovative technologies. [8.1, 8.2.1.2, 8.2.2, 8.3.1–8.3.3]

The various energy systems differ markedly between countries and regions around the world and each is complex. As a result, a range of approaches are needed to encourage RE integration, whether centralized or decentralized. Prior to making any significant change in an energy supply system that involves increasing the integration of RE, a careful assessment of the RE resource availability; the suitability of existing technologies; institutional, economic and social constraints; the potential risks; and the need for related capacity building and skills development should be undertaken. [8.1, 8.2]

The majority of scenarios that stabilize atmospheric GHG concentrations around 450 ppm CO_2eq show that RE will exceed a 50% share of low-carbon primary energy by 2050. This transition can be illustrated by many scenarios, the single example of increasing market shares shown in Figure TS.8.2 being based on the IEA's World Energy Outlook 2010 '450 Policy Scenario'. To achieve such increased shares of primary and consumer energy from RE by 2035 would require the annual average incremental growth in primary RE to more than treble from today's level to around 4.0 EJ/yr. [8.1, 10.2, 10.2.2.4]

In order to gain greater RE deployment in each of the transport, building, industry and agriculture sectors, strategic elements need to be better understood, as do the social issues. Transition pathways for increasing the shares of each RE technology through integration depend on the specific sector, technology and region. Facilitating a smoother integration with energy supply systems and providing multiple benefits for energy end users should be the ultimate aims. [8.2, 8.3]

Several mature RE technologies have already been successfully integrated into a wide range of energy supply systems, mostly at relatively low shares but with some examples (including small- and large-scale hydropower, wind power, geothermal heat and power, first-generation biofuels and solar water heating systems) exceeding 30%. This was due mainly to their improved cost-competitiveness, an increase in support policies and growing public support due to the threats of an insecure energy supply and climate change. Exceptional examples are large-scale hydropower in Norway and hydro and geothermal power in Iceland approaching 100% of RE electricity, as has also been achieved by several small islands and towns. [8.2.1.3, 8.2.5.5, 11.2, 11.5]

Other less mature technologies require continuing investment in research, development, and demonstration (RD&D), infrastructure, capacity building and other supporting measures over the longer term. Such technologies include advanced biofuels, fuel cells, solar fuels, distributed power generation control systems, electric vehicles, solar absorption cooling and enhanced geothermal systems. [11.5, 11.6]

The current status of RE use varies for each end-use sector. There are also major regional variations in future pathways to enhance further integration by removal of barriers. For example, in the building sector, integrating RE technologies is vastly different for commercial high-rise buildings and apartments in mega-cities than for integration into small, modest village dwellings in developing countries that currently have limited access to energy services. [8.3.2]

Most energy supply systems can accommodate a greater share of RE than at present, particularly if the RE share is at relatively low levels (usually assumed to be below a 20% share of electricity, heat, pipeline gas blend or biofuel blend). To accommodate higher RE shares in the future, most energy supply systems will need to evolve and be adapted. In all cases, the maximum practical RE share will depend on the technologies involved, the RE resources available and the type and age of the present energy system. Further integration and increased rates of deployment can be encouraged by local, national and regional initiatives. The overall aim of Chapter 8 is to present the current knowledge on opportunities and challenges relating to RE integration for governments wishing to develop a coherent framework in preparation for future higher levels of RE penetration. Existing power supply systems, natural gas grids, heating/cooling schemes, petroleum-based transport fuel supply distribution networks and vehicles can all be adapted to accommodate greater supplies of RE than at present. RE technologies range from mature to those at the early concept demonstration stage. New technologies could enable increased RE uptake and their integration will depend upon improved cost-effectiveness, social acceptance, reliability and political support at national and local government levels in order to gain greater market shares. [8.1.2, 11.5]

Taking a holistic approach to the whole energy system may be a prerequisite to ensure efficient and flexible RE integration. This would include achieving mutual support between the different energy sectors, an intelligent forecasting and control strategy and coherent long-term planning. Together, these would enable the provision of electricity, heating, cooling and mobility to be more closely inter-linked. The optimum combination of technologies and social mechanisms to enable RE integration to reach high shares varies with the limitations of specific site conditions, characteristics of the available RE resources, and local energy demands. Exactly how present energy supply and demand systems can be adapted and developed to accommodate higher shares of RE, and the additional costs involved for their integration, depend on the specific circumstances, so

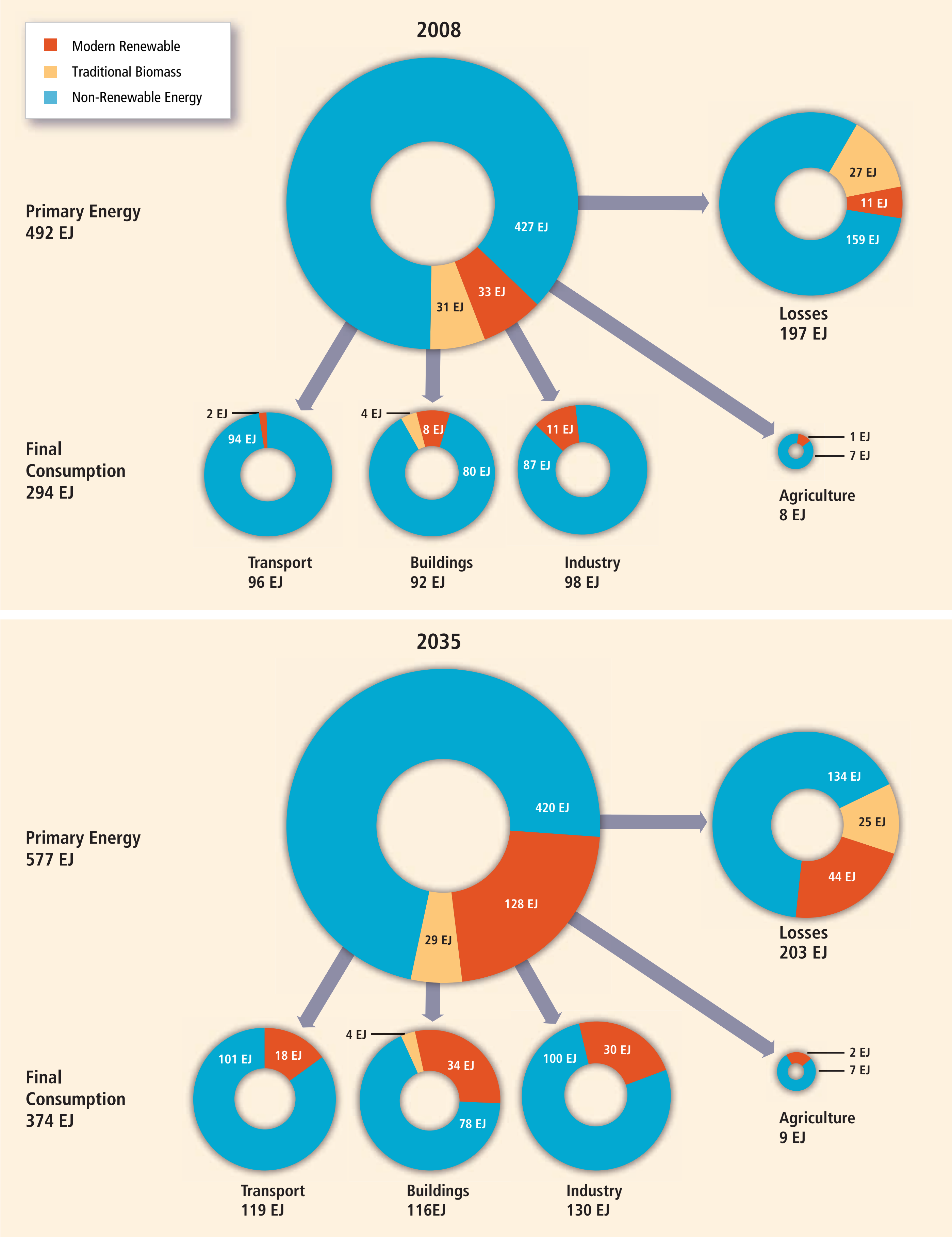
Modern Renewable
Traditional Biomass
Non-Renewable Energy
2008
Primary Energy
492 EJ
427 EJ
31 EJ
33 EJ
27 EJ
11 EJ
159 EJ
Losses
197 EJ
Final
Consumption
294 EJ
2 EJ
94 EJ
4 EJ
8 EJ
80 EJ
11 EJ
87 EJ
1 EJ
7 EJ
Agriculture
8 EJ
Transport
96 EJ
Buildings
92 EJ
Industry
98 EJ
2035
Primary Energy
577 EJ
420 EJ
128 EJ
29 EJ
134 EJ
25 EJ
44 EJ
Losses
203 EJ
Final
Consumption
374 EJ
101 EJ
18 EJ
4 EJ
34 EJ
78 EJ
100 EJ
30 EJ
2 EJ
7 EJ
Agriculture
9 EJ
Transport
119 EJ
Buildings
116EJ
Industry
130 EJ

Figure TS.8.2 | (Preceding page) RE shares (red) of primary and final consumption energy in the transport, buildings (including traditional biomass), industry and agriculture sectors in 2008 and an indication of the projected increased RE shares needed by 2035 in order to be consistent with a 450 ppm CO_2eq stabilization level. [Figure 8.2]

Notes: Area of circles are approximately to scale. Energy system losses occur during the conversion, refining and distribution of primary energy sources to produce energy services for final consumption. 'Non-renewable' energy (blue) includes coal, oil, natural gas (with and without CCS by 2035) and nuclear power. This scenario example is based on data taken from the IEA World Energy Outlook 2010 but converted to direct equivalents. [Annex II.4] Energy efficiency improvements above the baseline are included in the 2035 projection. RE in the buildings sector includes traditional solid biomass fuels (yellow) for cooking and heating for 2.7 billion people in developing countries [2.2] along with some coal. By 2035, some traditional biomass has been partly replaced by modern bioenergy conversion systems. Excluding traditional biomass, the overall RE system efficiency (when converting from primary to consumer energy) remains around 66%.

further studies will be required. This is particularly the case for the electricity sector due to the wide variety of existing power generation systems and scales that vary with country and region. [8.2.1, 8.2.2, 8.3]

8.2 Integration of renewable energy into electrical power systems

Electrical power systems have been evolving since the end of the 19th century. Today, electrical power systems vary in scale and technological sophistication from the synchronized Eastern Interconnection in North America to small individual diesel-powered autonomous systems, with some systems, as in China, undergoing rapid expansion and transformation. Within these differences, however, electrical power systems are operated and planned with a common purpose of providing a reliable and cost-effective supply of electricity. Looking forward, electric power systems are expected to continue to expand in importance given that they supply modern energy, enable the transport of energy over long distances, and provide a potential pathway for delivering low-carbon energy. [8.2.1]

Electric power systems have several important characteristics that affect the challenges of integrating RE. The majority of electric power systems operate using alternating current (AC) whereby the majority of generation is synchronized and operated at a frequency of approximately either 50 or 60 Hz, depending on the region. The demand for electricity varies throughout the day, week and season, depending on the needs of electricity users. The aggregate variation in demand is matched by variation in schedules and dispatch instructions for generation in order to continuously maintain a balance between supply and demand. Generators and other power system assets are used to provide active power control to maintain the system frequency and reactive power control to maintain voltage within specified limits. Minute-to-minute variations in supply and demand are managed with automatic control of generation through services called regulation and load following, while changes over longer time scales of hours to days are managed by dispatching and scheduling generation (including turning generation on or off, which is also known as unit commitment). This continuous balancing is required irrespective of the mechanism used to achieve it. Some regions choose organized electricity markets in order to determine which generation units should be committed and/or how they should be dispatched. Even autonomous systems must employ methods to maintain a balance between generation and demand (via controllable generators, controllable loads, or storage resources like batteries). [8.2.1.1]

In addition to maintaining a balance between supply and demand, electric power systems must also transfer electricity between generation and demand through transmission and distribution networks with limited capacity. Ensuring availability of adequate generation and network capacity requires planning over multiple years. Planning electrical power systems incorporates the knowledge that individual components of the system, including generation and network components, will periodically fail (a contingency). A target degree of reliability can be met, however, by building adequate resources. One important metric used to determine the contribution of generation—fossil-fuel based or renewable—to meeting demand with a target level of reliability is called the capacity credit. [8.2.1.1]

Based on the features of electrical power systems, several RE characteristics are important for integrating RE into power systems. In particular, variability and predictability (or uncertainty) of RE is relevant for scheduling and dispatch in the electrical power system, the location of RE resources is a relevant indicator for impact on needs for electrical networks, and capacity factor, capacity credit and power plant characteristics are indicators relevant for comparison, for example, with thermal generation. [8.2.1.2]

Some RE electricity resources (particularly ocean, solar PV, wind) are variable and only partially dispatchable: generation from these resources can be reduced if needed, but maximum generation depends on availability of the RE resource (e.g., tidal currents, sun or wind). The capacity credit can be low if the generation is not well correlated with times of high demand. In addition, the variability and partial predictability of some RE increases the burden on dispatchable generation or other resources to ensure balance between supply and demand given deviations in RE. In many cases variability and partial predictability are somewhat mitigated by geographic diversity—changes and forecast errors will not always occur at the same time in the same direction. A general challenge for most RE, however, is that renewable resources are location specific, therefore concentrated renewably generated electricity may need to be transported over considerable distances and require network expansion. Dispatchable renewable sources (including hydropower, bioenergy, geothermal energy, and CSP with thermal storage) can in many cases offer extra flexibility for the system to integrate other renewable sources and often have a higher capacity credit. [8.2.1.2]

A very brief summary of the particular characteristics for a selection of the technologies is given in Table TS.8.1. [8.2.1.3]

Table TS.8.1 | Summary of integration characteristics for a selection of RE technologies. [Table 8.1]

Technology		Plant size range (MW)	Variability: Characteristic time scales for power system operation (Time scale)	Dispatchability (See legend)	Geographical diversity potential (See legend)	Predictability (See legend)	Capacity factor range %	Capacity credit range %	Active power, frequency control (See legend)	Voltage, reactive power control (See legend)
Bioenergy		0.1–100	Seasons (depending on biomass availability)	+++	+	++	50–90	Similar to thermal and CHP	++	++
Direct solar energy	PV	0.004–100 modular	Minutes to years	+	++	+	12–27	<25–75	+	+
	CSP with thermal storage[1]	50–250	Hours to years	++	+[2]	++	35–42	90	++	++
Geothermal energy		2–100	Years	+++	N/A	++	60–90	Similar to thermal	++	++
Hydro power	Run of river	0.1–1,500	Hours to years	++	+	++	20–95	0–90	++	++
	Reservoir	1–20,000	Days to years	+++	+	++	30–60	Similar to thermal	++	++
Ocean Energy	Tidal range	0.1–300	Hours to days	+	+	++	22.5–28.5	<10%	++	++
	Tidal current	1–200	Hours to days	+	+	++	19–60	10–20	+	++
	Wave	1–200	Minutes to years	+	++	+	22–31	16	+	+
Wind energy		5–300	Minutes to years	+	++	+	20–40 onshore, 30–45 offshore	5–40	+	++

Notes: 1. Assuming a CSP system with six hours of thermal storage in US Southwest. 2. In areas with direct-normal irradiance (DNI) >2,000 kWh/m^2/yr (7,200 MJ/m^2/yr).

Plant size: range of typical rated plant capacity.

Characteristic time scales: time scales where variability significant for power system integration occurs.

Dispatchability: degree of plant dispatchability: + low partial dispatchability, ++ partial dispatchability, +++ dispatchable.

Geographical diversity potential: degree to which siting of the technology may mitigate variability and improve predictability, without substantial need for additional network: +moderate potential, ++ high diversity potential.

Predictability: Accuracy to which plant output power can be predicted at relevant time scales to assist power system operation: + moderate prediction accuracy (typical <10% Root Mean Square (RMS) error of rated power day ahead), ++ high prediction accuracy.

Active power and frequency control: technology possibilities enabling plant to participate in active power control and frequency response during normal situations (steady state, dynamic) and during network fault situations (for example active power support during fault ride-through): + good possibilities, ++ full control possibilities.

Voltage and reactive power control: technology possibilities enabling plant to participate in voltage and reactive power control during normal situations (steady state, dynamic) and during network fault situations (for example reactive power support during fault ride-through): + good possibilities, ++ full control possibilities.

There is already significant experience with operating electrical power systems with a large share of renewable sources, in particular hydropower and geothermal power. Hydropower storage and strong interconnections help manage fluctuations in river flows. Balancing costs for variable generation are incurred when there are differences between the scheduled generation (according to forecasts) and the actual production. Variability and uncertainty increase balancing requirements. Overall, balancing is expected to become more difficult to achieve as partially dispatchable RE penetrations increase. Studies show clearly that combining different variable renewable sources, and resources from larger geographical areas, will be beneficial in smoothing the variability and decreasing overall uncertainty for the power systems. [8.2.1.3]

The key issue is the importance of *network infrastructure,* both to deliver power from the generation plant to the consumer as well as to enable larger regions to be balanced. Strengthening connections within an electrical power system and introducing additional interconnections to other systems can directly mitigate the impact of variable and uncertain RE sources. Network expansion is required for most RE, although the level is dependent on the resource and location relative to existing network infrastructure. Amongst other challenges will be expanding network infrastructure within the context of public opposition to overhead network infrastructure. In general, major changes will be required in the generation plant mix, the electrical power systems' infrastructure and operational procedures to make the transition to increased renewable generation while maintaining cost and environmental effectiveness. These changes will require major investments far enough in advance to maintain a reliable and secure electricity supply. [8.2.1.3]

In addition to improving network infrastructure, several other important integration options have been identified through operating experience or studies:

Increased generation flexibility: An increasing penetration of variable renewable sources implies a greater need to manage variability and uncertainty. Greater flexibility is required from the generation mix. Generation provides most of a power system's existing flexibility to cope with variability and uncertainty through ramping up or down and cycling as needed. Greater need for flexibility can imply either investment in new flexible generation or improvements to existing power plants to enable them to operate in a more flexible manner. [8.2.1.3]

Demand side measures: Although demand side measures have historically been implemented only to reduce average demand or demand during peak load periods, demand side measures may potentially contribute to meeting needs resulting from increased variable renewable generation. The development of advanced communications technology, with smart electricity meters linked to control centres, offers the potential to access much greater levels of flexibility from demand. Electricity users can be provided with incentives to modify and/or reduce their consumption by pricing electricity differently at different times, in particular with higher prices during higher demand periods. This reduction in demand during high demand periods can mitigate the impact of the low capacity credit of some types of variable generation. Furthermore, demand that can quickly be curtailed without notice during any time of the year can provide reserves rather than requiring generation resources to provide this reserve. Demand that can be scheduled to be met at anytime of the day or that responds to real-time electricity prices can participate in intra-day balancing thereby mitigating operational challenges that are expected to become increasingly difficult with variable generation. [8.2.1.3]

Electrical energy storage: By storing electrical energy when renewable output is high and the demand low, and generating when renewable output is low and the demand high, the curtailment of RE can be reduced, and the base-load units on the system will operate more efficiently. Storage can also reduce transmission congestion and may reduce the need for, or delay, transmission upgrades. Technologies such as batteries or flywheels that store smaller amounts of energy (minutes to hours) can in theory be used to provide power in the intra-hour timeframe to regulate the balance between supply and demand. [8.2.1.3]

Improved operational/market and planning methods: To help cope with the variability and uncertainty associated with variable generation sources, forecasts of their output can be combined with improved operational methods to determine both the required reserve to maintain the demand-generation balance, and also optimal generation scheduling. Making scheduling decisions closer to real time (i.e., shorter gate closure time in markets) and more frequently allows newer, more accurate information to be used in dispatching generating units. Moving to larger balancing areas, or shared balancing between areas, is also desirable with large amounts of variable generation, due to the aggregation benefits of multiple, dispersed renewable sources. [8.2.1.3]

In summary, RE can be integrated into all types of electrical power systems from large interconnected continental-scale systems to small autonomous systems. System characteristics including the network infrastructure, demand pattern and its geographic location, generation mix, control and communication capability combined with the location, geographical footprint, variability and predictability of the renewable resources determine the scale of the integration challenge. As the amounts of RE resources increase, additional electricity network infrastructure (transmission and/or distribution) will generally have to be constructed. Variable renewable sources, such as wind, can be more difficult to integrate than dispatchable renewable sources, such as bioenergy, and with increasing levels maintaining reliability becomes more challenging and costly. These challenges and costs can be minimized by deploying a portfolio of options including electrical network interconnection, the development of complementary flexible generation, larger balancing areas, sub-hourly markets, demand that can respond in relation to supply availability, storage technologies, and better forecasting, system operating and planning tools.

8.3 Integration of renewable energy into heating and cooling networks

A district heating (DH) or district cooling (DC) network allows multiple energy sources (Figure TS.8.3) to be connected to many energy consumers by pumping the energy carriers (hot or cold water and sometimes steam) through insulated underground pipelines. Centralized heat production can facilitate the use of low-cost and/or low-grade RE heat from geothermal or solar thermal sources or combustion of biomass (including refuse-derived fuels and waste by-products that are often unsuitable for use by individual heating systems). Waste heat from CHP generation and industrial processes can also be used. This flexibility produces competition among various heat sources, fuels and technologies. Centralized heat production can also facilitate the application of cost-effective measures that reduce local air pollution compared with having a multitude of small individual boilers. Being flexible in the sources of heat or cold utilized, district heating and cooling systems allow for the continuing uptake of several types of RE so that a gradual or rapid substitution of competing fossil fuels is usually feasible. [8.2.2]

Occupiers of buildings and industries connected to a network can benefit from a professionally managed central system, hence avoiding the need to operate and maintain individual heating/cooling equipment. Several high-latitude countries already have a district heating market penetration of 30 to 50%, with Iceland reaching 96% using its geothermal resources. World annual delivery of district heat has been estimated to be around 11 EJ though heat data are uncertain. [8.2.2.1]

DH schemes can provide electricity through CHP system designs and can also provide demand response options that can facilitate increased integration of RE, including by using RE electricity for heat pumps and electric boilers. Thermal storage systems can bridge the heat supply/demand gap resulting from variable, discontinuous or non-synchronized heating systems. For short-term storage (hours and days), the thermal capacity of the distribution network itself can be used. Thermal storage systems with storage periods up to several months at temperatures up to hundreds of degrees Celsius use a variety of materials and corresponding storage mechanisms that can have capacities up to several TJ. Combined production of heat, cold and electricity (tri-generation), as well as the possibility for diurnal and seasonal storage of heat and cold, mean that high overall system efficiency can be obtained and higher shares of RE achieved through increased integration. [8.2.2.2, 8.2.2.3]

Many commercial geothermal and biomass heat and CHP plants have been successfully integrated into DH systems without government support. Several large-scale solar thermal systems with collector areas

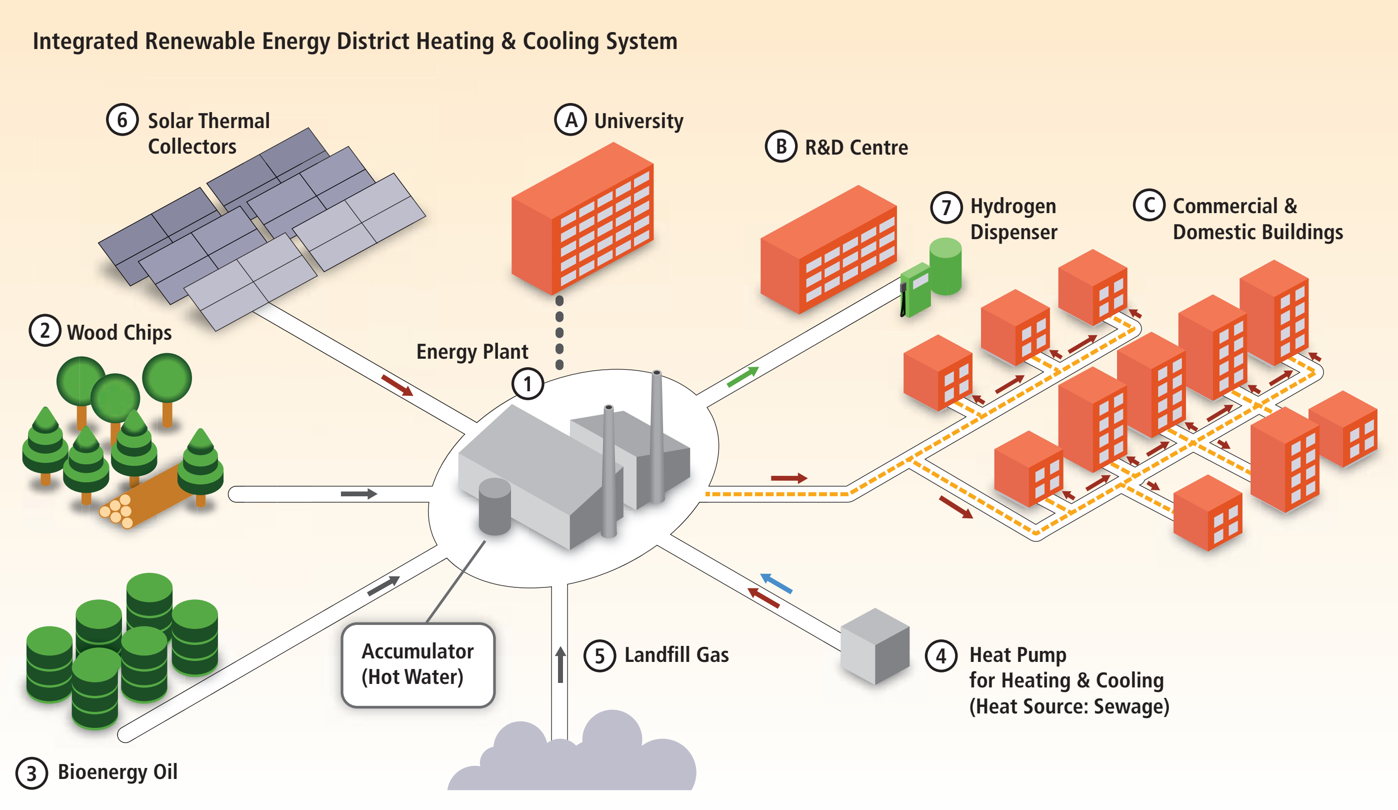

Figure TS.8.3 | An integrated RE-based energy plant in Lillestrøm, Norway, supplying the University, R&D Centre and a range of commercial and domestic buildings using a district heating and cooling system incorporating a range of RE heat sources, thermal storage and a hydrogen production and distribution system. (Total investment around USD_{2005} 25 million and due for completion in 2011.) 1) Central energy system with 1,200 m^3 accumulator hot water storage tank; (2) 20 MW_{th} wood burner system (with flue gas heat recovery); (3) 40 MW_{th} bio-oil burner; (4) 4.5 MW_{th} heat pump; (5) 1.5 MW_{th} landfill gas burner and a 5 km pipeline; (6) 10,000 m^2 solar thermal collector system; and (7) RE-based hydrogen production (using water electrolysis and sorption-enhanced steam methane reforming of landfill gas) and vehicle dispensing system. [Figure 8.3] of around 10,000 m^2 (Figure TS.8.3) have also been built in Denmark, Norway and elsewhere. The best mix of hot and cold sources, and heat transfer and storage technologies, depends strongly on local conditions, including user demand patterns. As a result, the heat energy supply mix varies widely between different systems. [3.5.3, 8.2.2]

Establishing or expanding a DH scheme involves high up-front capital costs for the piping network. Distribution costs alone can represent roughly half of the total cost but are subject to large variations depending on the heat demand density and the local conditions for building the insulated piping network. Increasing urbanization facilitates DH since network capital costs are lower for green-field sites and distribution losses per unit of heat delivered are lower in areas with higher heat demand densities. Heat distribution losses typically range from 5 to 30% but the extent to which high losses are considered a problem depends on the source and cost of the heat. [8.2.2.1, 8.2.2.3]

Expanding the use of deep geothermal and biomass CHP plants in DH systems can facilitate a higher share of RE sources, but to be economically viable this usually requires the overall system to have a large heat load. Some governments therefore support investments in DH networks as well as provide additional incentives for using RE in the system. [8.2.2.4]

Modern building designs and uses have tended to reduce their demand for additional heating whereas the global demand for cooling has tended to increase. The cooling demand to provide comfort has increased in some low-latitude regions where countries have become wealthier and in some higher latitudes where summers have become warmer. Cooling load reductions can be achieved by the use of passive cooling building design options or active RE solutions including solar absorption chillers. As for DH, the rate of uptake of energy efficiency to reduce cooling demand, deployment of new technologies, and the structure of the market, will determine the viability of developing a DC scheme. Modern DC systems, ranging from 5 to 300 MW_{th}, have been operating successfully for many years using natural aquifers, waterways, the sea or deep lakes as the sources of cold, classed as a form of RE. [8.2.2.4]

DH and DC schemes have typically been developed in situations where strong planning powers have existed, such as centrally planned economies, US university campuses, Western European countries with multi-utilities, and urban areas controlled by local municipalities.

8.4 Integration of renewable energy into gas grids

Over the past 50 years, large natural gas networks have been developed in several parts of the world. And more recently there has been increasing interest to 'green' them by integrating RE-based gases. Gaseous fuels from RE sources originate largely from biomass and can be produced either by anaerobic digestion to produce biogas (mainly methane and CO_2) or thermo-chemically to give synthesis (or producer) gas (mainly hydrogen and carbon monoxide). Biomethane, synthesis gas and, in the longer term, RE-based hydrogen can be injected into existing gas pipelines for distribution at the national, regional or local level. Differences in existing infrastructure, gas quality, and production and consumption levels can make planning difficult for increasing the RE share of gases by integration into an existing grid. [8.2.3, 8.2.3.1]

Biogas production is growing rapidly and several large gas companies are now making plans to upgrade large quantities for injection at the required quality into national or regional transmission gas pipelines. Most of the biomethane currently produced around the world is already distributed in local gas pipeline systems primarily dedicated for heating purposes. This can be a cheaper option per unit of energy delivered (Figure TS.8.4) than when transported by trucks (usually to filling stations for supplying gas-powered vehicles) depending on distance and the annual volume to be transported. [8.2.3.4]

Gas utilization can be highly efficient when combusted for heat; used to generate electricity by fuelling gas engines, gas boilers or gas turbines; or used in vehicles either compressed or converted to a range of liquid fuels using various processes. For example, biogas or landfill gas can be combusted onsite to produce heat and/or electricity; cleaned and upgraded to natural gas quality biomethane for injection into gas grids; or, after compressing or liquefying, distributed to vehicle filling stations for use in dedicated or dual gas-fuelled vehicles. [8.2.3.2–8.2.3.4]

Technical challenges relate to gas source, composition and quality. Only biogas and syngas of a specified quality can be injected into existing gas

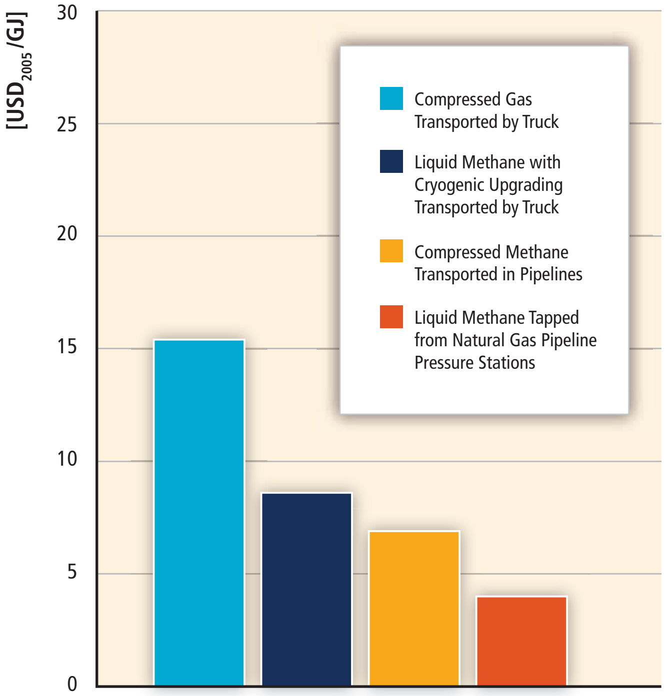

Figure TS.8.4 | Relative costs for distributing and dispensing biomethane (either compressed or liquefied) at the medium scale by truck or pipeline in Europe. [Figure 8.9] grids so clean-up is a critical step to remove water, CO_2 (thereby increasing the heating value) and additional by-products from the gas stream. The cost of upgrading varies according to the scale of the facility and the process, which can consume around 3 to 6% of the energy content of the gas. RE gas systems are likely to require significant storage capacity to account for variability and seasonality of supply. The size and shape of storage facilities and the required quality of the gas will depend on the primary energy source of production and its end use. [8.2.3]

Hydrogen gas can be produced from RE sources by several routes including biomass gasification, the reformation of biomethane, or electrolysis of water. The potential RE resource base for hydrogen is therefore greater than for biogas or syngas. Future production of hydrogen from variable RE resources, such as wind or solar power by electrolysis, will depend significantly on the interaction with existing electricity systems and the degree of surplus capacity. In the short term, blending of hydrogen with natural gas (up to 20% by volume) and transporting it long distances in existing gas grids could be an option. In the longer term, the construction of pipelines for carrying pure hydrogen is possible, constructed from special steels to avoid embrittlement. The rate-limiting factors for deploying hydrogen are likely to be the capital and time involved in building a new hydrogen infrastructure and any additional cost for storage in order to accommodate variable RE sources. [8.2.3.2, 8.2.3.4]

In order to blend a RE gas into a gas grid, the gas source needs to be located near to the existing system to avoid high costs of additional pipeline construction. In the case of remote plant locations due to resource availability, it may be better to use the gas onsite where feasible to avoid the need for transmission and upgrading. [8.2.3.5]

8.5 Integration of renewable energy into liquid fuels

Most of the projected demand for liquid biofuels is for transport purposes, though industrial demand could emerge for bio-lubricants and bio-chemicals such as methanol. In addition, large amounts of traditional solid biomass could eventually be replaced by more convenient, safer and healthier liquid fuels such as RE-derived dimethyl ether (DME) or ethanol gels. [8.2.4]

Producing bioethanol and biodiesel fuels from various crops, usually used for food, is well understood (Figure TS.8.5). The biofuels produced can take advantage of existing infrastructure components already used for petroleum-based fuels including storage, blending, distribution and dispensing. However, sharing petroleum-product infrastructure (storage tanks, pipelines, trucks) with ethanol or blends can lead to problems from water absorption and equipment corrosion, so may require investment in specialized pipeline materials or linings. Decentralized biomass production, seasonality and remote agricultural locations away from existing oil refineries or fuel distribution centres, can impact the supply chain logistics and storage of biofuels. Technologies continue to evolve to produce biofuels from non-food feedstocks and biofuels that are more compatible with existing petroleum fuels and infrastructure. Quality control procedures need to be implemented to ensure that such biofuels meet all applicable product specifications. [8.2.4.1, 8.2.4.3, 8.2.4.4]

The use of blended fuels produced by replacing a portion (typically 5 to 25% but can be up to 100% substitution) of gasoline with ethanol,

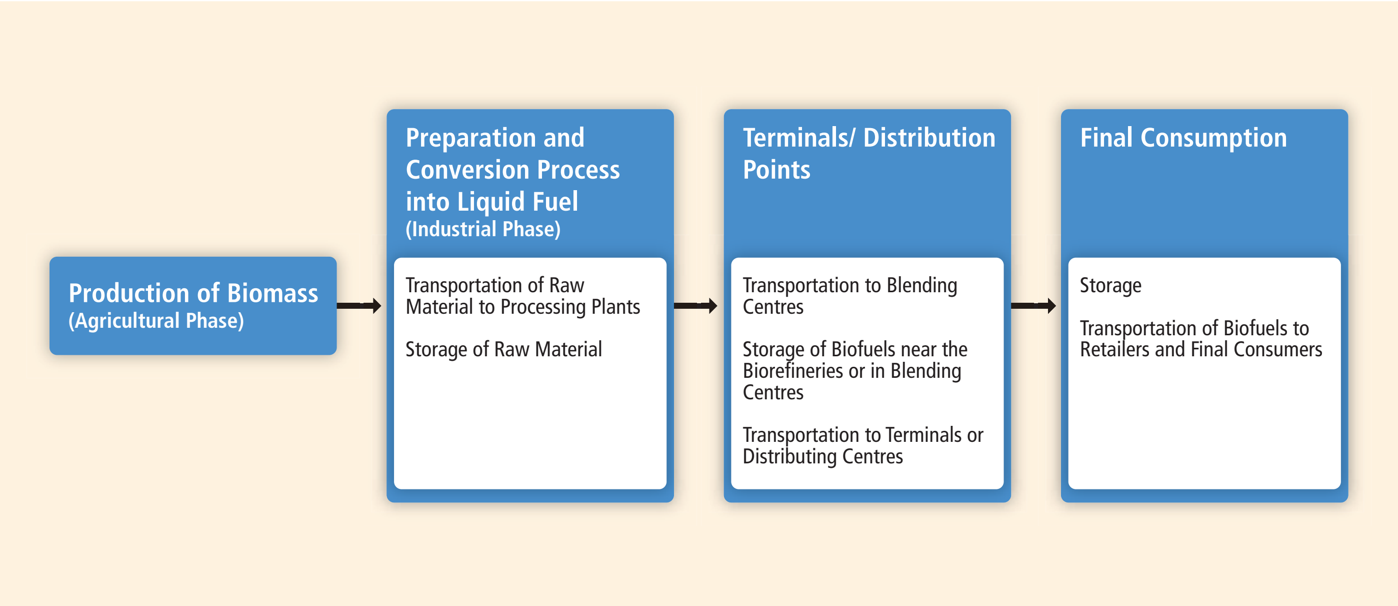

Figure TS.8.5 | The production, blending and distribution system for a range of liquid biofuels is similar regardless of the biomass feedstock. [Figure 8.11] or diesel with biodiesel, requires investment in infrastructure including additional tanks and pumps at vehicle service stations. Although the cost of biofuel delivery is a small fraction of the overall cost, the logistics and capital requirements for widespread integration and expansion could present major hurdles if not well planned. Since ethanol has only around two-thirds the energy density (by volume) of gasoline, larger storage systems, more rail cars or vessels, and larger capacity pipelines are needed to store and transport the same amount of energy. This increases the fuel storage and delivery costs. Although pipelines would, in theory, be the most economical method of delivery, and pipeline shipments of ethanol have been successfully achieved, a number of technical and logistical challenges remain. Typically, current volumes of ethanol produced in an agricultural region to meet local demand, or for export, are usually too low to justify the related investment costs and operational challenges of constructing a dedicated pipeline. [8.2.4.3]

8.6 Integration of renewable energy into autonomous systems

Autonomous energy supply systems are typically small scale and are often located in off-grid remote areas, on small islands, or in individual buildings where the provision of commercial energy is not readily available through grids and networks. Several types of autonomous systems exist and can make use of either single energy carriers, for example, electricity, heat, or liquid, gaseous or solid fuels, or a combination of carriers. [8.2.5, 8.2.5.1]

In principle, RE integration issues for autonomous systems are similar to centralized systems, for example, for supply/demand balancing of electricity supply systems, selection of heating and cooling options, production of RE gases and liquid biofuel production for local use. However, unlike larger centralized supply systems, smaller autonomous systems often have fewer RE supply options that are readily available at a local scale. Additionally, some of the technical and institutional options for managing integration within larger networks become more difficult or even implausible for smaller autonomous systems, such as RE supply forecasting, probabilistic unit commitment procedures, stringent fuel quality standards, and the smoothing effects of geographical and technical diversity. [8.2.1–8.2.5]

RE integration solutions typically become more restricted as supply systems become smaller. Therefore greater reliance must be placed on those solutions that are readily available. Focusing on variable RE resources, because of restricted options for interconnection and operating and planning procedures, autonomous systems will naturally have a tendency to focus on energy storage options, various types of demand response, and highly flexible fossil fuel generation to help match supply and demand. RE supply options that better match local load profiles, or that are dispatchable, may be chosen over other lower-cost options that do not have as strong a match with load patterns or are variable. Managing RE integration within autonomous systems will, all else being equal, be more costly than in larger integrated networks because of the restricted set of options, but in most instances, such as on islands or in remote rural areas, there is no choice for the energy users. One implication is that autonomous electricity system users and designers can face difficult trade-offs between a desire for reliable and continuous supply and minimizing overall supply costs. [8.2.5]

The integration of RE conversion technologies, balancing options and end-use technologies in an autonomous energy system depend on the site-specific availability of RE resources and the local energy demand. These can vary with local climate and lifestyles. The balance between cost and reliability is critical when designing and deploying autonomous power systems, particularly for rural areas of developing economies because the additional cost of providing continuous and reliable supply may become higher for smaller autonomous systems. [8.2.5.2]

8.7 End-use sectors: Strategic elements for transition pathways

RE technology developments have continued to evolve, resulting in increased deployment in the transport, building, industry, and agriculture, forestry and fishery sectors. In order to achieve greater RE deployment in all sectors, both technical and non-technical issues should be addressed. Regional variations exist for each sector due to the current status of RE uptake, the wide range of energy system types, the related infrastructure currently in place, the different possible pathways to enhance increased RE integration, the transition issues yet to be overcome, and the future trends affected by variations in national and local ambitions and cultures. [8.3, 8.3.1]

8.7.1 Transport

Recent trends and projections show strong growth in transport demand, including the rapidly increasing number of vehicles worldwide. Meeting this demand, whilst achieving a low-carbon, secure energy supply, will require strong policy initiatives, rapid technological change, monetary incentives and/or the willingness of customers to pay additional costs. [8.3.1]

In 2008, the combustion of fossil fuels for transport consumed around 19% of global primary energy use, equivalent to 30% of total consumer energy and producing around 22% of GHG emissions, plus a significant share of local air-polluting emissions. Light duty vehicles (LDVs) accounted for over half of transport fuel consumption worldwide, with heavy duty vehicles (HDVs) accounting for 24%, aviation 11%, shipping 10% and rail 3%. Demand for mobility is growing rapidly with the number of motorized vehicles projected to triple by 2050 and with a similar growth in air travel. Maintaining a secure supply of energy is therefore a serious concern for the transport sector with about 94% of transport fuels presently coming from oil products that, for most countries, are imported. [8.3.1]

There are a number of possible fuel/vehicle pathways from the conversion of the primary energy source to an energy carrier (or fuel) through to the end use, whether in advanced internal combustion engine vehicles (ICEVs), electric battery vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) or hydrogen fuel cell vehicles (HFCVs) (Figure TS.8.6). [8.3.1.2]

Improving the efficiency of the transport sector, and decarbonizing it, have been identified as being critically important to achieving long-term, deep reductions in global GHG emissions. The approaches to reducing transport-related emissions include a reduction in travel demand, increased vehicle efficiency, shifting to more efficient modes of transport, and replacing petroleum-based fuels with alternative low- or near-zero-carbon fuels (including biofuels, electricity or hydrogen produced from low-carbon primary energy sources). Scenario studies strongly suggest that a combination of technologies will be needed to accomplish 50 to 80% reductions (compared to current rates) in GHG emissions by 2050 whilst meeting the growing transport energy demand (Figure TS.8.7). [8.3.1.1]

The current use of RE for transport is only a few percent of the total energy demand, mainly through electric rail and the blending of liquid biofuels with petroleum products. Millions of LDVs capable of running on high-biofuel blends are already in the world fleet and biofuel technology is commercially mature, as is the use of compressed biomethane in vehicles suitable for running on compressed natural gas. [8.2.3]

However, making a transition to new fuels and engine types is a complex process involving technology development, cost, infrastructure, consumer acceptance, and environmental and resource impacts. Transition issues vary for biofuels, hydrogen, and electric vehicles (Table TS.8.2) with no one option seen to be a clear 'winner' and all needing several decades to be deployed at a large scale. Biofuels are well proven, contributing around 2% of road transport fuels in 2008, but there are issues of sustainability. [2.5] Many hydrogen fuel cell vehicles have been demonstrated, but these are unlikely to be commercialized until at least 2015 to 2020 due to the barriers of fuel cell durability, cost, onboard hydrogen storage issues and hydrogen infrastructure availability. For EVs and PHEVs, the cost and relatively short life of present

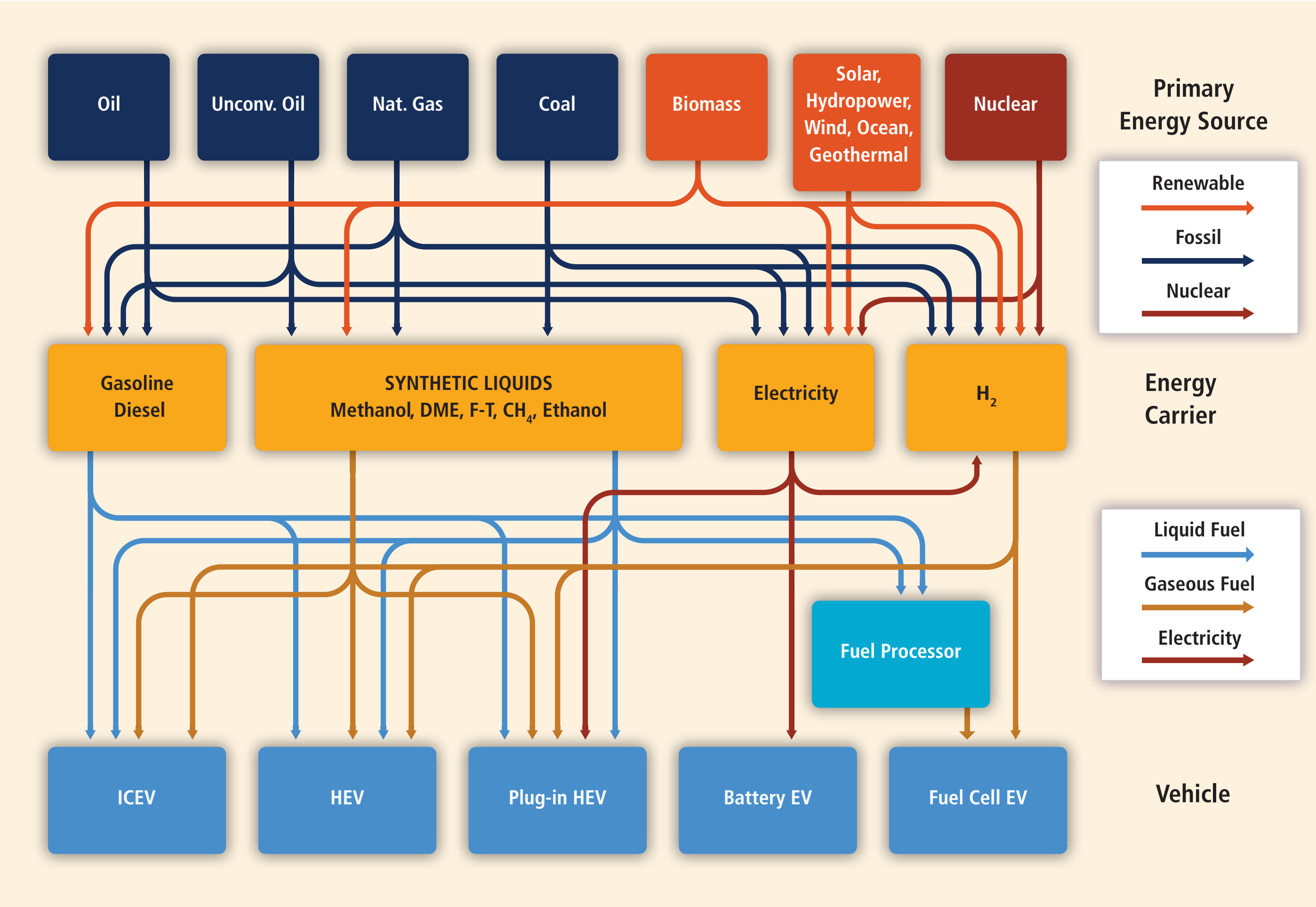

Figure TS.8.6 | A range of possible light duty vehicle fuel pathways, from primary energy sources (top), through energy carriers, to end-use vehicle drive train options (bottom) (with RE resources highlighted in green). [Figure 8.13]

Notes: F-T= Fischer-Tropsch process; DME = dimethyl ether; ICE = internal combustion engine; HEV = hybrid electric vehicle; EV = electric vehicle; 'unconventional oil' refers to oil sands, oil shale and other heavy crudes.

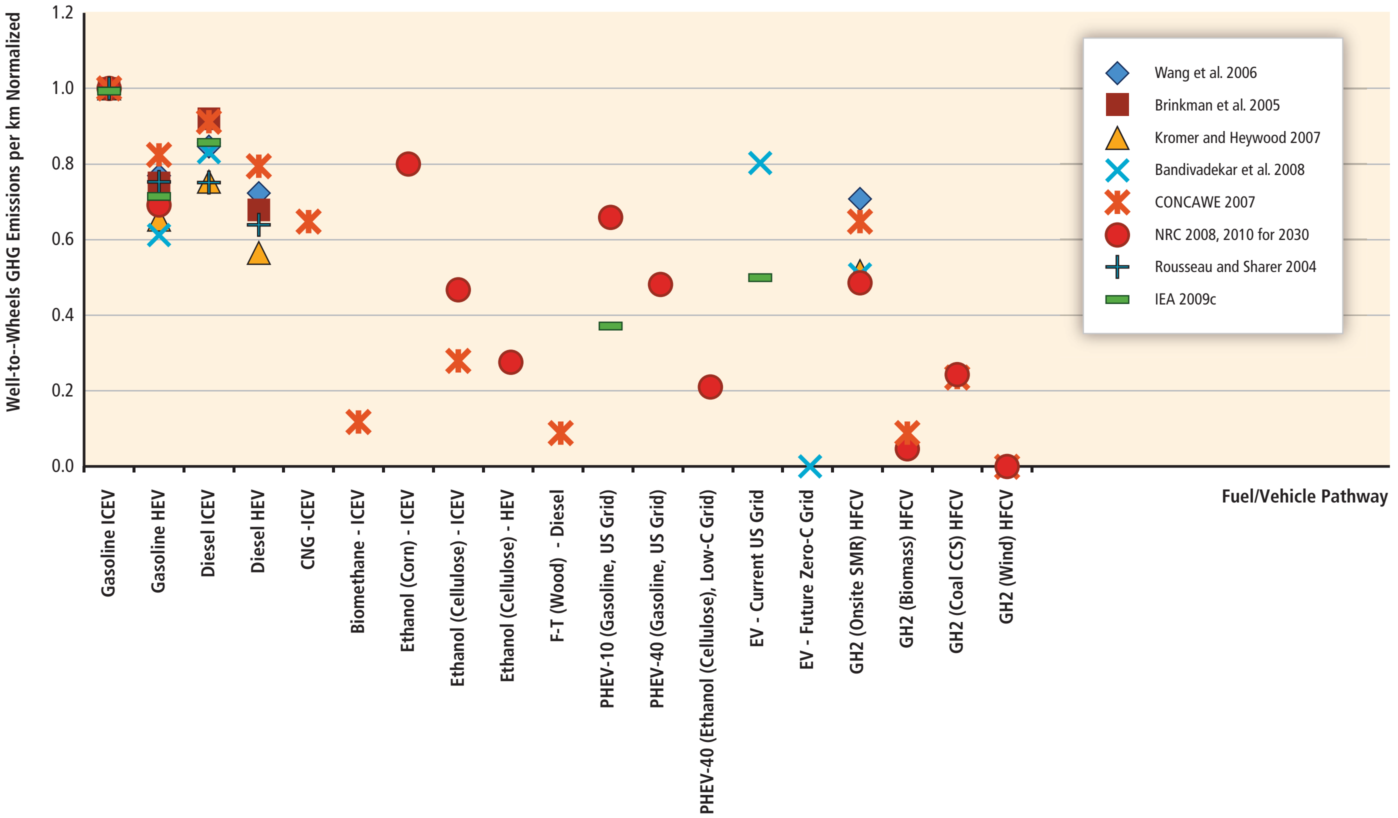

Figure TS.8.7 | Well-to-wheels (WTW) GHG emission reductions per kilometre travelled, with ranges shown taken from selected studies of alternative light duty fuel/vehicle pathways, normalized to the GHG emissions of a gasoline, internal combustion engine, light-duty vehicle. [Figure 8.17]

Notes: To allow for easier comparison among studies, WTW GHG emissions per km were normalized to emissions from a gasoline ICEV (such that 'Gasoline ICEV' = 1) taken from each study and ranging from 170 to 394 g CO_2/km. For all hydrogen pathways, hydrogen is stored onboard the vehicle as a compressed gas (GH2). CNG = compressed natural gas; SMR = steam methane reformer.

battery technologies, the limited vehicle range between recharging, and the time for recharging, can be barriers to consumer acceptance. EV and PHEV designs are undergoing rapid development, spurred by recent policy initiatives worldwide, and several companies have announced plans to commercialize them. One strategy could be to introduce PHEVs initially while developing and scaling up battery technologies. For hydrogen and electric vehicles, it may take several decades to implement a practical transport system by developing the necessary infrastructure at the large scale.

An advantage of *biofuels* is their relative compatibility with the existing liquid fuel infrastructure. They can be blended with petroleum products and most ICE vehicles can be run on blends, some even on up to 100% biofuel. They are similar to gasoline or diesel in terms of vehicle performance[14] and refuelling times, though some have limits on the concentrations that can be blended and they typically cannot be easily distributed using existing fuel pipelines without modifications. The sustainability of the available biomass resource is a serious issue for some biofuels. [2.5, 8.2.4, 8.3.1.2]

Hydrogen has the potential to tap vast new energy resources to provide transport with zero or near-zero emissions. The technology for hydrogen from biomass gasification is being developed, and could become competitive beyond 2025. Hydrogen derived from RE sources by electrolysis has cost barriers rather than issues of technical feasibility or resource availability. Initially RE and other low-carbon technologies will likely be used to generate electricity, a development that could help enable near-zero-carbon hydrogen to be co-produced with electricity or heat in future energy complexes. Hydrogen is not yet widely distributed compared to electricity, natural gas, gasoline, diesel or biofuels but could be preferred in the future for large HDVs that have a long range and need relatively fast refuelling times. Bringing hydrogen to large numbers of vehicles would require building a new refuelling infrastructure that could take several decades to construct. The first steps to provide hydrogen to test fleets and demonstrate refuelling technologies in mini-networks have begun in several countries. [2.6.3.2, 8.3.1, 8.3.1.2]

For RE *electricity* to supply high numbers of EVs and PHEVs in future markets, several innovations must occur such as development of batteries and low-cost electricity supply available for recharging when the EVs need it. If using night-time, off-peak recharging, new capacity is less likely to be needed and in some locations there may be a good temporal match with

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[14] Performance in this instance excludes energy content. The energy content of biofuels is generally lower than their equivalent petroleum product.

Table TS.8.2 | Transition issues for the use of biofuels, hydrogen and electricity as transport fuels for light duty vehicles. [Summarized from 8.3.1]

Technology Status	**Biofuels**	**Hydrogen**	**Electricity**
Existing and potential primary resources	Sugar, starch, oil crops; cellulosic crops; forest, agricultural and solid wastes; algae and other biological oils.	Fossil fuels; nuclear; all RE. Potential RE resource base is large but inefficiencies and costs of converting to H_2 can be an issue.	Fossil fuels, nuclear, all RE. Potential RE resource base is large.
Fuel production	First generation: ethanol from sugar and starch crops, biomethane, biodiesel. Advanced second-generation biofuels, e.g., from cellulosic biomass, bio-wastes, bio-oils, and algae after at least 2015.	Fossil H_2 commercial for large-scale industrial applications, but not competitive as transport fuel. Renewable H_2 generally more costly.	Commercial power readily available. RE electricity can be more costly, but preferred for transport due to low GHG emissions on a lifecycle basis.
Vehicles	Millions of flexi-fuel vehicles exist that use high shares of ethanol. Conventional ICEVs limited to low concentration blends of ethanol (<25%). Some commercial agricultural tractors and machinery can run on 100% biodiesel.	Demonstration HFCVs. Commercial HFCVs not until 2015 to 2020.	Demonstration PHEVs, Commercial PHEVs not until 2012 to 2015. Limited current use of EVs. Commercial EVs not until 2015 to 2020.
Costs[1] compared with gasoline ICE vehicles			
Incremental vehicle price compared to future gasoline ICEV (USD$_{2005}$)	Similar price.	HFCV experience (by 2035) price increment >USD 5,300	Experience (by 2035) price increment: PHEVs >USD 5,900; EVs >USD 14,000
Fuel cost (USD$_{2005}$/km)	Fuel cost per km varies with biofuel type and level of agricultural subsidy. Biofuel can compete if price per unit of energy equates to gasoline/diesel price per unit of energy. Ethanol in Brazil competes without subsidies.	Target fuel cost at USD 3 to 4/kg for mature H_2 infrastructure—may prove optimistic. When used in HFCVs, competes with gasoline in HCEVs at USD 0.40 to 0.53/l. Assumes HFCV has twice fuel economy of gasoline ICEV. RE-derived H_2 around 1.5 to 3 times more expensive than other from sources.	Electricity cost per km, when the power is purchased at USD 0.10 to 0.30/kWh, competes with gasoline when purchased at USD 0.3 to 0.9/l (assuming the EV has fuel economy 3 times that of the gasoline ICEV).
Compatibility with existing infrastructure	Partly compatible with existing petroleum distribution system. Separate distribution and storage infrastructure may be needed for ethanol.	New H_2 infrastructure needed, as well as renewable H_2 production sources. Infrastructure deployment must be coordinated with vehicle market growth.	Widespread electric infrastructure in place. Need to add in-home and public recharger costs, RE generation sources, and upgrading of transmission and distribution (especially for fast chargers).
Consumer acceptance	Depends upon comparative fuel costs. Alcohol vehicles can have shorter range than gasoline. Potential cost impact on food crops. Land use and water issues can be factors.	Depends upon comparative vehicle and fuel costs. Public perception of safety. Poor public refuelling station availability in early markets.	High initial vehicle cost. High electricity cost of charging on-peak. Limited range unless PHEV. Modest to long recharging time, but home recharging possible. Significantly degraded performance in extreme cold winters or hot summers. Poor public refuelling station availability in early markets
GHG emissions	Depends on feedstock, pathway and land use issue[2]. Low for fuels from biomass residues including sugarcane. Near-term can be high for corn ethanol. Advanced second-generation biofuels likely to be lower.	Depends on H_2 production mix. Compared to future hybrid gasoline ICEVs, WTW GHG emissions for HFCVs using H_2 from natural gas can be slightly more or less depending on assumptions. WTW GHG emissions can approach zero for RE or nuclear pathways.	Depends on grid mix. Using coal-dominated grid mix, EVs and PHEVs have WTW GHG emissions similar or higher than gasoline HEV. With larger fraction of RE and low-carbon electricity, WTW emissions are lower.
Petroleum consumption	Low for blends	Very low	Very low
Environmental and sustainability issues			
Air pollution	Similar to gasoline. Additional issues for ethanol due to permeation of volatile organic compounds through fuel tank seals. Aldehyde emissions.	Zero emission vehicle	Zero emission vehicle.
Water use	More than gasoline depending on feedstock and crop irrigation needs.	Potentially low but depends on pathway as electrolysis and steam reformation depend on water.	Potentially very low but depends on pathway used for power generation.
Land use	Might compete with food and fibre production on cropland.	Depends on pathway.	Depends on pathway.
Materials use		Platinum in fuel cells. Neodymium and other rare earths in electric motors. Material recycling.	Lithium in batteries. Neodymium and other rare earths in electric motors. Material recycling.

Notes: 1. Costs quoted do not always include payback of incremental first vehicle costs. 2. Indirect land use-related GHG emissions linked to biofuels is not included.

wind or hydropower resources. Grid flexibility and/or energy storage may also be needed to balance vehicle recharging electricity demand with RE source availability. [8.2.1]

Other than LDVs, it is possible to introduce RE options and lower GHG emissions in the other transport sectors: HDVs, aviation, maritime and rail. The use of biofuels is key for increasing the share of RE in these sub-sectors but current designs of ICEs would probably need to be modified to operate on high-biofuel blends (above 80%). Aviation has perhaps less potential for fuel switching than the other sub-sectors due to safety needs and to minimize fuel weight and volume. However, various airlines and aircraft manufacturers have 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, particularly at cold temperatures. For rail transport, as around 90% of the industry is powered by diesel fuel, greater electrification and the increased use of biodiesel are the two primary options for introducing RE. [8.3.1.5]

Given all these uncertainties and cost reduction challenges, it is important to maintain a portfolio approach over a long time line that includes behavioural changes (for example to reduce annual vehicle kilometres travelled or kilometres flown), more energy efficient vehicles, and a variety of low-carbon fuels. [8.3.1.5]

8.7.2 Buildings and households

The building sector provides shelter and a variety of energy services to support the livelihoods and well-being of people living in both developed and developing countries. In 2008, it accounted for approximately 120 EJ (about 37%) of total global final energy use (including between 30 and 45 EJ of primary energy from traditional biomass used for cooking and heating). The high share of total building energy demand for heating and cooling is usually met by fossil fuels (oil burners, gas heaters) and electricity (fans and air-conditioners). In many regions, these can be replaced economically by district heating and cooling (DHC) schemes or by the direct use of RE systems in buildings, such as modern biomass pellets and enclosed stoves, heat pumps (including ground source), solar thermal water and space heating, and solar sorption cooling systems. [2.2, 8.2.2, 8.3.2]

RE electricity generation technologies integrated into buildings (such as solar PV panels) provide the potential for buildings to become energy suppliers rather than energy consumers. Integration of RE into existing urban environments, combined with energy efficient appliances and 'green building' designs, are key to further deployment. For both household and commercial building sub-sectors, energy vectors and energy service delivery systems vary depending on the local characteristics and RE resources of a region, its wealth, and the average age of the current buildings and infrastructure impacting stock turnover. [8.3.2]

The features and conditions of energy demands in an existing or new building, and the prospects for RE integration, differ with location and between one building design and another. In both urban and rural settlements in developed countries, most buildings are connected to electricity, water and sewage distribution schemes. With a low building stock turnover rate of only around 1% per year in developed countries, future retrofitting of existing buildings will need to play a significant role in RE integration as well as energy efficiency improvements. Examples include installation of solar water heaters and ground source heat pumps and development or extensions of DHC systems that, being flexible on sources of heat or cold, allow for a transition to a greater share of RE over time. These can involve relatively high up-front investment costs and long payback periods, but these can possibly be offset by amended planning consents and regulations so they become more enabling, improved energy efficient designs, and the provision of economic incentives and financial arrangements. [8.2.2, 8.3.2.1]

Grid electricity supply is available in most urban areas of developing countries, although often the supply system has limited capacity and is unreliable. Increased integration of RE technologies using local RE resources could help ensure a secure energy supply and also improve energy access. In urban and rural settlements in developing countries, energy consumption patterns often include the unsustainable use of biomass and charcoal. The challenge is to reverse the increasing traditional biomass consumption patterns by providing improved access to modern energy carriers and services and increasing the share of RE through integration measures. The distributed nature of solar and other RE resources is beneficial for their integration into new and existing buildings however modest they might be, including dwellings in rural areas not connected to energy supply grids. [8.2.2.2, 8.2.5]

8.7.3 Industry

Manufacturing industries account for about 30% of global final energy use, although the share differs markedly between countries. The sector is highly diverse, but around 85% of industrial energy use is by the more energy-intensive 'heavy' industries including iron and steel, non-ferrous metals, chemicals and fertilizers, petroleum refining, mineral mining, and pulp and paper. [8.3.3.1]

There are no severe technical limits to increasing the direct and indirect use of RE in industry in the future. However, integration in the short term may be limited by factors such as land and space constraints or demands for high reliability and continuous operation. In addition to the integration of higher shares of RE, key measures to reduce industrial energy demands and/or GHG emissions include energy efficiency, recycling of materials, CCS for CO_2-emitting industries such as cement manufacturing, and the substitution of fossil fuel feedstocks. In addition, industry can provide demand-response facilities that are likely to achieve greater prominence in future electricity systems that have a higher penetration of variable RE sources. [8.3.3.1]

The main opportunities for RE integration in industry include:

- Direct use of biomass-derived fuels and process residues for onsite production, and use of biofuels, heat and CHP; [2.4.3]
- Indirect use through increased use of RE-based electricity, including electro-thermal processes; [8.3.3]
- Indirect use through other purchased RE-based energy carriers including heat, liquid fuels, biogas, and, possibly to a greater degree in the future, hydrogen; [8.2.2–8.2.4]
- Direct use of solar thermal energy for process heat and steam demands although few examples exist to date; [3.3.2] and
- Direct use of geothermal resources for process heat and steam demands. [4.3.5]

Industry is not only a potential user of RE but also a potential supplier of bioenergy as a co-product. The current direct use of RE in industry is dominated by biomass produced in the pulp and paper, sugar and ethanol industries as process by-products and used for cogenerated heat and electricity, mainly onsite for the process but also sold offsite. Biomass is also an important fuel for many small and medium enterprises such as brick making, notably as charcoal in developing countries. [8.3.3.1]

Possible pathways for increased use of RE in energy-intensive industries vary between the different industrial sub-sectors. Biomass, for example, is technically able to replace fossil fuels in boilers, kilns and furnaces or to replace petrochemicals with bio-based chemicals and materials. However, due to the scale of many industrial operations, access to sufficient volumes of local biomass may be a constraint. Use of solar technologies can be constrained in some locations with low annual sunshine hours. The direct supply of hydropower to aluminium smelters is not unusual but, for many energy-intensive processes, the main option is indirect integration of RE through switching to RE electricity from the grid, or, in the future, to hydrogen. The broad range of options for producing low-carbon electricity, and its versatility of use, implies that electro-thermal processes could become more important in the future for replacing fossil fuels in a range of industrial processes. [8.3.3.2]

Less energy-intensive 'light' industries, including food processing, textiles, light manufacturing of appliances and electronics, automotive assembly plants, and saw-milling, although numerous, account for a smaller share of total energy use than do the heavy industries. Much of the energy demand by these 'light' industries reflects the energy use in commercial buildings for lighting, space heating, cooling, ventilation and office equipment. In general, light industries are more flexible and offer more readily accessible opportunities for the integration of RE than do energy-intensive industries. [8.3.3.3]

RE integration for process heat is practical at temperatures below around 400°C using the combustion of biomass (including charcoal) as well as solar thermal or direct geothermal energy. To meet process heat demand above 400°C, RE resources, with the exception of high-temperature solar, are less suitable (Figure TS.8.8). [8.3.3.3]

The potentials and costs for increasing the use of RE in industry are poorly understood due to the complexity and diversity of industry and the various geographical and local climatic conditions. Near-term opportunities for achieving higher RE shares could result from the increased utilization of process residues, CHP in biomass-based industries, and substitution of fossil fuels used for heating. Solar thermal technologies are promising with further development of collectors, thermal storage, back-up systems, process adaptation and integration under evaluation. RE integration using electricity generated from RE sources for electrotechnologies may have the largest impact both in the near and long term. [8.3.3.2, 8.3.3.3]

Use of RE in industry has had difficulty in competing in the past in many regions due to relatively low fossil fuel prices together with low, or

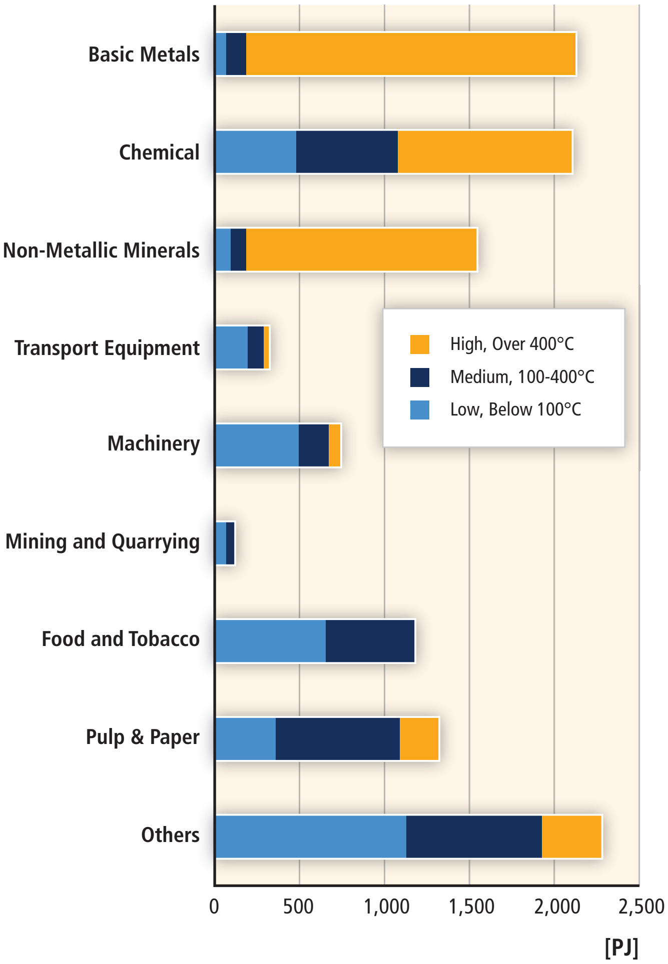


Figure TS.8.8 | Industrial heat demands for various temperature quality ranges by the heavy industrial and light manufacturing sub-sectors, based on an assessment within 32 European countries. [Figure 8.23] non-existent, energy and carbon taxes. RE support policies in different countries tend to focus more on the transport and building sectors than on industry and consequently the potential for RE integration is relatively uncertain. Where support policies have been applied, successful RE deployment has resulted. [8.3.3.3]

8.7.4 Agriculture, forestry and fishing

Agriculture is a relatively low energy-consuming sector, utilizing only around 3% of total global consumer energy. The sector includes large corporate-owned farms and forests as well as subsistence farmers and fisher-folk in developing countries. The relatively high indirect energy use for the manufacture of fertilizers and machinery is included in the industry sector. Pumping water for irrigation usually accounts for the highest on-farm energy demand, along with diesel use for machinery and electricity for milking, refrigeration and fixed equipment. [8.3.4.1]

In many regions, land under cultivation could simultaneously be used for RE production. Multi-use of land for agriculture and energy purposes is becoming common, such as wind turbines constructed on grazing land; biogas plants used for treating animal manure with the nutrients recycled to the land; waterways used for small- and micro-hydropower systems; crop residues collected and combusted for heat and power; and energy crops grown and managed specifically to provide a biomass feedstock for liquid biofuels, heat and power generation (with co-products possibly used for feed and fibre). [2.6, 8.3.4.2, 8.3.4.3]

Since RE resources including wind, solar, crop residues and animal wastes are often abundant in rural areas, their capture and integration can enable the landowner or farm manager to utilize them locally for the farming operations. They can also earn additional revenue when energy carriers such as RE electricity or biogas are exported off the farm. [8.3.4]

Despite barriers to greater RE technology deployment including high capital costs, lack of available financing and remoteness from energy demand, it is likely that RE will be used to a greater degree by the global agricultural sector in the future to meet energy demands for primary production and post-harvest operations at both large and small scales. [8.3.4.1–8.3.4.2]

Integration strategies that could increase the deployment of RE in the primary sector will partly depend upon the local and regional RE resources, on-farm energy demand patterns, project financing opportunities and existing energy markets. [8.3.4.3]

9. Renewable Energy in the Context of Sustainable Development

9.1 Introduction

Sustainable development (SD) addresses concerns about relationships between human society and nature. Traditionally, SD has been framed in the three-pillar model—Economy, Ecology, and Society—allowing a schematic categorization of development goals, with the three pillars being interdependent and mutually reinforcing. Within another conceptual framework, SD can be oriented along a continuum between the two paradigms of weak sustainability and strong sustainability. The two paradigms differ in assumptions about the substitutability of natural and human-made capital. RE can contribute to the development goals of the three-pillar model and can be assessed in terms of both weak and strong SD, since RE utilization is defined as sustaining natural capital as long as the resource use does not reduce the potential for future harvest. [9.1]

9.2 Interactions between sustainable development and renewable energy

The relationship between RE and SD can be viewed as a hierarchy of goals and constraints that involve both global and regional or local considerations. Though the exact contribution of RE to SD has to be evaluated in a country-specific context, RE offers the opportunity to contribute to a number of important SD goals: (1) social and economic development; (2) energy access; (3) energy security; and (4) climate change mitigation and the reduction of environmental and health impacts. The mitigation of dangerous anthropogenic climate change is seen as one strong driving force behind the increased use of RE worldwide. [9.2, 9.2.1]

These goals can be linked to both the three-pillar model and the weak and strong SD paradigms. SD concepts provide useful frameworks for policymakers to assess the contribution of RE to SD and to formulate appropriate economic, social and environmental measures. [9.2.1]

The use of indicators can assist countries in monitoring progress made in energy subsystems consistent with sustainability principles, although there are many different ways to classify indicators of SD. The assessments carried out for the report and Chapter 9 are based on different methodological tools, including bottom-up indicators derived from attributional lifecycle assessments (LCA) or energy statistics, dynamic integrated modelling approaches, and qualitative analyses. [9.2.2]

Conventional economic growth metrics (GDP) as well as the conceptually broader Human Development Index (HDI) are analyzed to evaluate the contribution of RE to social and economic development. Potential employment opportunities, which serve as a motivation for some countries to support RE deployment, as well as critical financing questions for developing countries are also addressed. [9.2.2]

Access to modern energy services, whether from renewable or non-renewable sources, is closely correlated with measures of development, particularly for those countries at earlier development stages. Providing access to modern energy for the poorest members of society is crucial for the achievement of any single of the eight Millennium Development Goals. Concrete indicators used include per capita final energy consumption related to income, as well as breakdowns of electricity access (divided into rural and urban areas), and numbers for those parts of the population using coal or traditional biomass for cooking. [9.2.2]

Despite the lack of a commonly accepted definition, the term 'energy security' can best be understood as robustness against (sudden) disruptions of energy supply. Two broad themes can be identified that are relevant to energy security, whether for current systems or for the planning of future RE systems: availability and distribution of resources; and variability and reliability of energy supply. The indicators used to provide information about the energy security criterion of SD are the magnitude of reserves, the reserves-to-production ratio, the share of imports in total primary energy consumption, the share of energy imports in total imports, as well as the share of variable and unpredictable RE sources. [9.2.2]

To evaluate the overall burden from the energy system on the environment, and to identify potential trade-offs, a range of impacts and categories have to be taken into account. These include mass emissions to air (in particular GHGs) and water, and usage of water, energy and land per unit of energy generated and these must be evaluated across technologies. While recognizing that LCAs do not give the only possible answer as to the sustainability of a given technology, they are a particularly useful methodology for determining total system impacts of a given technology, which can serve as a basis for comparison. [9.2.2]

Scenario analyses provide insights into what extent integrated models take account of the four SD goals in different RE deployment pathways. Pathways are primarily understood as scenario results that attempt to address the complex interrelations among the different energy technologies at a global scale. Therefore, Chapter 9 mainly refers to global scenarios derived from integrated models that are also at the core of the analysis in Chapter 10. [9.2.2]

9.3 Social, environmental and economic impacts: Global and regional assessment

Countries at different levels of development have different incentives to advance RE. For developing countries, the most likely reasons to adopt RE technologies are providing access to energy, creating employment opportunities in the formal (i.e., legally regulated and taxable) economy, and reducing the costs of energy imports (or, in the case of fossil energy exporters, prolonging the lifetime of their natural resource base). For industrialized countries, the primary reasons to encourage RE include reducing carbon emissions to mitigate climate change, enhancing energy security, and actively promoting structural change in the economy, such that job losses in declining manufacturing sectors are softened by new employment opportunities related to RE. [9.3]

9.3.1 Social and economic development

Globally, per capita incomes are positively correlated with per capita energy use and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. However, there is no agreement on the direction of the causal relationship between energy use and increased macroeconomic output. [9.3.1.1]

As economic activity expands and diversifies, demands for more sophisticated and flexible energy sources arise: from a sectoral perspective, countries at an early stage of development consume the largest part of total primary energy in the residential (and to a lesser extent agricultural) sector; in emerging economies the manufacturing sector dominates, while in fully industrialized countries services and transport account for steadily increasing shares (see Figure TS.9.1). [9.3.1.1]

Despite the close correlation between GDP and energy use, a wide variety of energy use patterns across countries prevails: some have achieved high levels of per capita incomes with relatively low energy consumption. Others remain rather poor despite elevated levels of energy use, in particular countries abundantly endowed with fossil fuel resources, in which energy is often heavily subsidized. One hypothesis suggests that economic growth can largely be decoupled from energy use by steady declines in energy intensity. Further, it is often asserted that developing economies and economies in transition can 'leapfrog', that is, limit their energy use by adopting modern, highly efficient energy technologies. [9.3.1.1, Box 9.5]

Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, such as health, education, gender equality and environmental safety. Using the HDI as a proxy indicator of development, countries that have achieved high HDI levels in general consume relatively large amounts of energy per capita and no country has achieved a high or even a medium HDI without significant access to non-traditional energy supplies. A certain minimum amount of energy is required to guarantee an acceptable standard of living (e.g., 42 GJ per capita), after which raising energy consumption yields only marginal improvements in the quality of life. [9.3.1.2]

Estimates of current net employment effects of RE differ due to disagreements regarding the use of the appropriate methodology. Still, there seems to be agreement about the positive long-term effects of RE

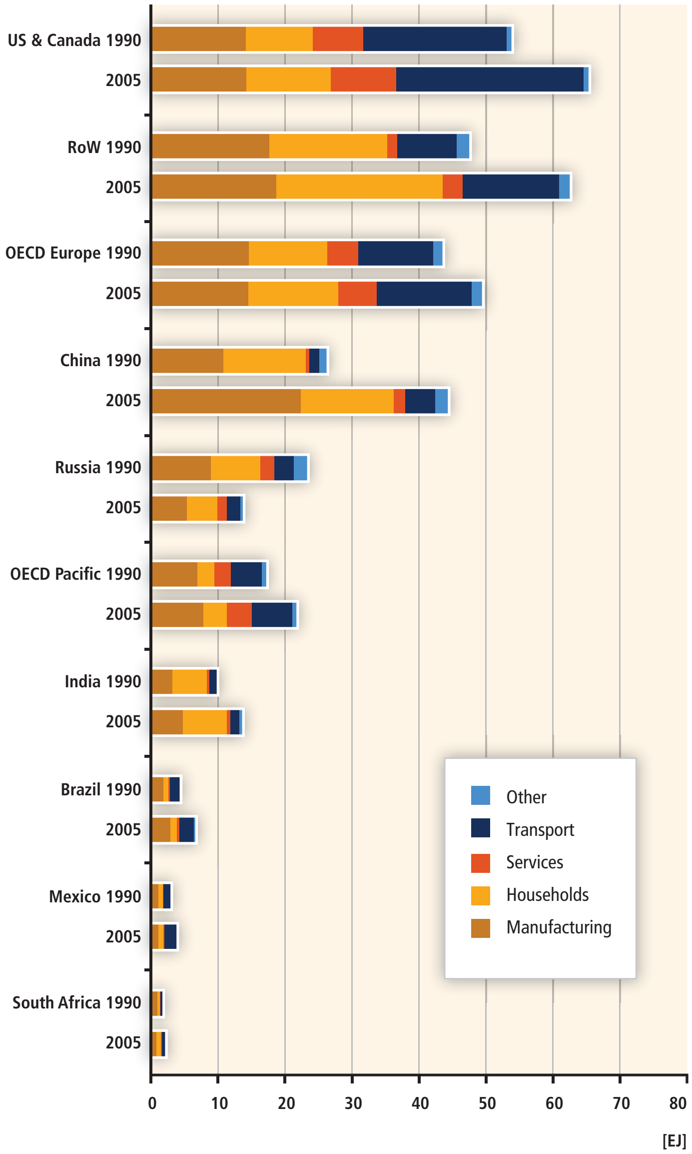


Figure TS.9.1 | Energy use (EJ) by economic sector. Note that the underlying data are calculated using the IEA physical content method, not the direct equivalent method.[1]

Notes: RoW = Rest of World. [Figure 9. 2] 1. Historical energy data have only been available for energy use by economic sector. For a conversion of the data using the direct equivalent method, the different energy carriers used by each economic sector would need to be known.

as an important contribution to job creation, which has been stressed in many national green-growth strategies. [9.3.1.3]

In general, the purely economic costs of RE exceed those of fossil fuel-based energy production in most instances. Especially for developing countries, the associated costs are a major factor determining the desirability of RE to meet increasing energy demand, and concerns have been voiced that increased energy prices might endanger industrializing countries' development prospects. Overall, cost considerations cannot be discussed independently of the burden-sharing regime adopted, that is, without specifying who assumes the costs for the benefits brought about from reduced GHG emissions, which can be characterized as a global public good. [9.3.1.4]

9.3.2 Energy access

Significant parts of the global population today have no or limited access to modern and clean energy services. From a sustainable development perspective, sustainable energy expansion needs to increase the availability of energy services to groups that currently have no or limited access to them: the poor (measured by wealth, income or more integrative indicators), those in rural areas and those without connections to the grid. [9.3.2]

Acknowledging the existing constraints regarding data availability and quality, 2009 estimates of the number of people without access to electricity are around 1.4 billion. The number of people relying on traditional biomass for cooking is around 2.7 billion, which causes significant health problems (notably indoor air pollution) and other social burdens (e.g., time spent gathering fuel) in the developing world. Given the strong correlation between household income and use of low quality fuels (Figure TS.9.2), a major challenge is to reverse the pattern of inefficient biomass consumption by changing the present, often unsustainable, use to more sustainable and efficient alternatives. [9.3.2]

By defining energy access as 'access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses', the incremental process of climbing the steps of the energy ladder is illustrated; even basic levels of access to modern energy services can provide substantial benefits to a community or household. [9.3.2]

In developing countries, decentralized grids based on RE have expanded and improved energy access; they are generally more competitive in rural areas with significant distances to the national grid and the low levels of rural electrification offer significant opportunities for RE-based mini-grid systems. In addition, non-electrical RE technologies offer opportunities for direct modernization of energy services, for example, using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping. While the specific role of RE in providing energy access in a more sustainable manner than other energy sources is not well understood, some of these technologies allow local communities to widen their energy choices; they stimulate economies, provide incentives for local entrepreneurial efforts and meet basic needs and services related to lighting and cooking, thus providing ancillary health and education benefits. [9.3.2]

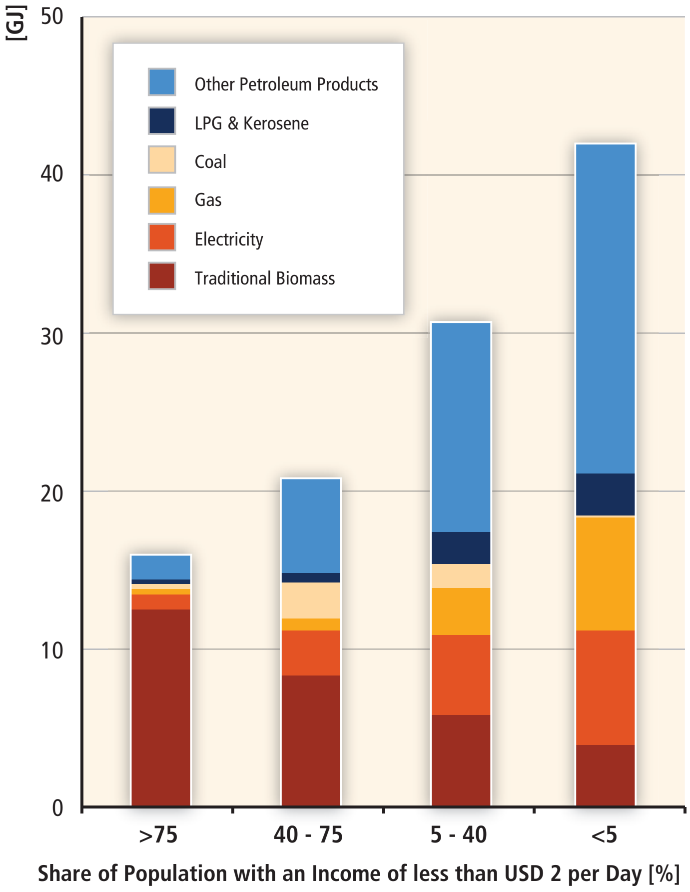


Figure TS.9.2 | The relationship between per capita final energy consumption and income in developing countries. Data refer to the most recent year available during the period 2000 to 2008. [Figure 9.5]

Note: LPG = liquid petroleum gas.

9.3.3 Energy security

The use of RE permits substitution away from increasingly scarce fossil fuel supplies; current estimates of the ratio of proven reserves to current production show that globally oil and natural gas would be exhausted in about four and six decades, respectively. [9.3.3.1]

As many renewable sources are localized and not internationally tradable, increasing their share in a country's energy portfolio diminishes the dependence on imports of fossil fuels, whose spatial distribution of reserves, production and exports is very uneven and highly concentrated in a few regions (Figure TS.9.3). As long as RE markets are not characterized by such geographically concentrated supply, this helps to diversify the portfolio of energy sources and to reduce the economy's vulnerability to price volatility. For oil-importing developing countries, increased uptake of RE technologies could be an avenue to redirect foreign exchange flows away from energy imports towards imports of goods that cannot be produced locally, such as high-tech capital goods. For example, Kenya and Senegal spend more than half of their export earnings for importing energy, while India spends over 45%. [9.3.3.1]

However, import dependencies can also occur in relation to the technologies needed for implementation of RE, with the secure access to required scarce inorganic mineral raw materials at reasonable prices constituting an upcoming challenge for all industries. [9.3.3.1]

The variable output profiles of some RE technologies often necessitate technical and institutional measures appropriate to local conditions to assure a constant and reliable energy supply. Reliable energy access is a particular challenge in developing countries and indicators for the reliability of infrastructure services show that in sub-Saharan Africa, almost 50% of firms maintain their own generation equipment. Many developing countries therefore specifically link energy access and security issues by broadening the definition of energy security to include stability and reliability of local supply. [9.3.3.2]

9.3.4 Climate change mitigation and reduction of environmental and health impacts

Sustainable development must ensure environmental quality and prevent undue environmental harm. No large-scale technology deployment comes without environmental trade-offs and a large body of literature is available that assesses various environmental impacts of the broad range of energy technologies (RE, fossil and nuclear) from a bottom-up perspective. [9.3.4]

Impacts on the climate through GHG emissions are generally well covered, and LCAs [Box 9.2] facilitate a quantitative comparison of 'cradle to grave' emissions across technologies. While a significant number of studies report on air pollutant emissions and operational water use, evidence is scarce for lifecycle emissions to water, land use, and health impacts other than those linked to air pollution. The assessment concentrates on those sectors which are best covered by the literature, such as electricity generation and transport fuels for GHG emissions. Heating and household energy are discussed only briefly, in particular with regards to air pollution and health. Impacts on biodiversity and ecosystems are mostly site-specific, difficult to quantify and are presented in a more qualitative manner. To account for burdens associated with accidents as opposed to normal operation, an overview of risks associated with energy technologies is provided. [9.3.4]

LCAs for electricity generation indicate that *GHG emissions from RE technologies* are, in general, considerably lower than those associated with fossil fuel options, and in a range of conditions, less than fossil fuels employing CCS. The maximum estimate for CSP, geothermal, hydropower, ocean and wind energy is less than or equal to 100 g CO_2eq/kWh, and median values for all RE range from 4 to 46 g CO_2eq/kWh. The upper quartile of the distribution of estimates for PV and biopower extend two to three times above the maximum for other RE technologies. However, GHG balances of bioenergy production have more uncertainties: excluding LUC, biopower could reduce GHG emissions compared to fossil fuelled systems and can lead to avoided GHG emissions from residues and wastes in landfill disposals and co-products; the combination of

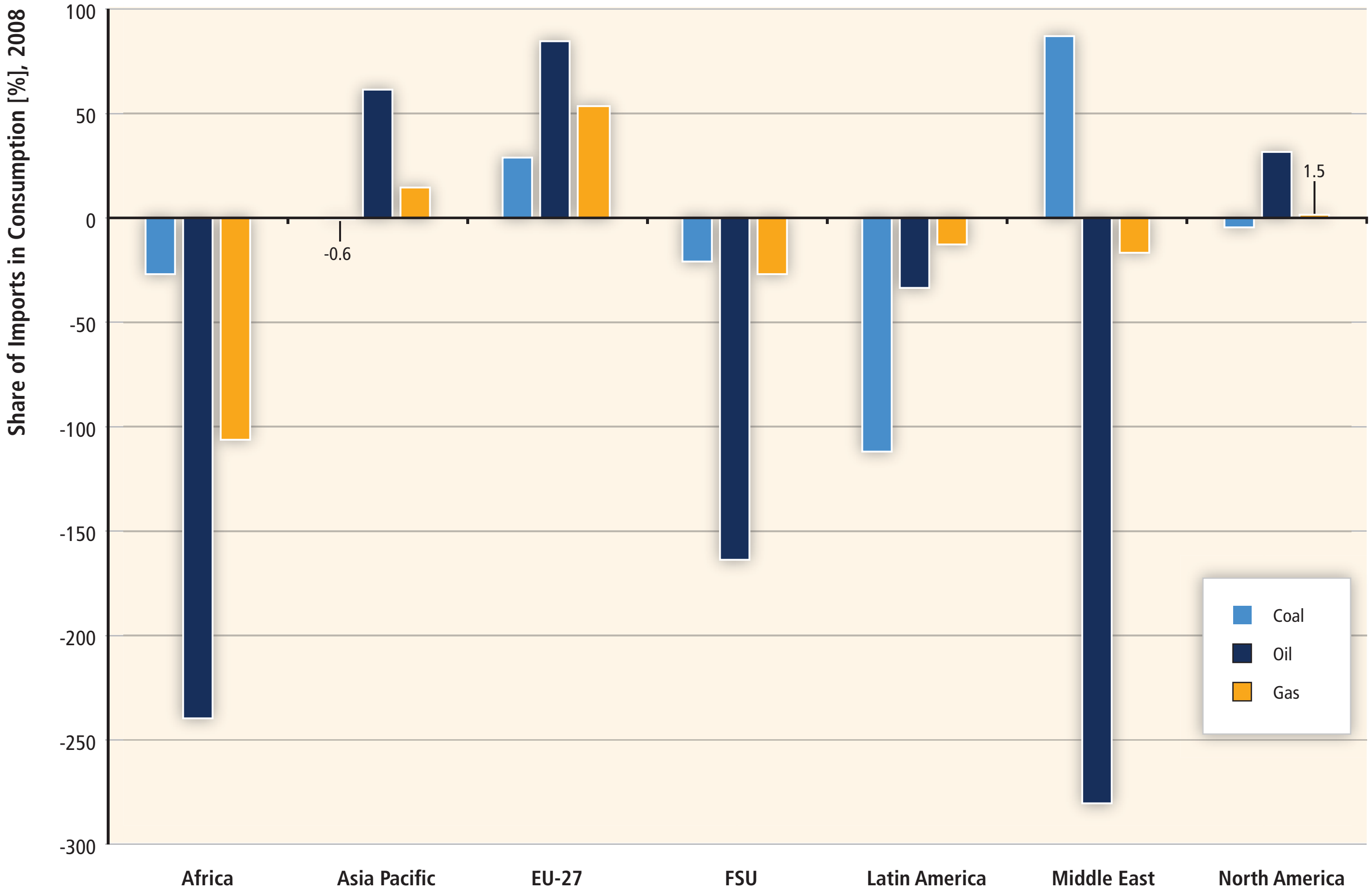


Figure TS.9.3 | Energy imports as the share of total primary energy consumption (%) for coal (hard coal and lignite), crude oil and natural gas for selected world regions in 2008. Negative values denote net exporters of energy carriers. [Figure 9.6]

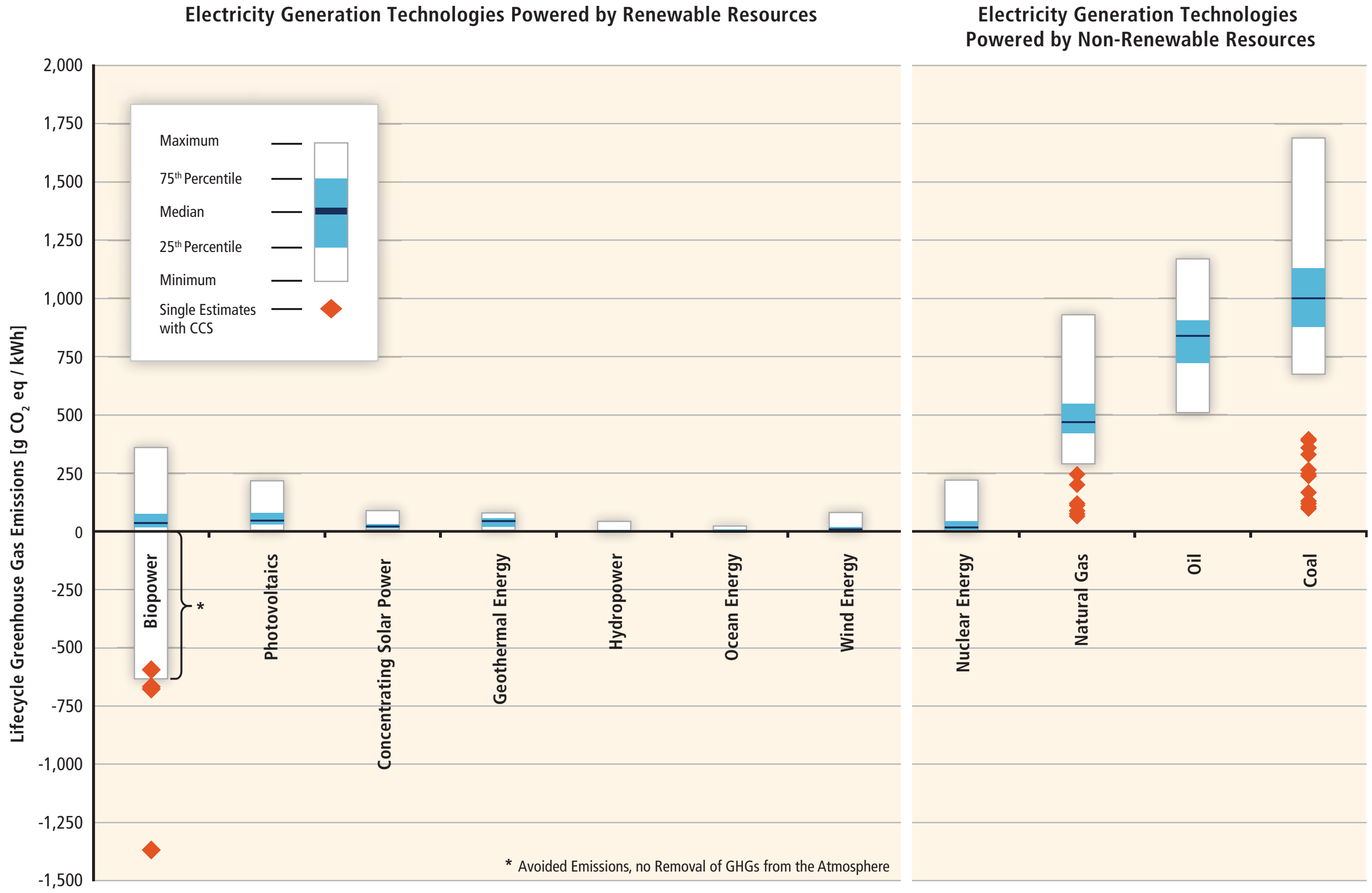
bioenergy with CCS may provide for further reductions (Figure TS.9.4). [9.3.4.1]

Accounting for differences in the quality of power produced, potential impacts to grid operation related to the addition of variable generation sources, and for direct or indirect LUC could reduce the GHG emissions benefit from switching to renewable electricity generation, but is not likely to negate the benefit. [9.3.4.1]

Measures such as the energy payback time, describing the energetic efficiency of technologies or fuels, have been declining rapidly for some RE technologies over recent years (e.g., wind and PV) due to technological advances and economies of scale. Fossil and nuclear power technologies are characterized by the continuous energy requirements for fuel extraction and processing, which might become increasingly important as qualities of conventional fuel supply decline and shares of unconventional fuels rise. [9.3.4.1]

For the assessment of *GHG emissions from transportation fuels*, selected petroleum fuels, first-generation biofuels (i.e., sugar- and starch-based ethanol, oilseed-based biodiesel and renewable diesel), and selected next-generation biofuels derived from lignocellulosic biomass (i.e., ethanol and Fischer-Tropsch diesel) are compared on a well-to-wheel basis. In this comparison, GHG emissions from LUC (direct and indirect) and other indirect effects (e.g., petroleum consumption rebound) have been excluded, but are separately considered below. Substituting biofuels for petroleum-based fuels has the potential to reduce lifecycle GHG emissions directly associated with the fuel supply chain. While first-generation biofuels result in relatively modest GHG mitigation potential (-19 to 77 g CO_2eq/MJ for first-generation biofuels versus 85 to 109 g CO_2eq/MJ for petroleum fuels), most next-generation biofuels (with lifecycle GHG emissions between -10 and 38 g CO_2eq/MJ) could provide greater climate benefits. Estimates of lifecycle GHG emissions are variable and uncertain for both biofuels and petroleum fuels, primarily due to assumptions about biophysical parameters, methodological issues and where and how the feedstocks are produced. [9.3.4.1]

Lifecycle *GHG emissions from LUC* are difficult to quantify, with land and biomass resource management practices strongly influencing any GHG emission reduction benefits and as such the sustainability of bioenergy. Changes to land use or management, brought about directly or indirectly by biomass production for use as fuels, power or heat, can lead to changes in terrestrial carbon stocks. Depending on the converted land's prior condition, this can either cause significant upfront emissions, requiring a time



Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure TS.9.4 | Estimates of lifecycle GHG emissions (g CO_2eq/kWh) for broad categories of electricity generation technologies, plus some technologies integrated with CCS. Land-use related net changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) and land management impacts are excluded; negative estimates[1] for biopower are based on assumptions about avoided emissions from residues and wastes in landfill disposals and co-products. References and methods for the review are reported in Annex II. The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions. [Figure 9.8]

Note: 1. 'Negative estimates' within the terminology of lifecycle assessments presented in this report refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere.

lag of decades to centuries before net savings are achieved, or improve the net uptake of carbon into soils and aboveground biomass. Assessments of the net GHG effects of bioenergy are made difficult by challenges in observation, measurement, and attribution of indirect LUC, which depends on the environmental, economic, social and policy context and is neither directly observable nor easily attributable to a single cause. Illustrative estimates of direct and indirect LUC-related GHG emissions induced by several first-generation biofuel pathways provide central tendencies (based on different reporting methods) for a 30-year timeframe: for ethanol (EU wheat, US maize, Brazilian sugarcane) 5 to 82 g CO_2eq/MJ and for diesel (soy and rapeseed) 35 to 63 g CO_2eq/MJ. [9.3.4.1]

Impacts from *local and regional air pollution* constitute another important assessment category, with air pollutants (including particulate matter (PM), nitrous oxides (NO_x), sulphur dioxide (SO_2) and non-methane volatile organic compounds (NMVOC)) having effects at the global [Box 9.4], regional and local scale. Compared to fossil-based power generation, non-combustion-based RE power generation technologies have the potential to significantly reduce regional and local air pollution and associated health impacts (see this section below). For transportation fuels, however, the effect of switching to biofuels on tailpipe emissions is not yet clear. [9.3.4.2]

Local air pollutant emissions from fossil fuels and biomass combustion constitute the most important energy related impacts on *human health*. Ambient air pollution, as well as exposure to indoor air pollution from the combustion of coal and traditional biomass, has major health impacts and is recognized as one of the most important causes of morbidity and mortality worldwide, particularly for women and children in developing countries. In 2000, for example, comparative quantifications of health risks showed that more than 1.6 million deaths and over 38.5 million of disability-adjusted life-years (DALYs) were attributable to indoor smoke from solid fuels. Besides a fuel switch, mitigation options include improved cookstoves, ventilation and building design and behavioural changes. [9.3.4.3]

Impacts on *water* relate to operational and upstream water consumption of energy technologies and to water quality. These impacts are site specific and need to be considered with respect to local resources and needs. RE technologies like hydropower and some bioenergy systems, for example, are dependent on water availability and can either increase competition or mitigate water scarcity. In water-scarce areas, non-thermal RE technologies (e.g., wind and PV) can provide clean electricity without putting additional stress on water resources. Conventionally cooled thermal RE technologies (e.g., CSP, geothermal, biopower) can use more water during operation than non-RE technologies, yet dry cooling configurations can reduce this impact (Figure TS.9.5). Water use in upstream processes can be high for some energy technologies, particularly for fuel extraction and biomass feedstock production; including the latter, the current water footprint for electricity generation from biomass can be up to several hundred times greater than operational water consumption requirements for thermal power plants. Feedstock production, mining operations and fuel processing can also affect water quality. [9.3.4.4]

Most energy technologies have substantial *land requirements* when the whole supply chain is included. While the literature on lifecycle estimates for land use by energy technologies is scarce, the available evidence suggests that lifecycle land use by fossil energy chains can be comparable to or higher than land use by RE sources. For most RE sources, land use requirements are largest during the operational stage. An exception is the land intensity of bioenergy from dedicated feedstocks, which is significantly higher than for any other energy technology and shows substantial variations in energy yields per hectare for different feedstocks and climatic zones. A number of RE technologies (wind, wave and ocean) occupy large areas, but allow secondary uses such as farming, fishing and recreational activities. [9.3.4.5] Connected to land use are (site-specific) impacts on *ecosystems and biodiversity*. Occurring through various pathways, the most evident ones are through large-scale direct physical alteration of habitats and, more indirectly, habitat deterioration. [9.3.4.6]

The comparative assessment of *accident risks* is a pivotal aspect in a comprehensive evaluation of energy security aspects and sustainability performance associated with current and future energy systems. Risks of various energy technologies to society and the environment occur not only during the actual energy generation, but at all stages of energy chains. Accident risks of RE technologies are not negligible, but the technologies' often decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. While RE technologies overall exhibit low fatality rates, dams associated with some hydropower projects may create a specific risk depending on site-specific factors. [9.3.4.7]

9.4 Implication of sustainable development pathways for renewable energy

Following the more static analysis of the impacts of current and emerging RE systems on the four SD goals, the SD implications of possible future RE deployment pathways are assessed in a more dynamic manner and thus incorporate the intertemporal component of SD. Since the interaction of future RE and SD pathways cannot be anticipated by relying on a partial analysis of individual energy technologies, the discussion is based on results from the scenario literature that typically treats the portfolio of technological alternatives in the framework of a global or regional energy system. [9.4]

The vast majority of models used to generate the scenarios reviewed (see Chapter 10, Section 10.2) capture the interactions between different options for supplying, transforming and using energy. The models range from regional, energy-economic models to integrated assessment models (IAMs) and are here referred to as integrated models. Historically, these models have focused much more on the technological and macroeconomic aspects of energy transitions, and in the process have produced largely aggregated measures of technological penetration or energy generated by particular sources of supply. The value of these models in generating long-term scenarios and their potential to help understand the interrelation between SD and RE rests on their ability to consider interactions across a broad set of human activities over different regional and time scales. Integrated models continually undergo developments, some of which will be crucial for the representation of sustainability concerns in the future, for example, increasing their temporal and spatial resolution, allowing for a better representation of the distribution of wealth across the population and incorporating greater detail in human and physical Earth system characterization. [9.4]

The assessment focuses on what model-based analyses currently have to say with respect to SD pathways and the role of RE and evaluates how model-based analyses can be improved to provide a better understanding of sustainability issues in the future. [9.4]

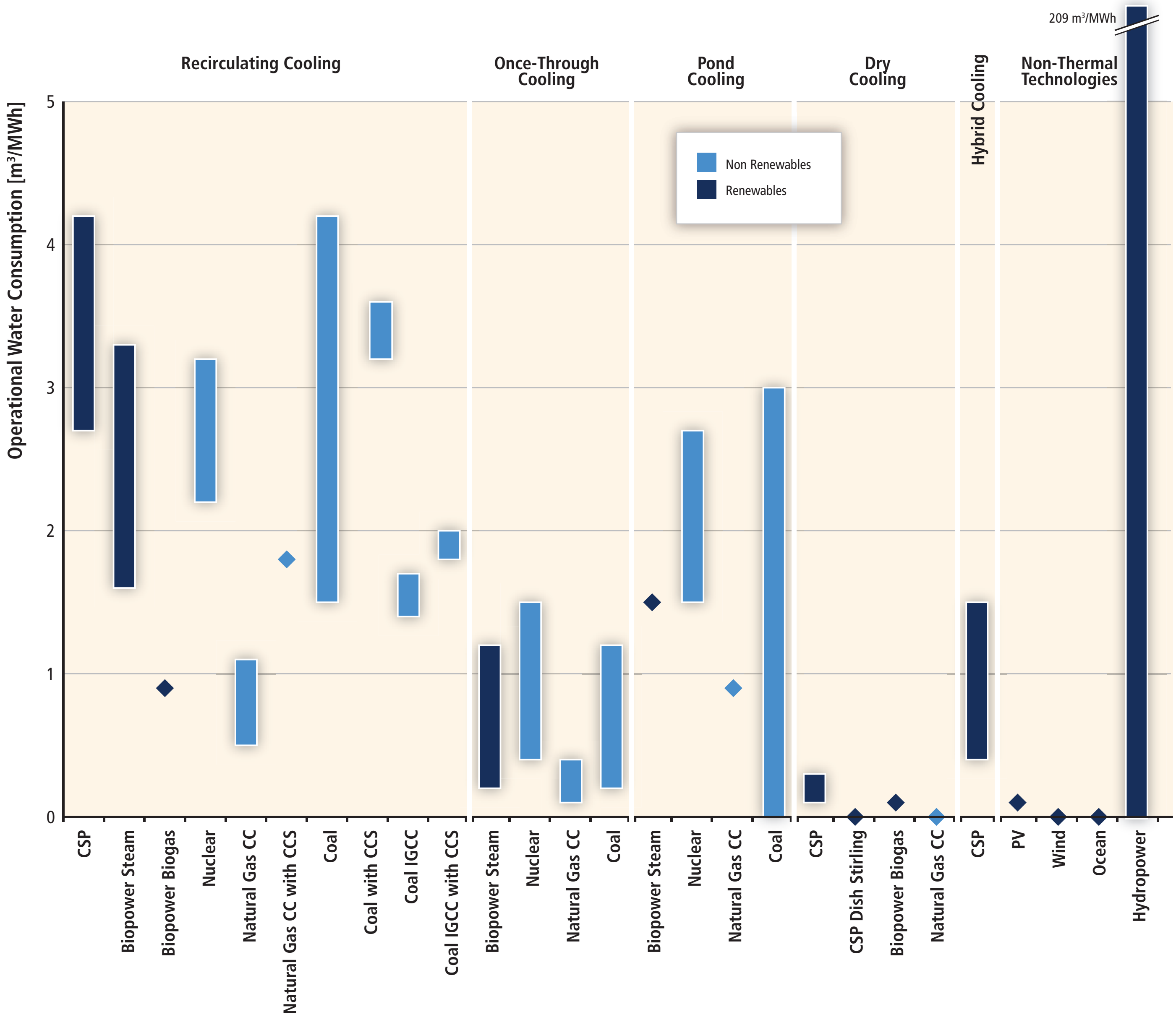


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Figure TS.9.5 | Ranges of rates of operational water consumption by thermal and non-thermal electricity-generating technologies based on a review of available literature (m³/MWh). Bars represent absolute ranges from available literature, diamonds single estimates; n represents the number of estimates reported in the sources. Methods and references used in this literature review are reported in Annex II. Note that upper values for hydropower result from a few studies measuring gross evaporation values, and may not be representative (see Box 5.2). [Figure 9.14]

Notes: CSP: concentrated solar power; CCS: carbon capture and storage; IGCC: integrated gasification combined cycle; CC: combined cycle; PV: photovoltaic.

9.4.1 Social and economic development

Integrated models usually have a strong macro-perspective and do not consider advanced welfare measures. [9.2.2, 9.3.1] Instead, they focus on economic growth, which in itself is an insufficient measure of sustainability, but can be used as an indicative welfare measure in the context of different stabilization pathways. Mitigation scenarios usually include a tentative strong sustainability constraint by putting an upper limit on future GHG emissions. This results in welfare losses (usually measured as GDP or consumption foregone) based on assumptions about the availability and costs of mitigation technologies. Limiting the availability of technological alternatives for constraining GHGs further increases welfare losses. Studies that specifically assess the implications of constraining RE for different GHG concentration stabilization levels show that the wide availability of all RE technologies is essential in order to reach low stabilization levels and that the full availability of low-carbon technologies, including RE, is crucial for keeping mitigation costs at relatively low levels, even for less strict stabilization levels. [9.4.1]

With respect to regional effects, scenario analyses show that developing countries are likely to see most of the expansion in RE production. With the challenge to overcome high LCOEs of RE technologies still to be met, these results hint at the potential of developing countries to leapfrog the emission-intensive developing paths that developed countries have taken so far. Regional mitigation opportunities will, however, vary, depending on many factors including technology availability, but also population and economic growth. Costs will also depend on the allocation of tradable emission permits, both initially and over time, under a global climate mitigation regime. [9.4.1]

In general, scenario analyses point to the same links between RE, mitigation and economic growth in developed and developing countries, only the forces are generally larger in non-Annex I countries than in Annex I countries due to more rapid assumed economic growth and the consequently increasing mitigation burden over time. However, the modelling structures used to generate long-term global scenarios generally assume perfectly functioning economic markets and institutional infrastructures across all regions of the globe. They also discount the special circumstances that prevail in all countries, particularly in developing countries where these assumptions are particularly tenuous. These sorts of differences and the influence they might have on social and economic development among countries should be an area of active future research. [9.4.1]

9.4.2 Energy access

Integrated models thus far have often been based on developed country information and experience and assumed energy systems in other parts of the world and at different stages of development to behave likewise. Usually, models do not capture important and determinative dynamics in developing countries, such as fuel choices, behavioural heterogeneity and informal economies. This impedes an assessment of the interaction between RE and the future availability of energy services for different populations, including basic household level tasks, transportation, and energy for commerce, manufacturing and agriculture. However, some models have started to integrate factors such as potential supply shortages, informal economies and diverse income groups, and to increase the distributional resolution. [9.4.2]

Available scenario analyses are still characterized by large uncertainties. For India, results suggested that income distribution in a society is as important for increasing energy access as income growth. Also, increasing energy access is not necessarily beneficial for all aspects of SD, as a shift to modern energy away from, for example, traditional biomass could simply be a shift to fossil fuels. In general, available scenario analyses highlight the role of policies and finance for increased energy access, even though forced shifts to RE that would provide access to modern energy services could negatively affect household budgets. [9.4.2]

Further improvements in the distribution resolution and structural rigidity (inability of many models to capture social phenomena and structural changes that underlie peoples' utilization of energy technologies) are particularly challenging. An explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output. In order to provide a more comprehensive view of the possible range of energy access options, future energy models should aim for a more explicit representation of relevant determinants (such as traditional fuels, modes of electrification, and income distribution) and link these to representations of alternative development pathways. [9.4.2]

9.4.3 Energy security

RE can influence energy security by mitigating concerns with respect to both availability and distribution of resources, as well as to the variability of energy sources. [9.2.2, 9.3.1] To the extent that RE deployment in mitigation scenarios reduces the overall risk of disruption by diversifying the energy portfolio, the energy system is less susceptible to (sudden) energy supply disruption. In scenarios, this role of RE will vary with the energy form. Solar, wind and ocean energy, which are closely associated with electricity production, have the potential to replace concentrated and increasingly scarce fossil fuels in the buildings and the industry sector. With appropriate carbon mitigation policies in place, electricity generation can be relatively easily decarbonized. In contrast, the demand for liquid fuels in the transport sector remains inelastic if no technological breakthrough can be achieved. While bioenergy could play an important role, this will depend on the availability of CCS that could divert its use to power generation with CCS—resulting in negative net carbon emissions for the system and smoothing the overall mitigation efforts significantly. [9.4.1, 9.4.3]

Against this background, energy security concerns raised in the past that related to oil supply disruptions are likely to remain relevant in the future. For developing countries the issue will become even more important, as their share in global total oil consumption increases in all assessed scenarios (Figure TS.9.6b). As long as technological alternatives for oil, for example, biofuels and/or the electrification of the transportation sector, do not play a dominant role in scenario analyses,

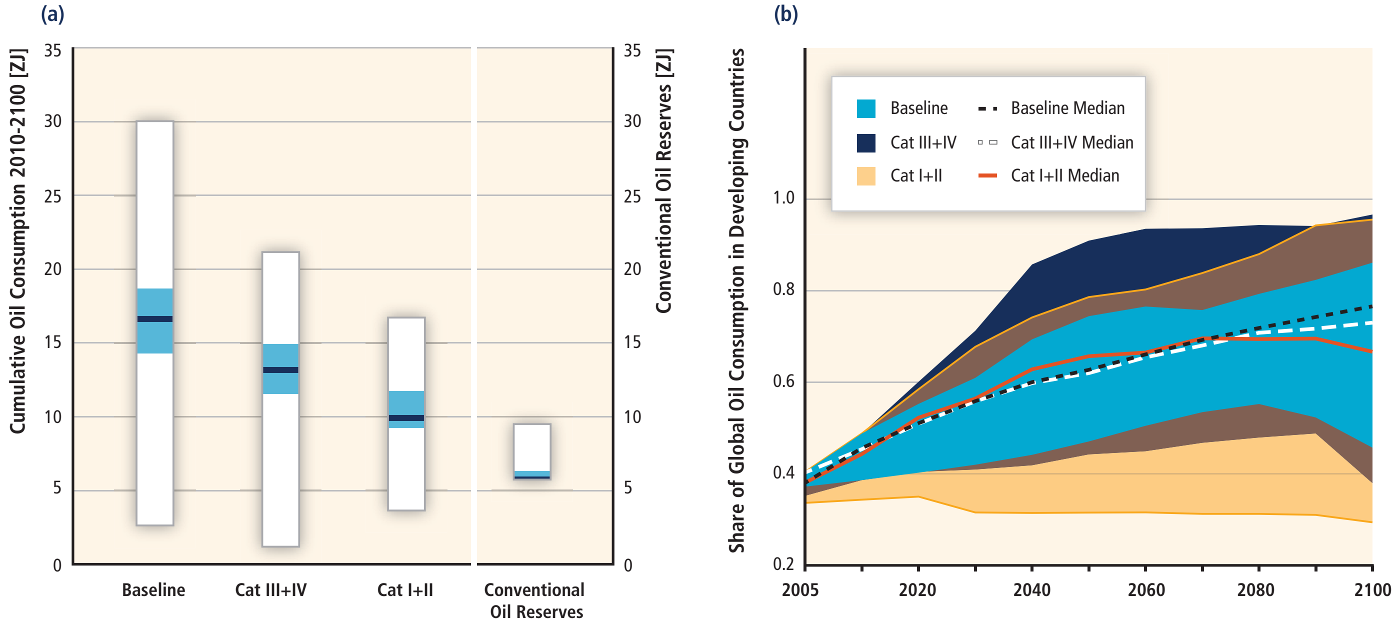


Figure TS.9.6 | (a) Conventional oil reserves compared to projected cumulative oil consumption (ZJ) from 2010 to 2100 in scenarios assessed in Chapter 10 for different scenario categories: baseline scenarios, Category III and IV scenarios and low stabilization (Category I+II) scenarios. The thick dark blue line corresponds to the median, the light blue bar corresponds to the inter-quartile range (25th to 75th percentile) and the white surrounding bar corresponds to the total range across all reviewed scenarios. The last column shows the range of proven recoverable conventional oil reserves (light blue bar) and estimated additional reserves (white surrounding bar). (b) Range of share of global oil consumed in non-Annex I countries for different scenario categories over time, based on scenarios assessed in Chapter 10. [Figure 9.18]

most mitigation scenarios do not see dramatic differences between the baseline and policy scenarios with respect to cumulative oil consumption (Figure TS.9.6a). [9.4.3]

An increased market for bioenergy could raise additional energy security concerns in the future if it was characterized by a small number of sellers and thus showed parallels to today's oil market. In such an environment, the risk that food prices could be linked to volatile bioenergy markets would have to be mitigated to impede severe impacts on SD as high and volatile food prices would clearly hurt the poor. [9.4.3]

The introduction of variable RE technologies also adds new concerns, such as vulnerability to extreme natural events or international price fluctuations, which are not yet satisfactorily addressed by large integrated models. Additional efforts to increase system reliability are likely to add costs and involve balancing needs (such as holding stocks of energy), the development of complementary flexible generation, strengthening network infrastructure and interconnections, energy storage technologies and modified institutional arrangements including regulatory and market mechanisms [7.5, 8.2.1, 9.4.3]

Energy security considerations today usually focus on the most prominent energy security issues in recent memory. However, energy security aspects of the future might go well beyond these issues, for example, in relation to critical material inputs for RE technologies. These broader concerns as well as options for addressing them, for example, recycling, are largely absent from future scenarios of mitigation and RE. [9.4.3]

9.4.4 Climate change mitigation and environmental and health impacts in scenarios of the future

Replacing fossil fuels with RE or other low-carbon technologies can significantly contribute to the reduction of NO_x and SO_2 emissions. Several models have included explicit representation of factors, such as sulphate pollution, that are linked to environmental or health impacts. Some scenario results show that climate policy can help drive improvements in local air pollution (i.e., PM), but air pollution reduction policies alone do not necessarily drive reductions in GHG emissions. Another implication of some potential energy trajectories is the possible diversion of land to support biofuel production. Scenario results have pointed at the possibility that, if not accompanied by other policy measures, climate policy could drive widespread deforestation, with land use being shifted to bioenergy crops with possibly adverse SD implications, including GHG emissions. [9.4.4]

Unfortunately, existing scenario literature does not explicitly treat the many non-emissions related elements of sustainable energy development, such as water use, the impacts of energy choices on household-level services, or indoor air quality. This can be partly explained by models being designed to look at fairly large world regions without income or geographic distributional detail. For a broad assessment of environmental impacts at the regional and local level, models would need to look at smaller scales of geographical impacts, which is currently a matter of ongoing research. Finally, many models do not explicitly allow for incorporation of LCA results of the technological alternatives. What these impacts are, whether and how to compare them across categories, and whether they might be incorporated into future scenarios would constitute useful areas for future research. [9.4.4]

9.5 Barriers and opportunities for renewable energy in the context of sustainable development

Pursuing a renewable energy deployment strategy in the context of SD implies that most environmental, social and economic effects are taken explicitly into account. Integrated planning, policy and implementation processes can support this by anticipating and overcoming potential barriers to and exploiting opportunities of RE deployment. [9.5]

Barriers that are particularly pertinent in a sustainable development context and that may either impede RE deployment or result in trade-offs with SD criteria relate to socio-cultural, information and awareness, market-related and economic barriers. [9.5.1]

Socio-cultural barriers or concerns have different origins and are intrinsically linked to societal and personal values and norms. Such values and norms affect the perception and acceptance of RE technologies and the potential impacts of their deployment by individuals, groups and societies. From a sustainable development perspective, barriers may arise from inadequate attention to such socio-cultural concerns, which include barriers related to behaviour; natural habitats and natural and human heritage sites, including impacts on biodiversity and ecosystems; landscape aesthetics; and water/land use and water/land use rights, as well as their availability for competing uses. [9.5.1.1]

Public awareness and acceptance is an important element in the need to rapidly and significantly scale up RE deployment to help meet climate change mitigation goals. Large-scale implementation can only be undertaken successfully with the understanding and support of the public. This may require dedicated communication efforts related to the achievements and the opportunities associated with wider-scale applications. At the same time, however, public participation in planning decisions as well as fairness and equity considerations in the distribution of the benefits and costs of RE deployment play an equally important role and cannot be side-stepped. [9.5.1.1]

In developing countries, limited technical and business skills and the absence of technical support systems are particularly apparent in the energy sector, where awareness of and information dissemination regarding available and appropriate RE options among potential consumers is a key determinant of uptake and market creation. This gap in awareness is often perceived as the single most important factor affecting the deployment of RE and development of small and medium enterprises that contribute to economic growth. Also, there is a need to focus on the capacity of private actors to develop, implement and deploy RE technologies, which includes increasing technical and business capability at the micro or firm level. [9.5.1.2]

Attitudes towards RE in addition to rationality are driven by emotions and psychological issues. To be successful, RE deployment and information and awareness efforts and strategies need to take this explicitly into account. [9.5.1.2]

To assess the economics of RE in the context of SD, social costs and benefits need to be explicitly considered. RE should be assessed against quantifiable criteria targeted at cost effectiveness, regional appropriateness, and environmental and distributional consequences. Grid size and technologies are key determinants of the *economic viability* of RE and of the competitiveness of RE compared to non-renewable energy. Appropriate RE technologies that are economically viable are often found to be available for expanding rural off-grid energy access, in particular smaller off-grid and mini-grid applications. [9.5.1.3]

In cases where deployment of RE is viable from an economic perspective, other economic and financial barriers may affect its deployment. High upfront costs of investments, including high installation and grid connection costs, are examples of frequently identified barriers to RE deployment. In developing countries, policy and entrepreneurial support systems are needed along with RE deployment to stimulate economic growth and SD and catalyze rural and peri-urban cash economies. Lack of adequate resource potential data directly affects uncertainty regarding resource availability, which may translate into higher risk premiums for investors and project developers. The internalization of environmental and social externalities frequently results in changes in the ranking of various energy sources and technologies, with important lessons for SD objectives and strategies. [9.5.1.3]

Strategies for SD at international, national and local levels as well as in private and nongovernmental spheres of society can help overcome barriers and create opportunities for RE deployment by integrating RE and SD policies and practices. [9.5.2]

Integrating RE policy into national and local SD strategies (explicitly recognized at the 2002 World Summit on Sustainable Development) provides a framework for countries to select effective SD and RE strategies and to align those with international policy measures. To that end, national strategies should include the removal of existing financial mechanisms that work against SD. For example, the removal of fossil fuel subsidies may have the potential to open up opportunities for more extensive use or even market entry of RE, but any subsidy reform towards the use of RE technologies needs to address the specific needs of the poor and demands a case-specific analysis. [9.5.2.1]

The CDM established under the Kyoto Protocol is a practical example of a mechanism for SD that internalizes environmental and social externalities. However, there are no international standards for sustainability assessments (including comparable SD indicators) to counter weaknesses in the existing system regarding sustainability approval. As input to the negotiations for a post-2012 climate regime, many suggestions have been made about how to reform the CDM to better achieve new and improved mechanisms for SD. [9.5.2.1]

Opportunities for RE to play a role in national strategies for SD can be approached by integrating SD and RE goals into development policies and by development of sectoral strategies for RE that contribute to goals for green growth and low-carbon and sustainable development including leapfrogging. [9.5.2.1]

At the local level, SD initiatives by cities, local governments, and private and nongovernmental organizations can be drivers of change and contribute to overcome local resistance to RE installations. [9.5.2.2]

9.6 Synthesis, knowledge gaps and future research needs

RE can contribute to SD and the four goals assessed to varying degrees. While benefits with respect to reduced environmental and health impacts may appear more clear-cut, the exact contribution to, for example, social and economic development is more ambiguous. Also, countries may prioritize the four SD goals according to their level of development. To some extent, however, these SD goals are also strongly interlinked. Climate change mitigation constitutes in itself a necessary prerequisite for successful social and economic development in many developing countries. [9.6.6]

Following this logic, climate change mitigation can be assessed under the strong SD paradigm, if mitigation goals are imposed as constraints on future development pathways. If climate change mitigation is balanced against economic growth or other socioeconomic criteria, the problem is framed within the paradigm of weak SD allowing for trade-offs between these goals and using cost-benefit type analyses to provide guidance in their prioritization. [9.6.6]

However, the existence of uncertainty and ignorance as inherent components of any development pathway, as well as the existence of associated and possibly ‘unacceptably high’ opportunity costs, will make continued adjustments crucial. In the future, integrated models may be in a favourable position to better link the weak and strong SD paradigms for decision-making processes. Within well-defined guardrails, integrated models could explore scenarios for different mitigation pathways, taking account of the remaining SD goals by including important and relevant bottom-up indicators. According to model type, these alternative development pathways might be optimized for socially beneficial outcomes. Equally, however, the incorporation of GHG emission-related LCA data will be crucial for a clear definition of appropriate GHG concentration stabilization levels in the first place. [9.6.6]

In order to improve the knowledge regarding the interrelations between SD and RE and to find answers to the question of effective, economically efficient and socially acceptable transformations of the energy system, it is necessary to develop a closer integration of insights from social, natural and economic sciences (e.g., through risk analysis approaches), reflecting the different dimensions of sustainability (especially intertemporal, spatial, and intergenerational). So far, the knowledge base is often limited to very narrow views from specific branches of research, which do not fully account for the complexity of the issue. [9.7]

10. Mitigation Potential and Costs

10.1 Introduction

Future GHG emission estimates are highly dependent on the evolution of many variables, including, among others, economic growth, population growth, energy demand, energy resources and the future costs and performance of energy supply and end-use technologies. Mitigation and other non-mitigation policy structures in the future will also influence deployment of mitigation technologies and therefore GHG emissions and the ability to meet climate goals. Not only must all these different forces be considered simultaneously when exploring the role of RE in climate mitigation [see Figure 1.14], it is not possible to know today with any certainty how these different key forces might evolve decades into the future. [10.1]

Questions about the role that RE sources are likely to play in the future, and how they might contribute to GHG mitigation pathways, need to be explored within this broader context. Chapter 10 provides such an exploration through the review of 164 existing medium- to long-term scenarios from large-scale, integrated models. The comprehensive review explores the range of global RE deployment levels emerging in recent published scenarios and identifies many of the key forces that drive the variation among scenarios (note that the chapter relies exclusively on existing published scenarios and does not create any new scenarios). It does so both at the scale of RE as a whole and also in the context of individual RE technologies. The review highlights the importance of interactions and competition with other technologies as well as the evolution of energy demand more generally. [10.2]

This large-scale review is complemented with a more detailed discussion of future RE deployment, using 4 of the 164 scenarios as illustrative examples. The chosen scenarios span a range of different future expectations about RE characteristics, are based on different methodologies and cover different GHG concentration stabilization levels. This approach provides a next level of detail for exploring the role of RE in climate change mitigation, distinguishing between different applications (electricity generation, heating and cooling, transport) and regions. [10.3]

As the resulting role of RE is significantly determined by cost factors, a more general discussion about cost curves and cost aspects is then provided. This discussion starts with an assessment of the strengths and shortcomings of supply curves for RE and GHG mitigation, and then reviews the existing literature on regional RE supply curves, as well as abatement cost curves, as they pertain to mitigation using RE sources. [10.4]

Costs of RE commercialization and deployment are then addressed. The chapter reviews present RE technology costs, as well as expectations about how these costs might evolve into the future. To allow an assessment of future market volumes and investment needs, based on the results of the four illustrative scenarios investments in RE are discussed in particular with respect to what might be required if ambitious climate protection goals are to be achieved. [10.5]

Standard economic measures do not cover the full set of costs. Therefore, social and environmental costs and benefits of increased deployment of RE in relation to climate change mitigation and SD are synthesized and discussed. [10.6]

10.2 Synthesis of mitigation scenarios for different renewable energy strategies

An increasing number of integrated scenario analyses that are able to provide relevant insights into the potential contribution of RE to future energy supplies and climate change mitigation has become available. To provide a broad context for understanding the role of RE in mitigation and the influence of RE on the costs of mitigation, 164 recent medium- to long-term scenarios from 16 global energy-economic and integrated assessment models were reviewed. The scenarios were collected through an open call. The scenarios cover a large range of CO_2 concentrations (350 to 1,050 ppm atmospheric CO_2 concentration by 2100), representing both mitigation and baseline scenarios. [10.2.2.1]

Although these scenarios represent some of the most recent and sophisticated thinking regarding climate mitigation and the role of RE in climate mitigation in the medium- to long-term, they, as with any analysis looking decades into the future, must be interpreted carefully. All of the scenarios were developed using quantitative modelling, but there is enormous variation in the detail and structure of the models used to construct the scenarios. In addition, the scenarios do not represent a random sample of possible scenarios that could be used for formal uncertainty analysis. Some modelling groups provided more scenarios than others. In scenario ensemble analyses based on collecting scenarios from different studies, such as the review here, there is an inevitable tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into our knowledge about the future, or lack thereof. [10.2.1.2, 10.2.2.1]

A fundamental question relating to the role of RE in climate mitigation is how closely RE deployment levels are correlated with long-term atmospheric CO_2 concentration or related climate goals. The scenarios indicate that although there is a strong correlation between fossil and industrial CO_2 emissions pathways and long-term CO_2 concentration goals across the scenarios, the relationship between RE deployment and CO_2 concentration goals is far less robust (Figure TS.10.1). RE deployment generally increases with the stringency of the CO_2 concentration goal, but there is enormous variation among RE deployment levels for any given CO_2 concentration goal. For example, in scenarios that stabilize the atmospheric CO_2 concentration at a level of less than 440 ppm (Categories I and II), the median RE deployment levels are 139 EJ/yr in 2030 and 248 EJ/yr in 2050, with the highest levels reaching 252 EJ/yr in 2030 and up to 428 EJ/yr in 2050. These levels are considerably higher than the corresponding RE deployment levels in baseline scenarios, although it has to be acknowledged that the range of RE deployment in each of the CO_2 stabilization categories is wide. [10.2.2.2]

At the same time, it is also important to note that despite the variation, the absolute magnitudes of RE deployment are dramatically higher than those of today in the vast majority of the scenarios. In 2008, global renewable primary energy supply in direct equivalent stood at roughly 64 EJ/yr. The majority of this, about 30 EJ/yr, was traditional biomass. In contrast, by 2030, many scenarios indicate a doubling of RE deployment or more compared to today, and this is accompanied in most scenarios by a reduction in traditional biomass, implying substantial growth in non-traditional RE sources. By 2050, RE deployment levels in most scenarios are higher than 100 EJ/yr (median at 173 EJ/yr), reach 200 EJ/yr in many of the scenarios and more than 400 EJ/yr in some cases. Given that traditional biomass use decreases in most scenarios, the scenarios represent an increase in RE production (excluding traditional biomass) of anywhere from roughly three- to more than ten-fold. More than half of the scenarios show a contribution of RE in excess of a 17% share of primary energy supply in 2030, rising to more than 27% in 2050. The scenarios with the highest RE shares reach approximately 43% in 2030 and 77% in 2050. Deployments after 2050 are even larger. This is an extraordinary expansion in energy production from RE. [10.2.2.2]

Indeed, RE deployment is quite large in many of the baseline scenarios with no assumed GHG concentration stabilization level. By 2030, RE deployment levels of up to about 120 EJ/yr are projected, with many baseline scenarios reaching more than 100 EJ/yr in 2050 and in some cases up to 250 EJ/yr. These large RE baseline deployments result from a range of underlying scenario assumptions, for example, the assumption that energy consumption will continue to grow substantially throughout the century, assumptions about the ability of RE to contribute to increased energy access, assumptions about the availability of fossil resources, and other assumptions (e.g., improved costs and performance of RE technologies) that would render RE technologies economically increasingly competitive in many applications even absent climate policy. [10.2.2.2]

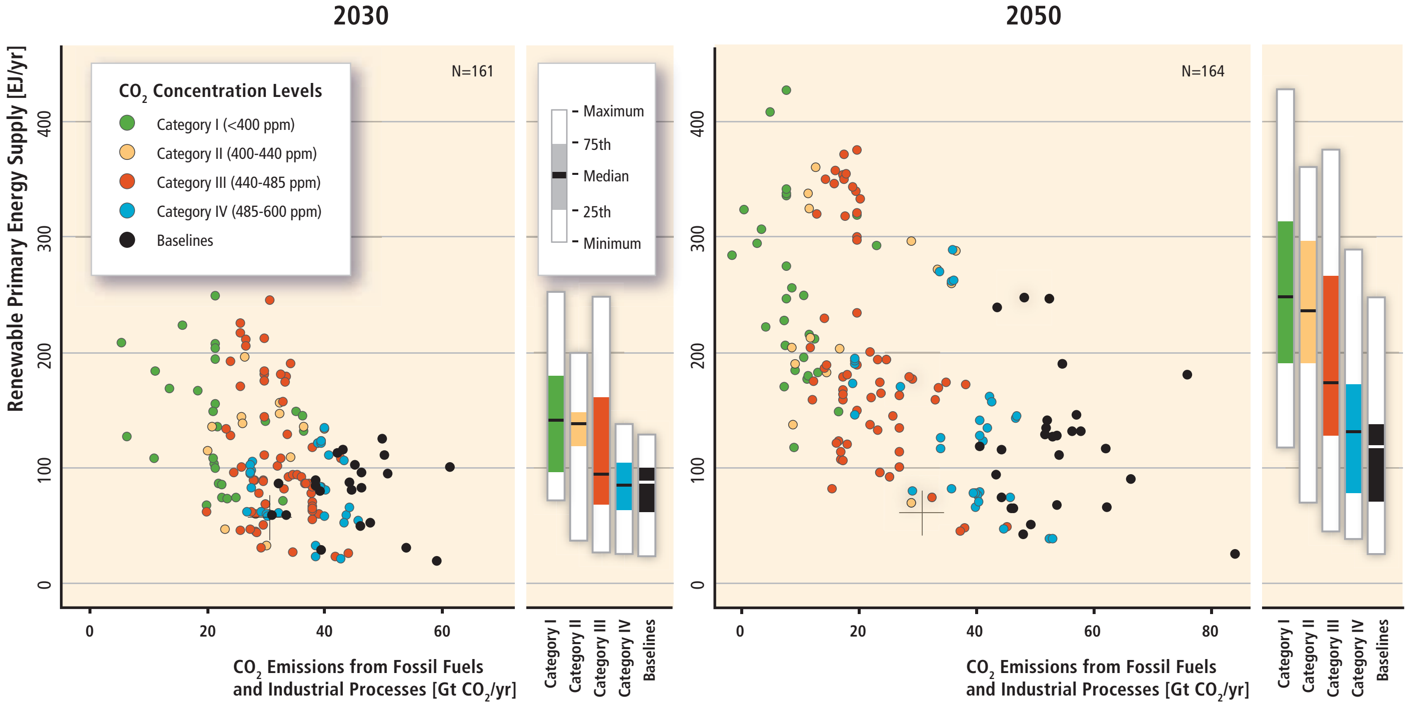


Figure TS.10.1 | Global RE primary energy supply (direct equivalent) from 164 long-term scenarios as a function of fossil and industrial CO_2 emissions in 2030 and 2050. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100. The panels to the right of the scatterplots show the deployment levels of RE in each of the atmospheric CO_2 concentration categories. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. The blue crossed-lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are -0.40 (2030) and -0.55 (2050). For data reporting reasons, only 161 scenarios are included in the 2030 results shown here, as opposed to the full set of 164 scenarios. RE deployment levels below those of today are a result both of model output as well as differences in the reporting of traditional biomass. [Figure 10.2]

The uncertainty in RE's role in climate mitigation results from uncertainty regarding a number of important forces that influence the deployment of RE. Two important factors are energy demand growth and the competition with other options to reduce CO_2 emissions (primarily nuclear energy and fossil energy with CCS). Meeting long-term climate goals requires a reduction in the CO_2 emissions from energy and other anthropogenic sources. For any given climate goal, this reduction is relatively well defined; there is a tight relationship between fossil and industrial CO_2 emissions and the deployment of freely emitting fossil energy across the scenarios (Figure TS.10.2). The demand for low-carbon energy (including RE, nuclear energy and fossil energy with CCS) is simply the difference between total primary energy demand and the production of freely-emitting fossil energy; that is, whatever energy cannot be supplied by freely-emitting fossil energy because of climate constraints must be supplied either by low-carbon energy or by measures that reduce energy consumption. However, scenarios indicate enormous uncertainty about energy demand growth, particularly many decades into the future. This variation is generally much larger than the effect of mitigation on energy consumption. Hence, there is substantial variability in low-carbon energy for any given CO_2 concentration goal due to variability in energy demand (Figure TS.10.2). [10.2.2.3]

The competition between RE, nuclear energy, and fossil energy with CCS then adds another layer of variability in the relationship between RE deployment and the CO_2 concentration goal. The cost, performance and availability of the competing supply side options—nuclear energy and fossil energy with CCS—is also uncertain. If the option to deploy these other supply-side mitigation technologies is constrained—because of cost and performance, but also potentially due to environmental, social or national security barriers—then, all things being equal, RE deployment levels will be higher (Figure TS.10.3). [10.2.2.4]

There is also great variation in the deployment characteristics of individual RE technologies. The absolute scales of deployments vary considerably among technologies and also deployment magnitudes are characterized by greater variation for some technologies relative to others (Figures TS.10.4 and TS.10.5). Further, the time scale of deployment varies across different RE sources, in large part representing differences in deployment levels today and (often) associated assumptions about relative technological maturity. [10.2.2.5]

The scenarios generally indicate that RE deployment is larger in non-Annex I countries over time than in the Annex I countries. Virtually all scenarios include the assumption that economic and energy demand growth will be larger at some point in the future in the non-Annex I countries than in the Annex I countries. The result is that the non-Annex I countries account for an increasingly large proportion of CO_2 emissions in baseline, or no-policy, cases and must therefore make larger emissions reductions over time (Figure TS.10.4). [10.2.2.5]

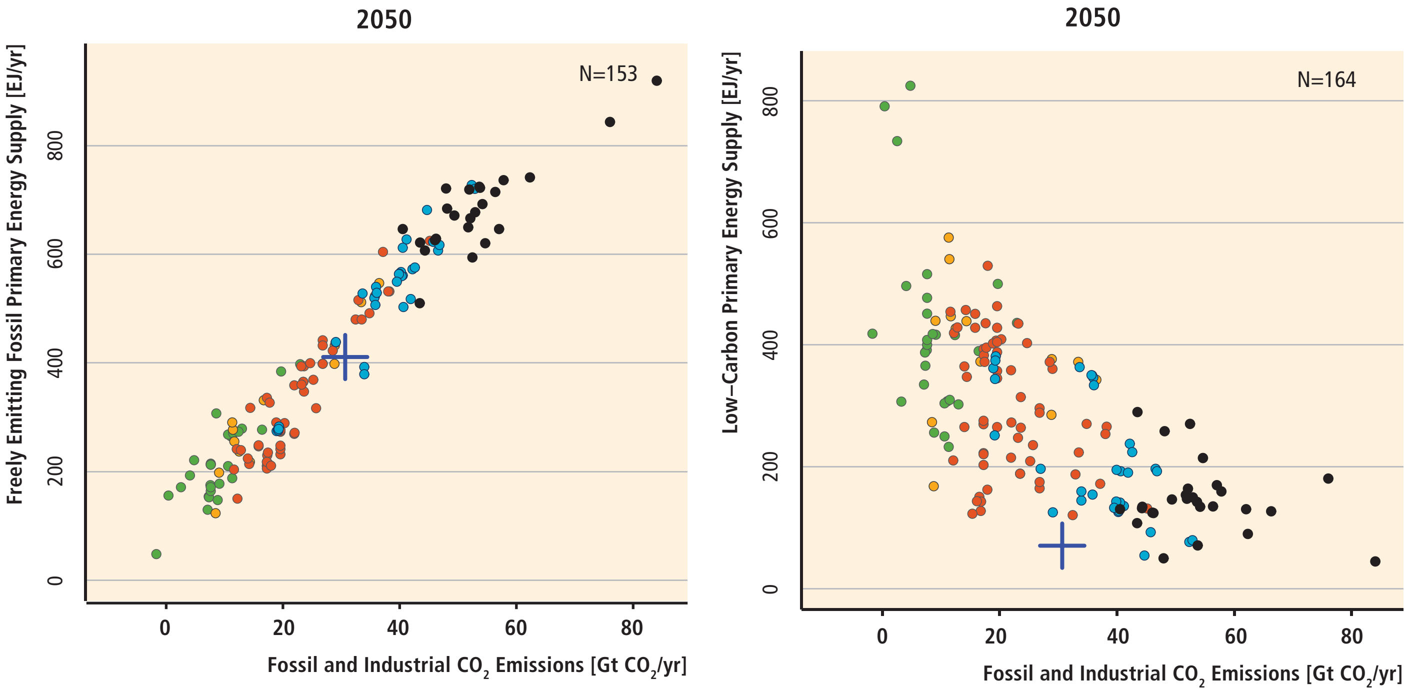


Figure TS.10.2 | Global freely emitting fossil fuel (left panel; direct equivalent) and low-carbon primary energy supply (right panel; direct equivalent) in 164 long-term scenarios in 2050 as a function of fossil and industrial CO_2 emissions. Low-carbon energy refers to energy from RE, fossil energy with CCS, and nuclear energy. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100. The blue crossed lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are 0.97 (freely emitting fossil) and -0.68 (low-carbon energy). For data reporting reasons, only 153 scenarios and 161 scenarios are included in the freely-emitting fossil and low-carbon primary energy results shown here, respectively, as opposed to the full set of 164 scenarios. [Figure 10.4, right panel, Figure 10.5, right panel]

Another fundamental question regarding RE and mitigation is the relationship between RE and mitigation costs. A number of studies have pursued scenario sensitivities that assume constraints on the deployment of individual mitigation options, including RE as well as nuclear energy and fossil energy with CCS (Figures TS.10.6 and TS.10.7). These studies indicate that mitigation costs are higher when options, including RE, are not available. Indeed, the cost penalty for limits on RE is often at least of the same order of magnitude as the cost penalty for limits on nuclear energy and fossil energy with CCS. The studies also indicate that more aggressive concentration goals may not be possible when RE options, or other low-carbon options, are not available. At the same time, when taking into account the wide range of assumptions across the full range of scenarios explored in this assessment, the scenarios demonstrate no meaningful link between measures of cost (e.g., carbon prices) and absolute RE deployment levels. This variation is a reflection of the fact that large-scale integrated models used to generate scenarios are characterized by a wide range of carbon prices and mitigation costs based on both parameter assumptions and model structure. To summarize, while there is an agreement in the literature that mitigation costs will increase if the deployment of RE technologies is constrained and that more ambitious concentration stabilization levels may not be reachable, there is little agreement on the precise magnitude of the cost increase. [10.2.2.6]

10.3 Assessment of representative mitigation scenarios for different renewable energy strategies

An in-depth analysis of 4 selected illustrative scenarios from the larger set of 164 scenarios allowed a more detailed look at the possible contribution of specific RE technologies in different regions and sectors. The IEA's World Energy Outlook (IEA WEO 2009) was selected as an example of a baseline scenario, while the other scenarios set clear GHG concentration stabilization levels. The chosen mitigation scenarios are ReMIND-RECIPE from the Potsdam Institute, MiniCAM EMF 22 from the Energy Modelling Forum Study 22 and the Energy [R] evolution scenario from the German Aerospace Centre, Greenpeace International and EREC (ER 2010). The scenarios work as illustrative examples, but they are not representative in a strict sense. However they represent four different future paths based on different methodologies and a wide range of underlying assumptions. Particularly, they stand for different RE deployment paths reaching from a typical

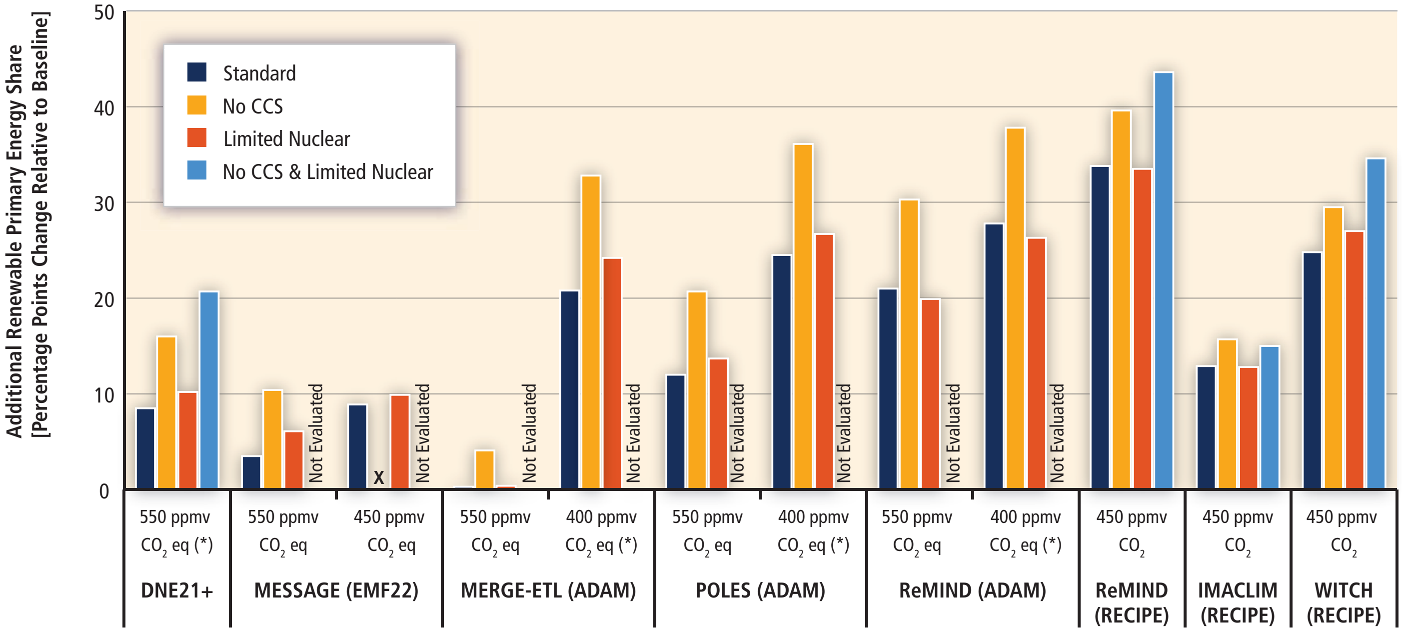


Figure TS.10.3 | Increase in global renewable primary energy share (direct equivalent) in 2050 in selected constrained technology scenarios compared to the respective baseline scenarios. The 'X' indicates that the respective concentration level for the scenario was not achieved. The definition of 'lim Nuclear' and 'no CCS' cases varies across models. The DNE21+, MERGE-ETL and POLES scenarios represent nuclear phase-outs at different speeds; the MESSAGE scenarios limit the deployment to 2010; and the ReMIND, IMACLIM and WITCH scenarios limit nuclear energy to the contribution in the respective baseline scenarios, which can still imply a significant expansion compared to current deployment levels. The REMIND (ADAM) 400 ppmv no CCS scenario refers to a scenario in which cumulative CO_2 storage is constrained to 120 Gt CO_2. The MERGE-ETL 400 ppmv no CCS case allows cumulative CO_2 storage of about 720 Gt CO_2. The POLES 400 ppmv CO_2eq no CCS scenario was infeasible and therefore the respective concentration level of the scenario shown here was relaxed by approximately 50 ppm CO_2. The DNE21+ scenario is approximated at 550 ppmv CO_2eq based on the emissions pathway through 2050. [Figure 10.6]

baseline perspective to a scenario that follows an optimistic application path for RE assuming that amongst others driven by specific policies the current high dynamic (increase rates) in the sector can be maintained. [10.3.1]

Figure TS.10.8 provides an overview of the resulting primary energy production by source for the four selected scenarios for 2020, 2030 and 2050 and compares the numbers with the range of the global primary energy supply. Using the direct equivalent methodology as done here, in 2050 bioenergy has the highest market share in all selected scenarios, followed by solar energy. The total RE share in the primary energy mix by 2050 has a substantial variation across all four scenarios. With 15% by 2050—more or less about today's level (12.9% in 2008)—the IEA WEO 2009 projects the lowest primary RE share, while the ER 2010 with 77% marks the upper level. The MiniCam EMF 22 expects that 31% and ReMIND-RECIPE that 48% of the world's primary energy demand will be provided by RE in 2050. The wide ranges of RE shares are a function of different assumptions for technology cost and performance data, availability of other mitigation technologies (e.g., CCS, nuclear power), infrastructure or integration constraints, non-economic barriers (e.g., sustainability aspects), specific policies and future energy demand projections. [10.3.1.4]

In addition, although deployment of the different technologies significantly increases over time, the resulting contribution of RE in the scenarios for most technologies in the different regions of the world is much lower than their corresponding technical potentials (Figure TS.10.9). The overall total global RE deployment by 2050 in all analyzed scenarios represents less than 3% of the available technical RE potential. On a regional level, the maximum deployment share out of the overall technical potential for RE in 2050 was found for China, with a total of 18% (ER 2010), followed by OECD Europe with 15% (ER 2010) and India with 13% (MiniCam EMF 22). Two regions have deployment rates of around 6% of the regional available technical RE potential by 2050: 7% in Developing Asia (MiniCam EMF 22) and 6% in OECD North America (ER 2010). The remaining five regions use less than 5% of the available technical potential for RE. [10.3.2.1]

Based on the resulting RE deployment for the selected four illustrative scenarios, the corresponding GHG mitigation potential has been calculated. For each sector, emission factors have been specified, addressing the kind of electricity generation or heat supply that RE displaces. As the substituted energy form depends on the overall system behaviour, this cannot be done exactly without conducting new and consistent scenario analysis or complex power plant dispatching analysis. Therefore, the calculation is necessarily based on simplified assumptions and can only be seen as indicative. Generally, attribution of precise mitigation potentials to RE should be viewed with caution. [10.3.3]

Very often RE applications are supposed to fully substitute for the existing mix of fossil fuel use, but in reality that may not be true as RE can compete, for instance, with nuclear energy or within the RE portfolio itself. To cover the uncertainties even partly for the specification of the emission factor, three different cases have been distinguished

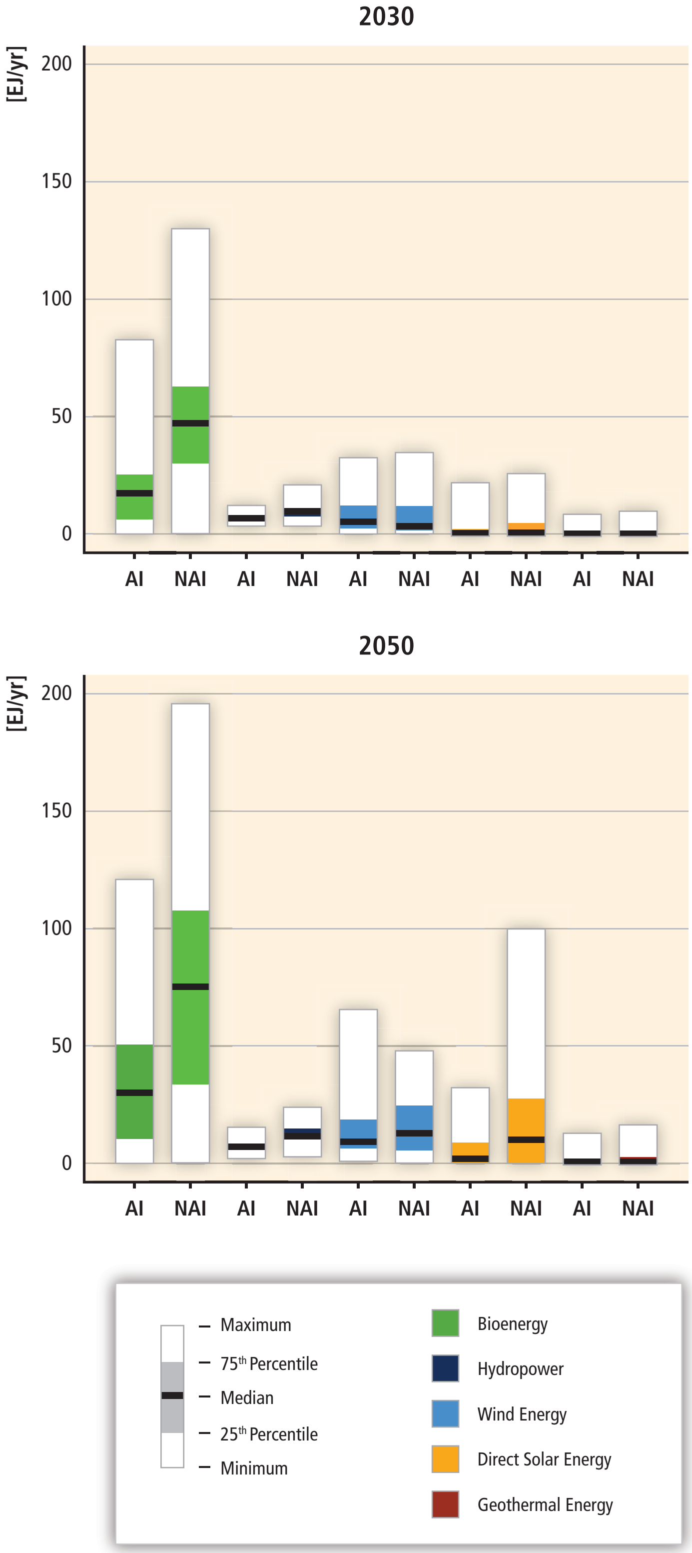


Figure TS.10.4 | Global RE primary energy supply (direct equivalent) by source in Annex I (AI) and Non-Annex I (NAI) countries in 164 long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. Depending on the source, the number of scenarios underlying these figures varies between 122 and 164. Although instructive for interpreting the information, it is important to note that the 164 scenarios are not explicitly a random sample meant for formal statistical analysis. (One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as ethanol or electricity. The other technologies produce primarily (but not entirely) electricity, and they are accounted for based on the electricity produced. If primary equivalents were used, based on the substitution method, rather than direct equivalents, then energy production from non-biomass RE would be of the order of three times larger than shown here.) Ocean energy is not presented here as only very few scenarios consider this RE technology. [Figure 10.8]

(upper case: specific average CO_2 emissions of the fossil generation mix under the baseline scenario; medium case: specific average CO_2 emissions of the overall generation mix under the baseline scenario; and lower case: specific average CO_2 emissions of the generation mix of the particular analyzed scenario). Biofuels and other RE options for transport are excluded from the calculation due to limited data availability.

Additionally, to reflect the embedded GHG emissions from bioenergy used for direct heating, only half of the theoretical CO_2 savings have been considered in the calculation. Given the high uncertainties and variability of embedded GHG emissions, this is necessarily once more a simplified assumption. [10.3.3]

Figure TS.10.10 shows cumulative CO_2 reduction potentials from RE sources up to 2020, 2030 and 2050 resulting from the four scenarios reviewed here in detail. The analyzed scenarios outline a cumulative reduction potential (2010 to 2050) in the medium-case approach of between 244 Gt CO_2 (IEA WEO 2009) under the baseline conditions, 297 Gt CO_2 (MiniCam EMF 22), 482 Gt CO_2 (ER 2010) and 490 Gt CO_2 (ReMIND-RECIPE scenario). The full range across all calculated cases and scenarios is cumulative CO_2 savings of 218 Gt CO_2 (IEA WEO 2009) to 561 Gt CO_2 (ReMIND-RECIPE) compared to about 1,530 Gt CO_2 cumulative fossil and industrial CO_2 emissions in the WEO 2009 Reference scenario during the same period. However, these numbers exclude CO_2 savings for RE use in the transport sector (including biofuels and electric vehicles). The overall CO_2 mitigation potential can therefore be higher. [10.3.3]

10.4 Regional cost curves for mitigation with renewable energy sources

The concept of supply curves of carbon abatement, energy, or conserved energy all rest on the same foundation. They are curves consisting typically of discrete steps, each step relating the marginal cost of the abatement measure/energy generation technology or measure to conserve energy to its potential; these steps are ranked according to their cost. Graphically, the steps start at the lowest cost on the left with the next highest cost added to the right and so on, making an upward sloping left-to-right marginal cost curve. As a result, a curve is obtained that can be interpreted similarly to the concept of supply curves in traditional economics. [10.4.2.1]

The concept of energy conservation supply curves is often used, but it has common and specific limitations. The most often cited limitations in

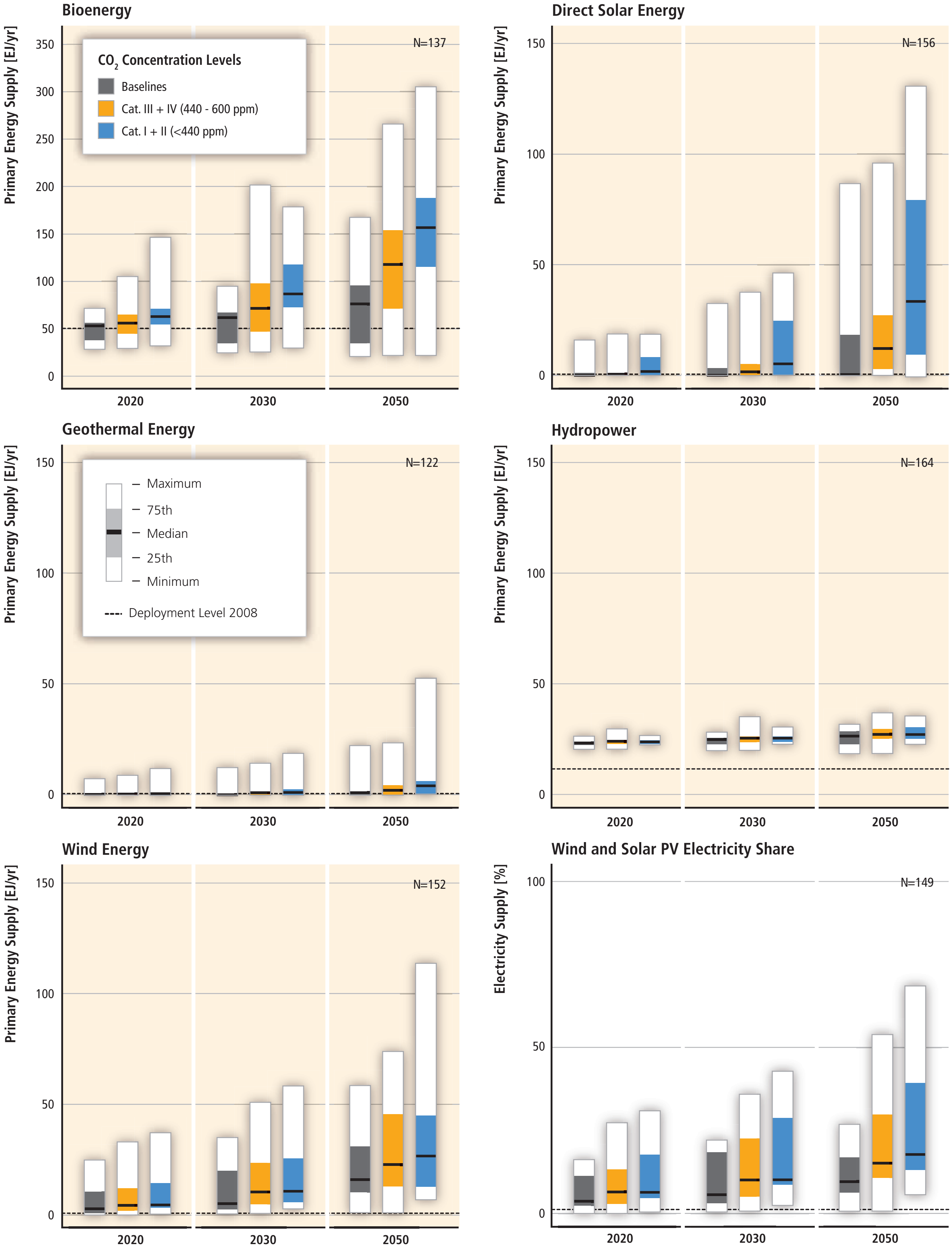

Bioenergy
CO₂ Concentration Levels
Baselines
Cat. III + IV (440 - 600 ppm)
Cat. I + II (<440 ppm)
N=137
Primary Energy Supply [EJ/yr]
350
300
250
200
150
100
50
0
2020
2030
2050
Direct Solar Energy
N=156
Primary Energy Supply [EJ/yr]
150
100
50
0
2020
2030
2050
Geothermal Energy
Maximum
75th
Median
25th
Minimum
Deployment Level 2008
N=122
Primary Energy Supply [EJ/yr]
150
100
50
0
2020
2030
2050
Hydropower
N=164
Primary Energy Supply [EJ/yr]
150
100
50
0
2020
2030
2050
Wind Energy
N=152
Primary Energy Supply [EJ/yr]
150
100
50
0
2020
2030
2050
Wind and Solar PV Electricity Share
N=149
Electricity Supply [%]
100
50
0
2020
2030
2050

Figure TS.10.5 | (Preceding page) Global primary energy supply (direct equivalent) of biomass, wind, solar, hydro, and geothermal energy in 164 long-term scenarios in 2020, 2030 and 2050, and grouped by different categories of atmospheric CO_2 concentration level in 2100. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. [Figure 10.9]

Notes: For data reporting reasons, the number of scenarios included in each of the panels shown here varies considerably. The number of scenarios underlying the individual panels, as opposed to the full set of 164 scenarios, is indicated in the right upper corner of each panel. One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as biofuels, electricity and heat. The other technologies produce primarily (but not entirely) electricity and heat, and they are accounted for based on this secondary energy produced. If primary equivalents based on the substitution method were used rather than direct equivalent accounting, then energy production from non-biomass RE would be of the order of two to three times larger than shown here. Ocean energy is not presented here as scenarios so far seldom consider this RE technology. Finally, categories V and above are not included and Category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100, and because the lowest baselines scenarios reach concentration levels of slightly more than 600 ppm by 2100.

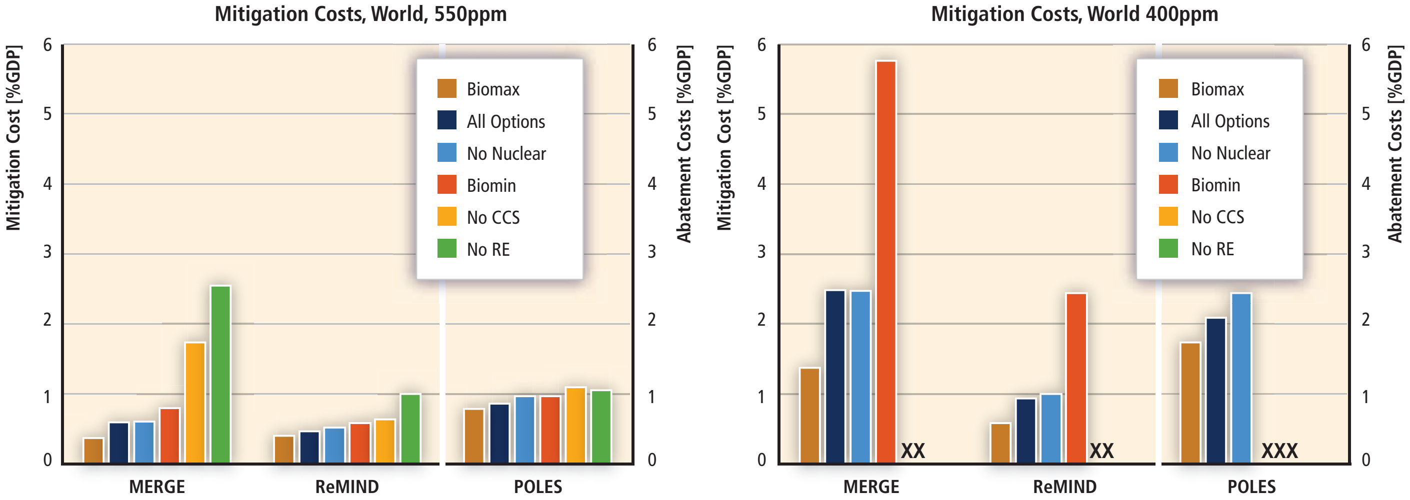


Figure TS.10.6 | Global mitigation costs (measured in terms of consumption loss) from the ADAM project under varying assumptions regarding technology availability for long-term stabilization levels of 550 and 400 ppmv CO_2eq. 'All options' refers to the standard technology portfolio assumptions in the different models, while 'biomax' and 'biomin' assume double and half the standard biomass potential of 200 EJ respectively. 'noccs' excludes CCS from the mitigation portfolio and 'nonuke' and 'norenew' constrain the deployment levels of nuclear and RE to the baseline level, which still potentially means a considerable expansion compared to today. The 'X' in the right panel indicates non-attainability of the 400 ppmv CO_2eq level in the case of limited technology options. [Figure 10.11]

this context are: controversy among scientists about potentials at negative costs; simplification of reality as actors also base their decisions on other criteria than those reflected in the curves; economic and technological uncertainty inherent to predicting the future, including energy price developments and discount rates; further uncertainty due to strong aggregation; high sensitivity relative to baseline assumptions and the entire future generation and transmission portfolio; consideration of individual measures separately, ignoring interdependencies between measures applied together or in different order; and, for carbon abatement curves, high sensitivity to (uncertain) emission factor assumptions. [10.4.2.1]

Having these criticisms in mind, it is also worth noting that it is very difficult to compare data and findings from RE abatement cost and supply curves, as very few studies have used a comprehensive and consistent approach that details their methodologies. Many of the regional and country studies provide less than 10% abatement of the baseline CO_2 emissions over the medium term at abatement costs under approximately USD_{2005} 100/t CO_2. The resulting low-cost abatement potentials are quite low compared to the reported mitigation potentials of many of the scenarios reviewed here. [10.4.3.2]

10.5 Cost of commercialization and deployment

Some RE technologies are broadly competitive with current market energy prices. Many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favourable resource conditions or that lack the infrastructure for other low-cost energy supplies. In most regions of the world, however, policy measures are still required to ensure rapid deployment of many RE sources. [2.7, 3.8, 4.6, 5.8, 6.7, 7.8, 10.5.1, Figure TS.1.9]

Figures TS.10.11 and TS.10.12 provide additional data on levelized costs of energy (LCOE), also called levelized unit costs or levelized generation costs, for selected renewable power technologies and for renewable heating technologies, respectively. Figure TS.10.13 shows the levelized

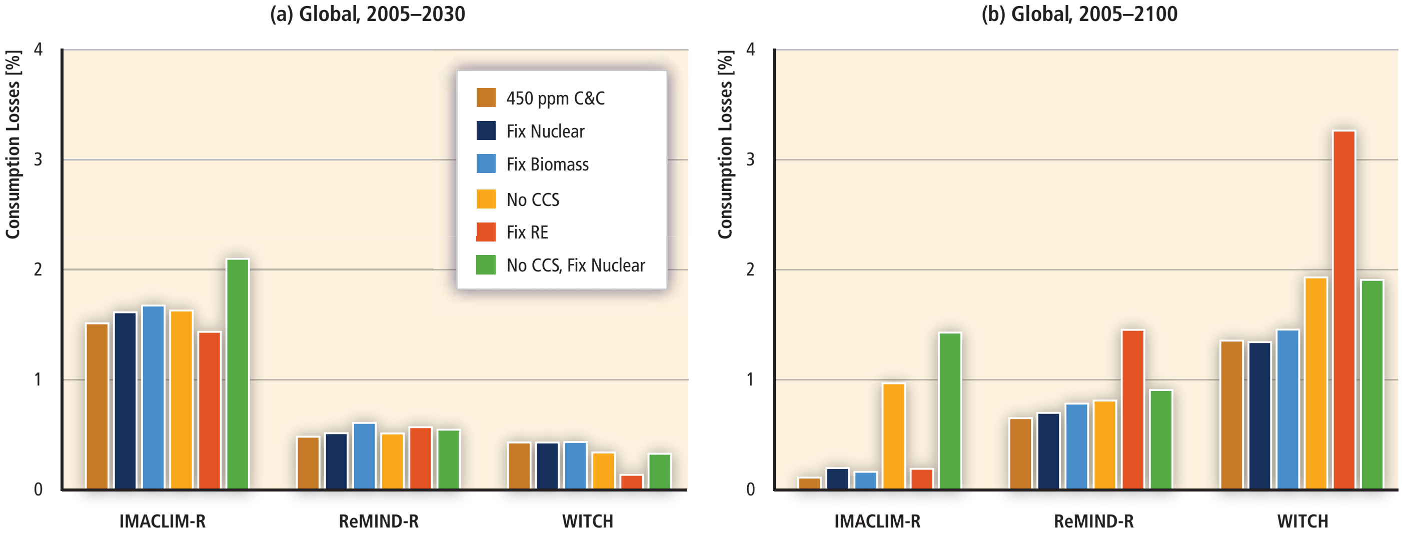


Figure TS.10.7 | Mitigation costs from the RECIPE project under varying assumptions regarding technology availability for a long-term stabilization level of 450 ppmv CO$_2$. Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to baseline levels (all other technologies) for the periods a) 2005 to 2030 and b) 2005 to 2100. Option values are calculated as differences in consumption losses for a scenario in which the use of certain technologies is limited with respect to the baseline scenario. Note that for WITCH, the generic backstop technology was assumed to be unavailable in the 'fix RE' scenario. [Figure 10.12]

cost of transport fuels (LCOF). LCOEs capture the full costs (i.e., investment costs, O&M costs, fuel costs and decommissioning costs) of an energy conversion installation and allocate these costs over the energy output during its lifetime, although not taking into account subsidies or policy incentives. As some RE technologies (e.g., PV, CSP and wind energy) are characterized by high shares of investment costs relative to variable costs, the applied discount rate has a prominent influence on the LCOE of these technologies (see Figures TS.10.11, TS.10.12 and TS.10.13). [10.5.1] The LCOEs are based on literature reviews and represent the most current cost data available. The respective ranges are rather broad as the levelized cost of identical technologies can vary across the globe depending on the RE resource base and local costs of investment, financing and O&M. Comparison between different technologies should not be based solely on the cost data provided in Figures TS 1.9,

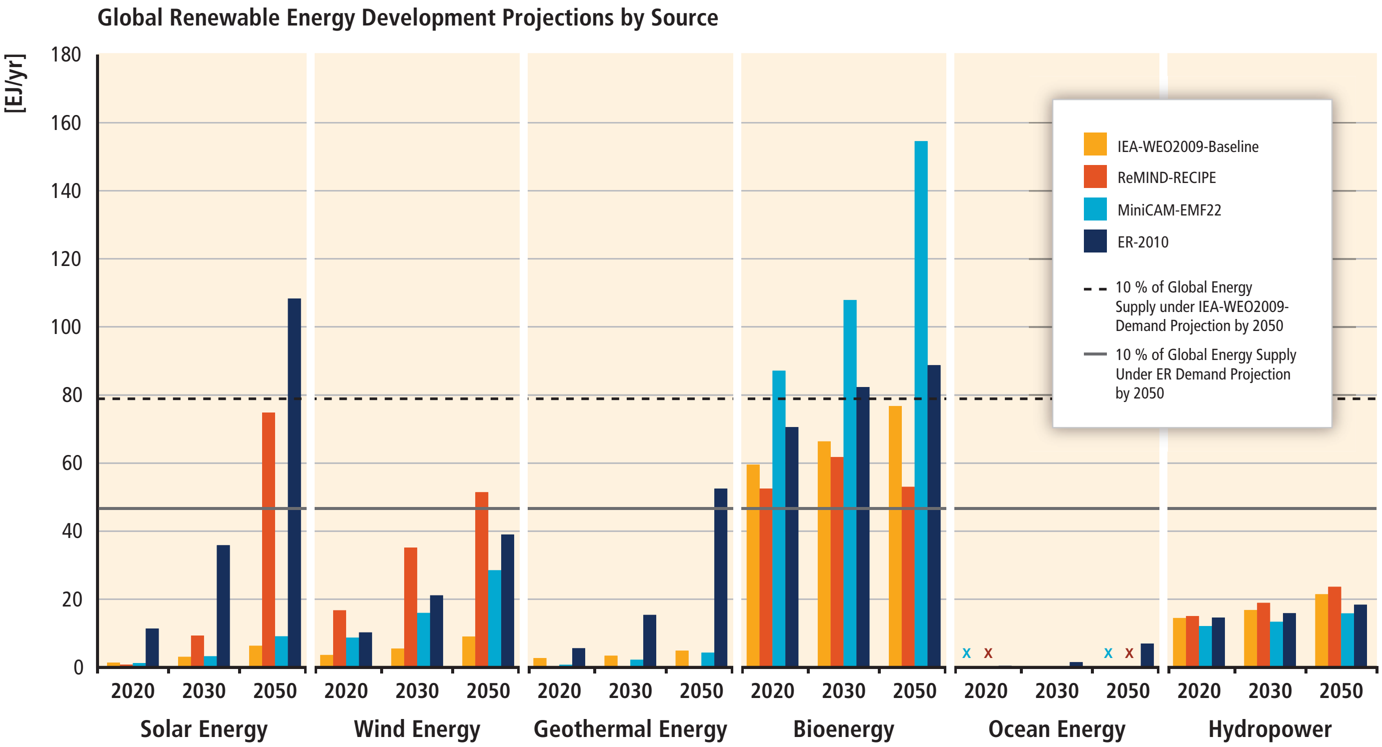
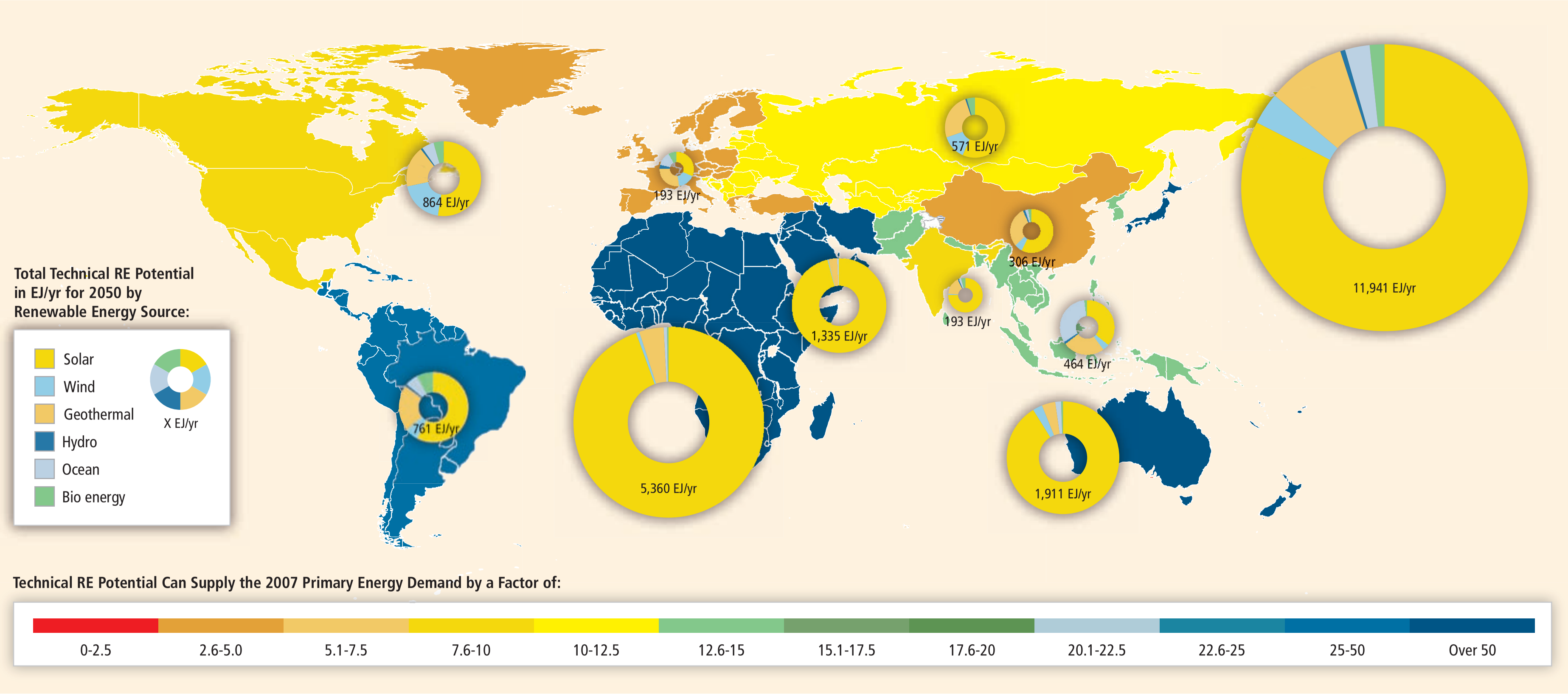


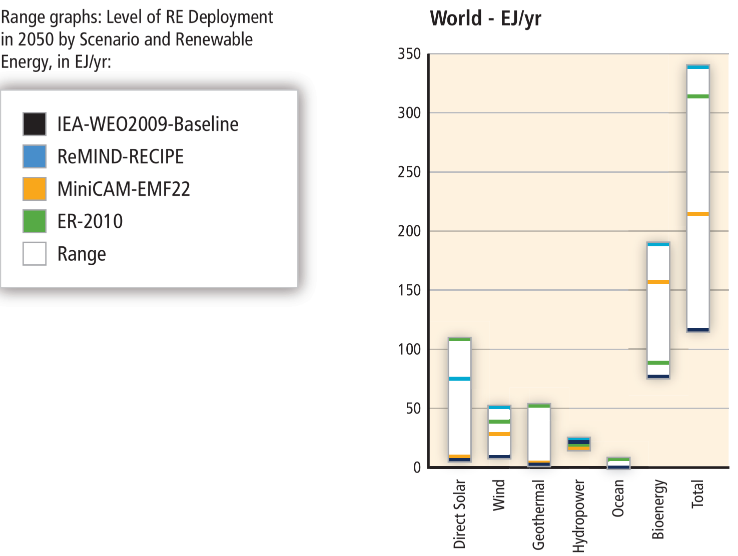
Figure TS.10.8 | Global RE development projections by source and global primary RE shares by source for a set of four illustrative scenarios. [Figure 10.14]

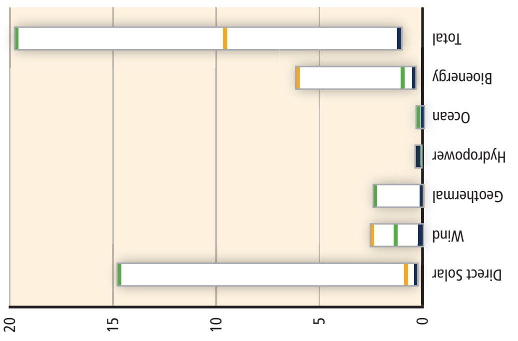


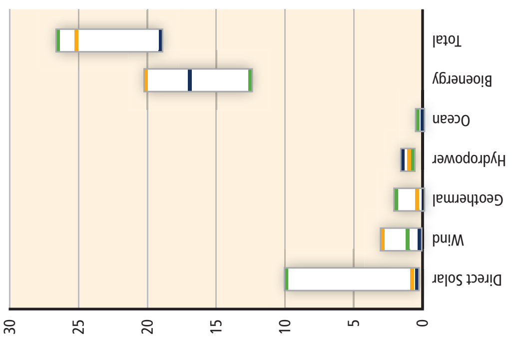
RE potential analysis: Technical RE potentials reported here represent total worldwide and regional potentials based on a review of studies published before 2009 by Krewitt et al. (2009). They do not deduct any potential that is already being utilized for energy production. Due to methodological differences and accounting methods among studies, strict comparability of these estimates across technologies and regions, as well as to primary energy demand, is not possible. Technical RE potential analyses published after 2009 show higher results in some cases but are not included in this figure. However, some RE technologies may compete for land which could lower the overall RE potential.

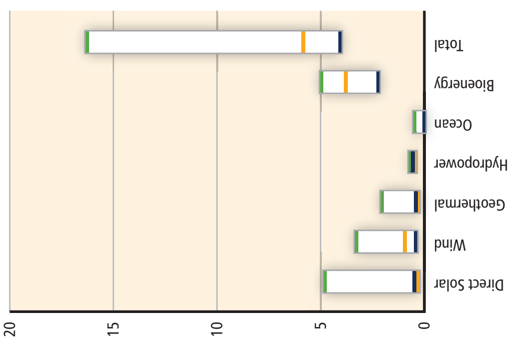
Scenario data: IEA WEO 2009 Reference Scenario (International Energy Agency (IEA), 2009; Teske et al., 2010), ReMIND-RECIPE 450ppm Stabilization Scenario (Luderer et al., 2009), MiniCAM EMF22 1st-best 2.6 W/2 Overshoot Scenario (Calvin et al., 2009), Advanced Energy
[R]evolution 2010 (Teske et al., 2010)

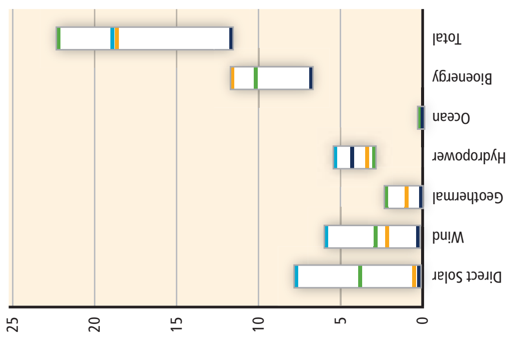
Range graphs: Level of RE Deployment in 2050 by Scenario and Renewable Energy, in EJ/yr:

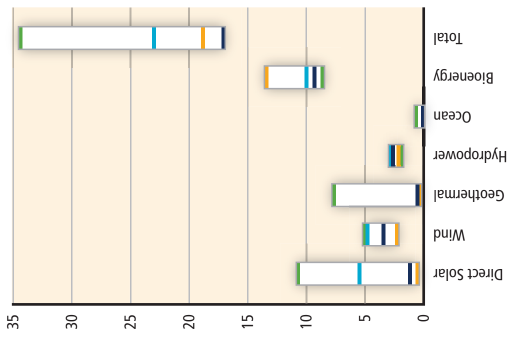


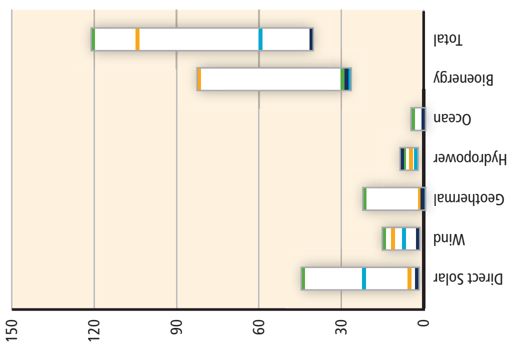

Middle East - EJ/yr

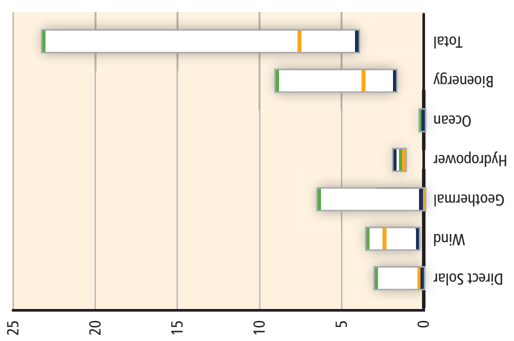

Africa - EJ/yr


OECD Pacific - EJ/yr


Latin America - EJ/yr


OECD Europe - EJ/yr


Developing Asia - EJ/yr


Transition Economies - EJ/yr

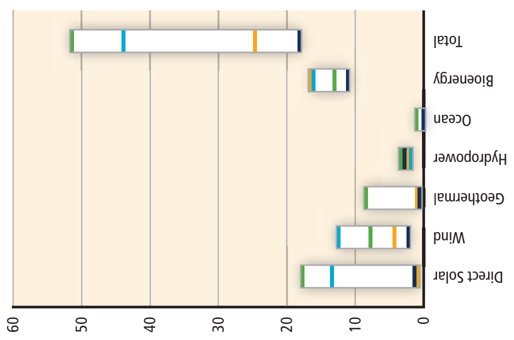

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Figure TS.10.9 | (Preceding pages) Regional breakdown of RE deployment in 2050 for an illustrative set of four scenarios and comparison of the potential deployment to the corresponding technical potential for different technologies. The selected four illustrative scenarios are a part of the comprehensive survey of 164 scenarios. They represent a span from a reference scenario (IEA WEO 2009) without specific GHG concentration stabilization levels to three scenarios representing different CO_2 concentration categories, one of them (REMind-RECIPE) Category III (440 to 485 ppm) and two of them (MiniCam EMF 22 and ER 2010 Category I (<400 ppm). Of the latter, MiniCam EMF 22 includes nuclear energy and CCS as mitigation options and allows overshoot to get to the concentration level, while ER 2010 follows an optimistic application path for RE. Transition economies are countries that changed from a former centrally planned economy to a free market system. [Figure 10.19]

TS 10.11, TS.10.12 and TS.10.13; instead site, project and/or investor-specific conditions should be taken into account. The technology chapters [2.7, 3.8, 4.7, 5.8, 6.7, 7.8] provide useful sensitivities in this respect. [10.5.1]

The cost ranges provided here do not reflect costs of integration (Chapter 8), external costs or benefits (Chapter 9) or costs of policies (Chapter 11). Given suitable conditions, the lower ends of the ranges indicate that some RE technologies already can compete with traditional forms at current energy market prices in many regions of the world. [10.5.1]

The supply cost curves presented [10.4.4, Figures 10.23, 10.25, 10.26, and 10.27] provide additional information about the available resource base (given as a function of the LCOE associated with harvesting it). The supply cost curves discussed [10.3.2.1, Figures 10.15–10.17], in contrast, illustrate the amount of RE that is harnessed (once again as a function of the associated LCOE) in different regions once specific trajectories for the expansion of RE are followed. In addition, it must be emphasized that most of the supply cost curves refer to future points in time (e.g., 2030 or 2050), whereas the LCOE given in the cost sections of the technology chapters as well as those shown in Figures TS.10.11, TS.10.12, and TS.10.13 (and in Annex III) refer to current costs. [10.5.1]

Significant advances in RE technologies and associated cost reductions have been demonstrated over the last decades, though the contribution and mutual interaction of different drivers (e.g., learning by searching, learning by doing, learning by using, learning by interacting, upsizing of technologies, and economies of scale) is not always understood in detail. [2.7, 3.8, 7.8, 10.5.2]

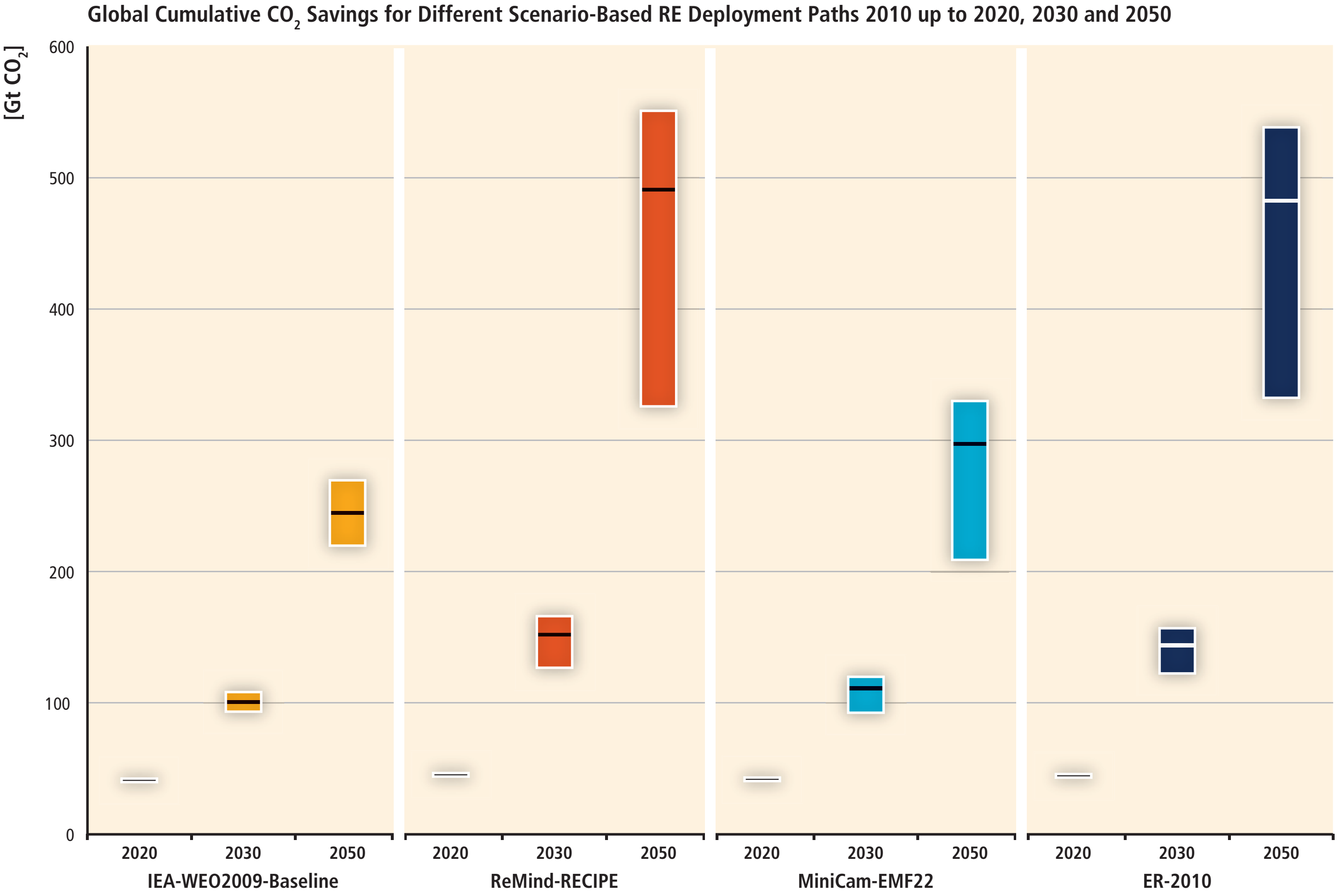


Figure TS.10.10 | Global cumulative CO_2 savings between 2010 and 2050 for four illustrative scenarios. The presented ranges mark the high uncertainties regarding the substituted conventional energy source. While the upper limit assumes a full substitution of high-carbon fossil fuels, the lower limit considers specific CO_2 emissions of the analyzed scenario itself. The line in the middle was calculated assuming that RE displaces the specific energy mix of a reference scenario. [Figure 10.22]

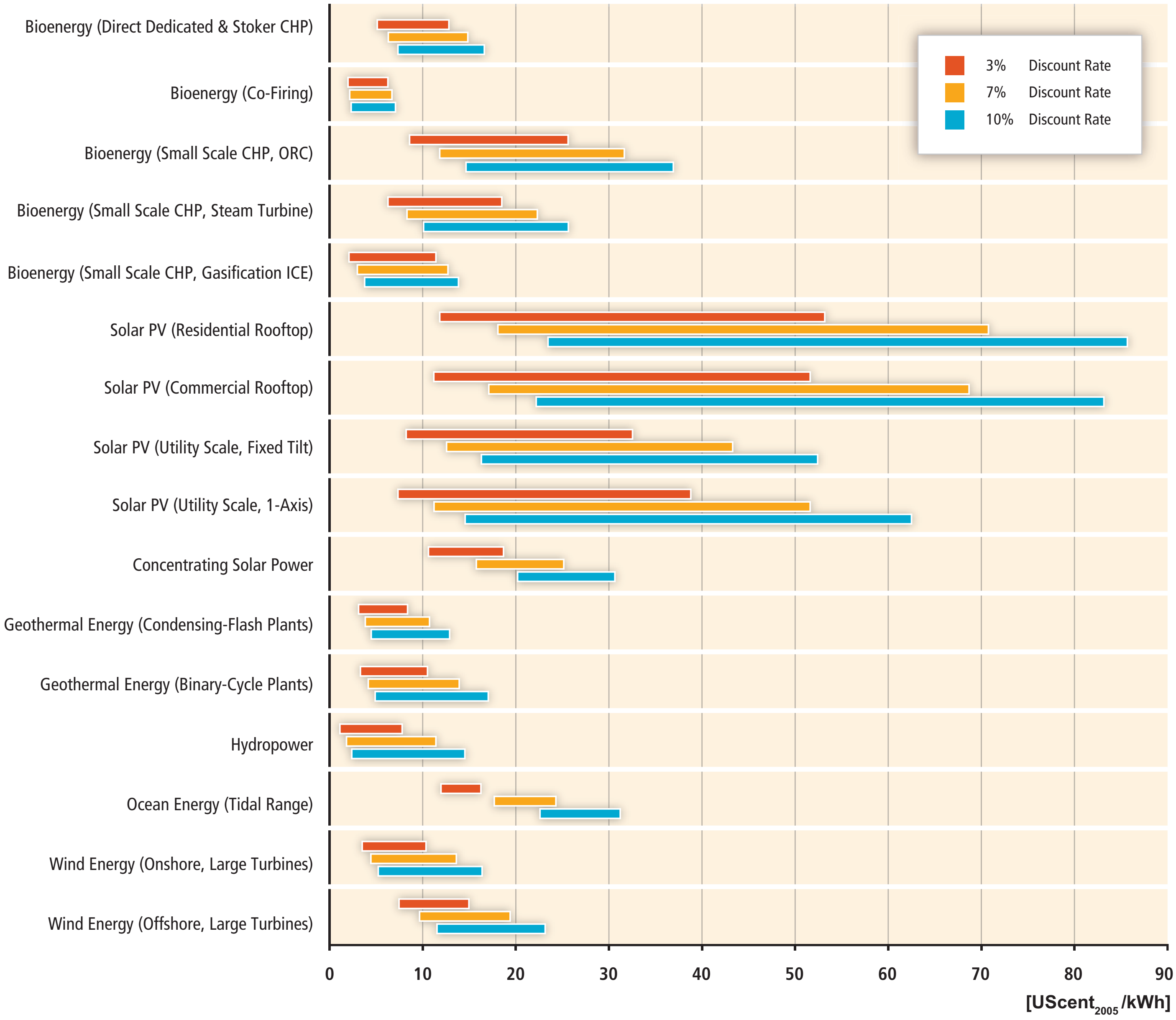


Figure TS.10.11 | Levelized cost of electricity for commercially available RE technologies at 3, 7 and 10% discount rates. The levelized cost of electricity estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that conversion efficiencies, by-product revenue and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III. (CHP: combined heat and power; ORC: organic Rankine cycle, ICE: internal combustion engine.) [Figure 10.29]

From an empirical point of view, the resulting cost decrease can be described by experience (or 'learning') curves. For a doubling of the (cumulative) installed capacity, many technologies showed a more or less constant percentage decrease in the specific investment costs (or in the levelized costs or unit price, depending on the selected cost indicator). The numerical value describing this improvement is called the learning rate (LR). A summary of observed learning rates is provided in Table TS.10.1. [10.5.2]

Any efforts to assess future costs by extrapolating historic experience curves must take into account the uncertainty of learning rates as well as caveats and knowledge gaps discussed. [10.5.6, 7.8.4.1] As a supplementary approach, expert elicitations could be used to gather additional information about future cost reduction potentials, which might be contrasted with the assessments gained by using learning rates. Furthermore, engineering model analyses to identify technology improvement potentials could also provide additional information for developing cost projections. [2.6, 3.7, 4.6, 6.6, 7.7, 10.5.2]

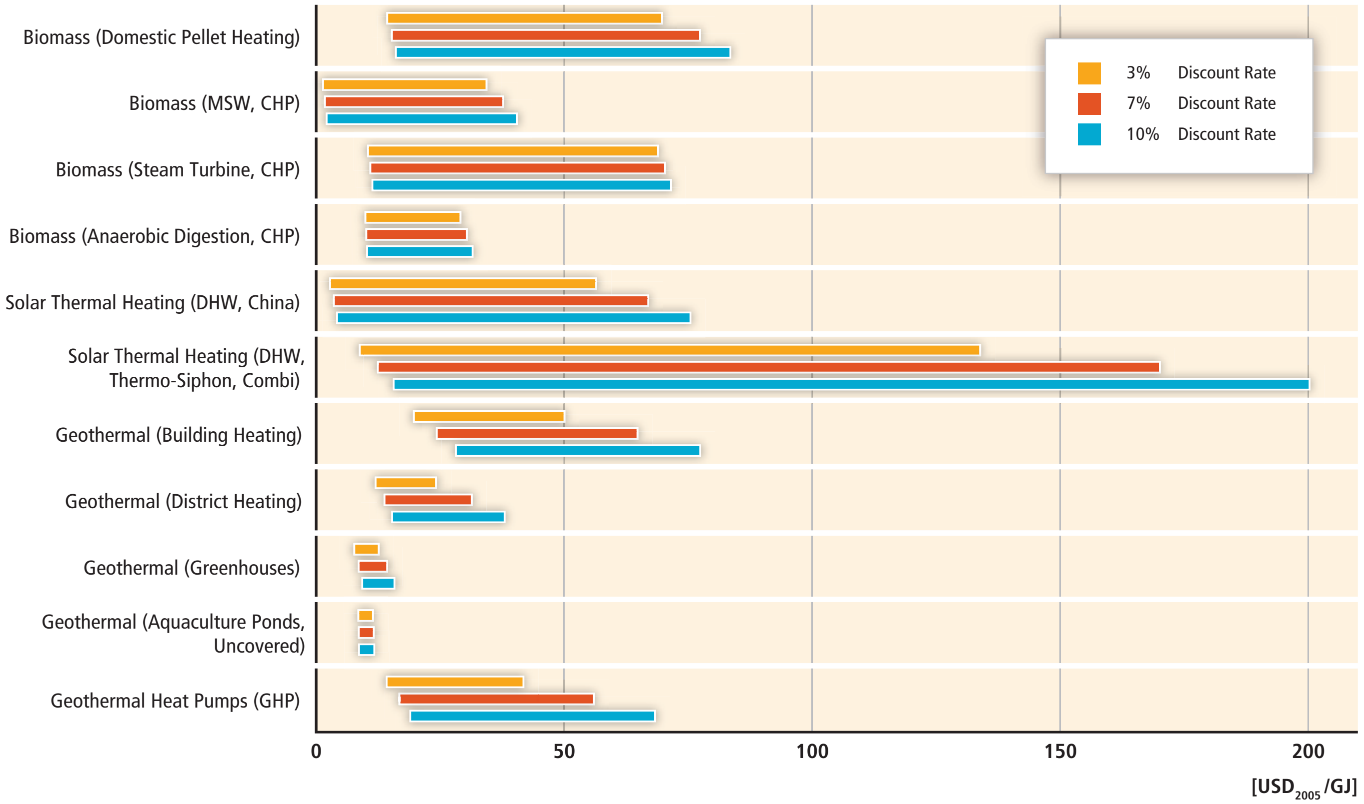


Figure TS.10.12 | Levelized cost of heat (LCOH) for commercially available RE technologies at 3, 7 and 10% discount rates. The LCOH estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that capacity factors and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III. (MSW: municipal solid waste; DHW: domestic hot water.) [Figure 10.30]

Important potential technological advances and associated cost reductions, for instance, are expected in (but are not limited to) the following application fields: next-generation biofuels and biorefineries; advanced PV and CSP technologies and manufacturing processes; enhanced geothermal systems; multiple emerging ocean technologies; and foundation and turbine designs for offshore wind energy. Further cost reductions for hydropower are likely to be less significant than some of the other RE technologies, but R&D opportunities exist to make hydropower projects technically feasible in a wider range of natural conditions and to improve the technical performance of new and existing projects. [2.6, 3.7, 4.6, 5.3, 5.7, 5.8, 6.6, 7.7]

An answer to the question whether or not upfront investments in a specific innovative technology are justified cannot be given as long as the technology is treated in isolation. In a first attempt to clarify this issue and, especially, to investigate the mutual competition of prospective climate protection technologies, integrated assessment modellers have started to model technological learning in an endogenous way. The results obtained from these modelling comparison exercises indicate that—in the context of stringent climate goals—upfront investments in learning technologies can be justified in many cases. [10.5.3.]

However, as the different scenarios considered in Figure TS.10.14 and other studies clearly show, considerable uncertainty surrounds the exact volume and timing of these investments. [10.5.4]

The four illustrative scenarios that were analyzed in detail in Section 10.3 span a range of cumulative global decadal investments (in the power generation sector) ranging from USD$_{2005}$ 1,360 to 5,100 billion (for the decade 2011 to 2020) and from USD$_{2005}$ 1,490 to 7,180 billion (for the decade 2021 to 2030). These numbers allow the assessment of future market volumes and resulting investment opportunities. The lower values refer to the IEA World Energy Outlook 2009 Reference Scenario and the higher ones to a scenario that seeks to stabilize atmospheric CO_2 (only) concentration at 450 ppm. The average annual investments in the reference scenario are slightly lower than the respective investments reported for 2009. Between 2011and 2020, the higher values of the annual averages of the RE power generation sector investment approximately correspond to a three-fold increase in the current global investments in this field. For the next decade (2021 to 2030), a five-fold increase is projected. Even the upper level of the annual investments is smaller than 1% of the world's GDP. Additionally, increasing the installed capacity of

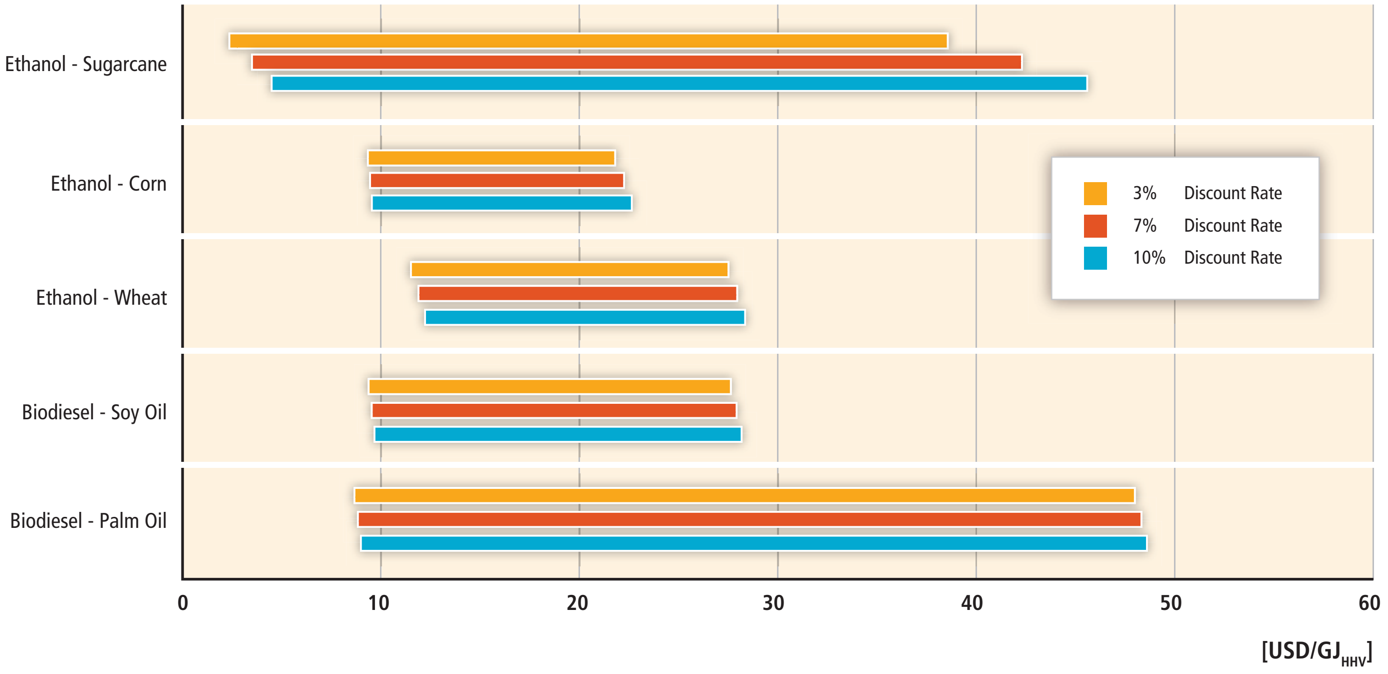


Figure TS.10.13 | Levelized cost of fuels (LCOF) for commercially available biomass conversion technologies at 3, 7 and 10% discount rates. LCOF estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, O&M and feedstock cost. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and feedstock costs. Note that conversion efficiencies, by-product revenue, capacity factors and lifetimes were set to average values. For data and supplementary information see Annex III. (HHV: higher heating value.) [Figure 10.31]

RE power plants will reduce the amount of fossil and nuclear fuels that otherwise would be needed in order to meet a given electricity demand. [10.5.4]

10.6 Social and environmental costs and benefits

Energy extraction, conversion and use cause significant environmental impacts and external costs. Although replacing fossil fuel-based energy with RE often can reduce GHG emissions and also to some extent other environmental impacts and external costs, RE technologies can also have environmental impacts and external costs themselves, depending on the energy source and technology. These impacts and costs should be considered if a comprehensive cost assessment is required. [10.6.2]

Figure TS.10.15 shows the large uncertainty ranges of two dominant external cost components, namely climate- and health-related external costs. Small-scale biomass fired CHP plants cause relatively high external costs due to health effects via particulate emissions. Offshore wind energy seems to cause the smallest external cost. External cost estimates for nuclear power are not reported here because the character and assessment of external costs and risk from release of radionuclides due to low-probability accidents or due to leakages from waste repositories in a distant future are very different, for example, from climate change and air pollution, which are practically unavoidable. Those external impacts related to nuclear power can be, however, considered by discussion and judgment in the society. Accident risks in terms of fatalities due to various energy production chains (e.g., coal, oil, gas and hydro) are generally higher in non-OECD countries than in OECD countries. [10.6.3, 9.3.4.7]

As only external costs of individual technologies are shown in Figure TS.10.15, benefits can be derived when assuming that one technology replaces another one. RE sources and the technologies using them for electricity generation have mostly lower external costs per produced electricity than fossil fuel-based technologies. However, case-specific considerations are needed as there can also be exceptions. [10.6.3]

There are, however, considerable uncertainties in the assessment and valuation of external impacts of energy sources. The assessment of physical, biological and health damages includes considerable uncertainty and the estimates are based typically on calculational models, the results of which are often difficult to validate. The damages or changes seldom have market values that could be used in cost estimation, thus indirect information or other approaches must be used for damage valuation. Further, many of the damages will take place far in the future or in societies very different from those benefiting from the use of the considered energy production, which complicates the

Table TS.10.1 | Observed learning rates for various energy supply technologies. Note that values cited by older publications are less reliable as these refer to shorter time periods. [Table 10.10]

Technology	Source	Country / region	Period	Learning rate (%)	Performance measure
Onshore wind					
	Neij, 1997	Denmark	1982-1995	4	Price of wind turbine (USD/kW)
	Mackay and Probert, 1998	USA	1981-1996	14	Price of wind turbine (USD/kW)
	Neij, 1999	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)
	Neij, 2003	Denmark	1982-1997	8	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)
	Söderholm and Sundqvist, 2007	Germany, UK, Denmark	1986-2000	5	Turnkey investment costs (EUR/kW)
	Neij, 2008	Denmark	1981-2000	17	Electricity production cost (USD/kWh)
	Kahouli-Brahmi, 2009	Global	1979-1997	17	Investment costs (USD/kW)
	Nemet, 2009	Global	1981-2004	11	Investment costs (USD/kW)
	Wiser and Bolinger, 2010	Global	1982-2009	9	Investment costs (USD/kW)
Offshore wind					
	Isles, 2006	8 EU countries	1991-2006	3	Investment cost of wind farms (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 and Eltrop, 2007	Germany	1977-2005	13	Price PV module (EUR/Wpeak)
	Kruck and Eltrop, 2007	Germany	1999-2005	26	Price of balance of system costs
	Nemet, 2009	Global	1976-2006	15-21	Price PV module (USD/Wpeak)
Concentrating Solar Power (CSP)					
	Enermodal, 1999	USA	1984-1998	8-15	Plant investment cost (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., 2005b	Sweden, Finland	1975-2003	15	Forest wood chip prices (EUR/GJ)
	Junginger et al., 2006	Denmark	1984-1991	15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Sweden	1990-2002	8-9	Biomass CHP power (EUR/kWh)
	Junginger et al., 2006	Denmark	1984-2001	0-15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Denmark	1984-1998	12	Biogas plants (€/m^3 biogas/day)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	19	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1980-1985	7	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1985-2002	29	Ethanol from sugarcane (USD/m^3)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	20	Ethanol from sugarcane (USD/m^3)
	Hettinga et al., 2009	USA	1983-2005	18	Ethanol from corn (USD/m^3)
	Hettinga et al., 2009	USA	1975-2005	45	Corn production costs (USD/t corn)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	32	Sugarcane production costs (USD/t)

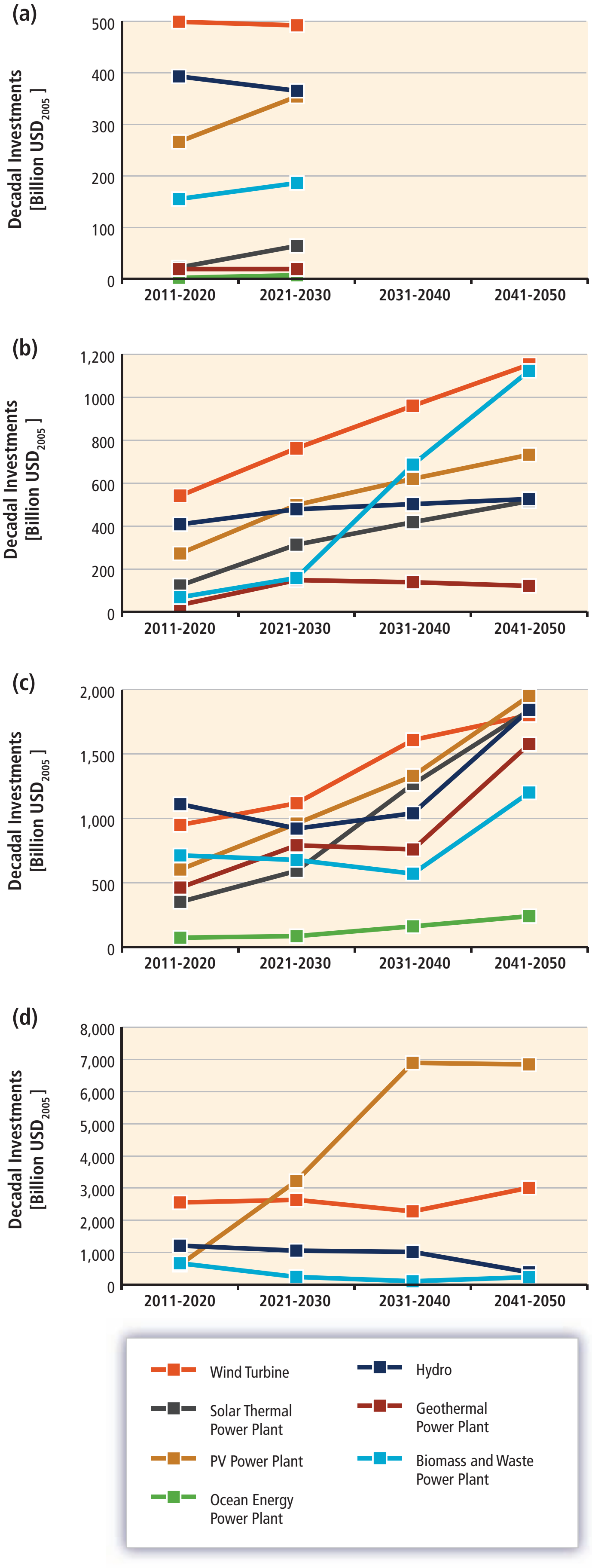


Figure TS.10.14 | Illustrative global *decadal* investments (in billion USD$_{2005}$) needed in order to achieve ambitious climate protection goals: (b) MiniCAM-EMF22 (first-best 2.6 W/m^2 overshoot scenario, nuclear and carbon capture technologies are permitted); (c) ER-2010 (450 ppm CO_2eq, nuclear and carbon capture technologies are not permitted); and (d) ReMIND-RECIPE (450 ppm CO_2, nuclear power plants and carbon capture technologies are permitted). Compared to the other scenarios, the PV share is high in (d) as concentrating solar power has not been considered. For comparison, (a) shows the IEA-WEO2009-Baseline (baseline scenario without climate protection). Sources: (a) IEA (2009); (b) Calvin et al. (2009); (c) Teske et al. (2010); and (d) Luderer et al. (2009).

considerations. These factors contribute to the uncertainty of external costs. [10.6.5]

However, the knowledge about external costs and benefits due to RE sources can provide some guidance for society to select best alternatives and to steer the energy system towards overall efficiency and high welfare gains. [10.6.5]

11. Policy, Financing and Implementation

11.1 Introduction

RE capacity is increasing rapidly around the world, but a number of barriers continue to hold back further advances. Therefore, if RE is to contribute substantially to the mitigation of climate change, and to do so quickly, various forms of economic support policies as well as policies to create an enabling environment are likely to be required. [11.1]

RE policies have promoted an increase in RE shares by helping to overcome various barriers that impede technology development and deployment of RE. RE policies might be enacted at all levels of government—from local to state/provincial to national to international—and range from basic R&D for technology development through to support for installed RE systems or the electricity, heat or fuels they produce. In some countries, regulatory agencies and public utilities may be given responsibility for, or on their own initiative, design and implement support mechanisms for RE. Nongovernmental actors, such as international agencies and development banks, also have important roles to play. [1.4, 11.1, 11.4, 11.5]

RE may be measured by additional qualifiers such as time and reliability of delivery (availability) and other metrics related to RE's integration into networks. There is also much that governments and other actors can do to create an environment conducive for RE deployment. [11.1, 11.6]

11.1.1 The rationale of renewable energy-specific policies in addition to climate change policies

Renewable energies can provide a host of benefits to society. Some RE technologies are broadly competitive with current market energy prices.

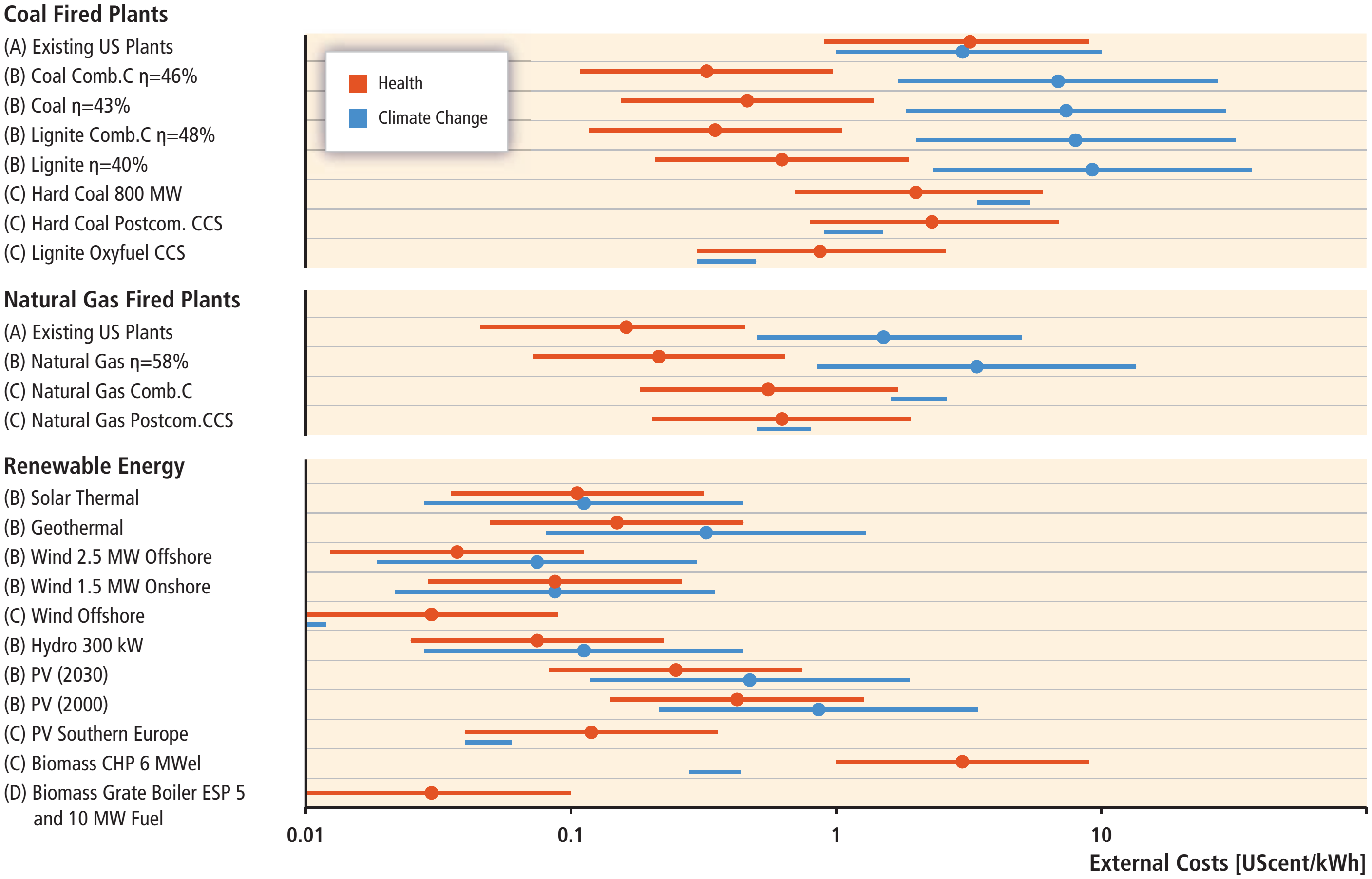


Figure TS.10.15 | Illustration of external costs due to the lifecycle of electricity production based on RE and fossil energy. Note the logarithmic scale of the figure. The black lines indicate the range of the external cost due to climate change and the red lines indicate the range of the external costs due to air pollutant health effects. External costs due to climate change mainly dominate in fossil energy if not equipped with CCS. Comb.C: Combined Cycle; Postcom: Post-Combustion; η: efficiency factor. The results are based on four studies having different assumptions (A–D). The uncertainty for the external costs of health impacts is assumed to be a factor of three. [Figure 10.36]

Of the other RE technologies that are not yet broadly competitive, many can provide competitive energy services in certain circumstances. In most regions of the world, however, policy measures are still required to facilitate an increasing deployment of RE. [11.1, 10.5]

Climate policies (carbon taxes, emissions trading or regulatory policies) decrease the relative costs of low-carbon technologies compared to carbon-intensive technologies. It is questionable, however, whether climate policies (e.g., carbon pricing) alone are capable of promoting RE at sufficient levels to meet the broader environmental, economic and social objectives related to RE. [11.1.1]

Two separate market failures create the rationale for the additional support of innovative RE technologies that have high potential for technological development, even if an emission market (or GHG pricing policy in general) exists. The first market failure refers to the external cost of GHG emissions. The second market failure is in the field of innovation: if firms underestimate the future benefits of investments into learning RE technologies or if they cannot appropriate these benefits, they will invest less than is optimal from a macroeconomic perspective. In addition to GHG pricing policies, RE-specific policies may be appropriate from an economic point of view if the related opportunities for technological development are to be addressed (or if the goals beyond climate change mitigation are pursued). Potentially adverse consequences such as lock-in, carbon leakage and rebound effects should be taken into account in the design of a portfolio of policies. [11.1.1, 11.5.7.3]

11.1.2 Policy timing and strength

The timing, strength and level of coordination of R&D versus deployment policies have implications for the efficiency and effectiveness of the policies, and for the total cost to society in three main ways: 1) whether a country promotes RE immediately or waits until costs have declined further; 2) once a country has decided to support RE, the timing, strength and coordination of when R&D policies give way to deployment policies; and 3) the cost and benefit of accelerated versus slower 'market demand' policy implementation. With regard to the first, in order to achieve full competitiveness with fossil fuel technologies, significant upfront investments in RE will be required until the break-even point is achieved. When those investments should be made depends on the goal. If the international community aims to stabilize global temperature increases at 2°C, then investments in low-carbon technologies must start almost immediately.

11.2 Current trends: Policies, financing and investment

An increasing number and variety of RE policies have driven substantial growth in RE technologies in recent years. 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 a growing number of countries at the municipal, state/provincial and national levels, as well as internationally (see Figure TS.11.1). [1.4, 11.1, 11.2.1, 11.4, 11.5]

Initially, most policies adopted were in developed countries, but an increasing number of developing countries have enacted policy frameworks at various levels of government to promote RE since the late 1990s and early 2000s. Of those countries with RE electricity policies by early 2010, approximately half were developing countries from every region of the world. [11.2.1]

Most countries with RE policies have more than one type of mechanism in place, and many existing policies and targets have been strengthened over time. Beyond national policies, the number of international policies and partnerships is increasing. 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 deployment. [11.2.1]

The focus of RE policies is shifting from a concentration almost entirely on electricity to include the heating/cooling and transportation sectors. These trends are matched by increasing success in the development of a range of RE technologies and their manufacture and implementation (see Chapters 2 through 7), as well as by a rapid increase in annual investment in RE and a diversification of financing institutions, particularly since 2004/2005. [11.2.2]

In response to the increasingly supportive policy environment, the overall RE sector globally has seen a significant rise in the level of investment since 2004-2005. Financing occurs over what is known as the 'continuum' or stages of technology development. The five segments of the continuum are: 1) R&D; 2) technology development and commercialization; 3) equipment manufacture and sales; 4) project construction; and 5) the refinancing and sale of companies, largely through mergers and acquisitions. Financing has been increasing over time in each of these stages, providing indications of the RE sector's current and expected growth, as follows: [11.2.2]

- Trends in (1) R&D funding and (2) technology investment are indicators of the long- to mid-term expectations for the sector—investments are being made that will begin to pay off in several years' time, once the technology is fully commercialized. [11.2.2.2, 11.2.2.3]
- Trends in (3) manufacturing and sales investment are an indicator of near-term expectations for the sector—essentially, that the growth in market demand will continue. [11.2.2.4]
- Trends in (4) construction investment are an indicator of current sector activity, including the extent to which internalizing costs associated with GHGs can result in new financial flows to RE projects. [11.2.2.5]
- Trends in (5) industry mergers and acquisitions can reflect the overall maturity of the sector, and increasing refinancing activity over time indicates that larger, more conventional investors are entering the sector, buying up successful early investments from first movers. [11.2.2.6]

11.3 Key drivers, opportunities and benefits

Renewable energy can provide a host of benefits to society. In addition to the reduction of CO_2 emissions, governments have enacted RE policies to meet any number of objectives, including the creation of local environmental and health benefits; facilitation of energy access, particularly for rural areas; advancement of energy security goals by diversifying the portfolio of energy technologies and resources; and improving social and economic development through potential employment opportunities and economic growth. [11.3.1–11.3.4]

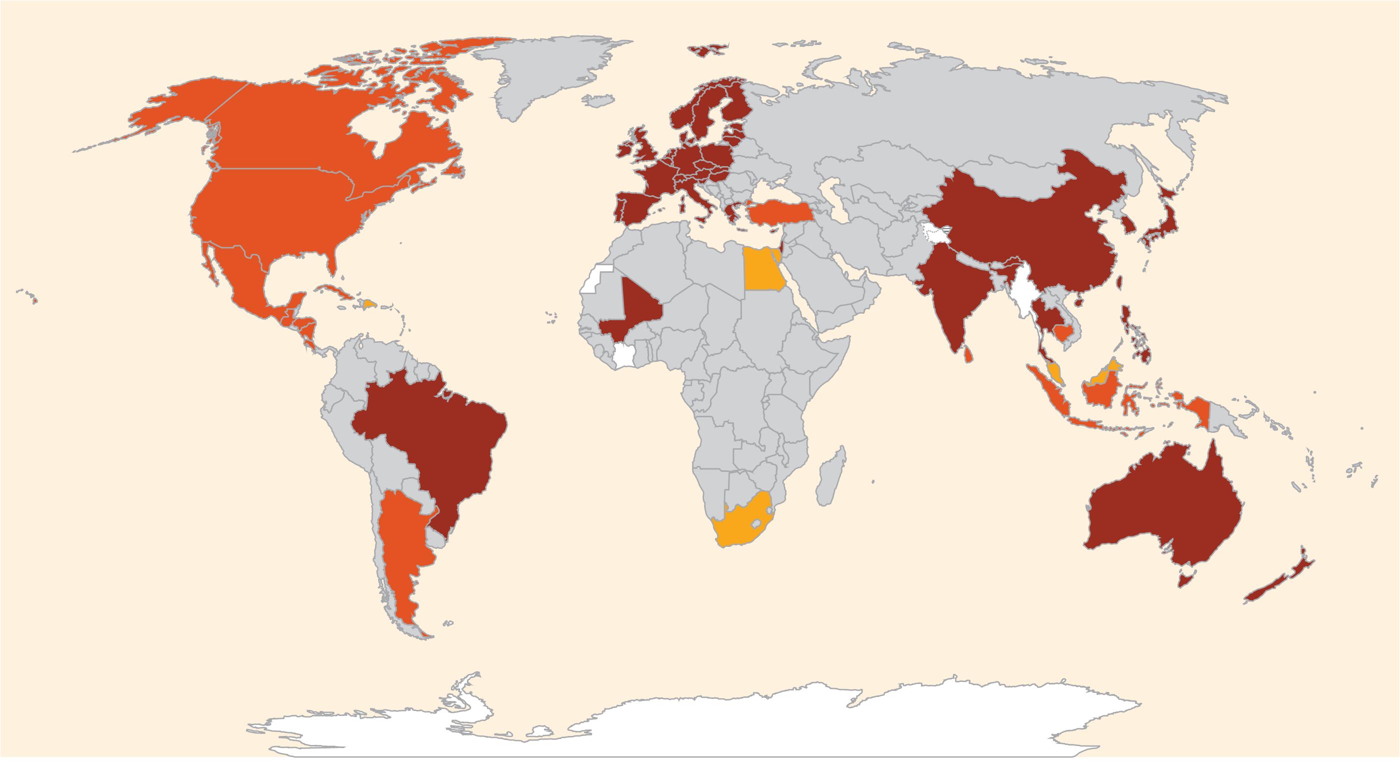
The relative importance of the drivers for RE differ from country to country, and may vary over time. Energy access has been described as the primary driver in developing countries whereas energy security and environmental concerns have been most important in developed countries. [11.3]

11.4 Barriers to renewable energy policymaking, implementation and financing

RE policies have promoted an increase in RE shares by helping to overcome various barriers that impede technology development and deployment of RE. Barriers specific to RE policymaking, to implementation and to financing (e.g., market failures) may further impede deployment of RE. [1.4, 11.4]

Barriers to making and enacting policy include a lack of information and awareness about RE resources, technologies and policy options; lack of understanding about best policy design or how to undertake energy transitions; difficulties associated with quantifying and internalizing external costs and benefits; and lock-in to existing technologies and policies. [11.4.1]

2005



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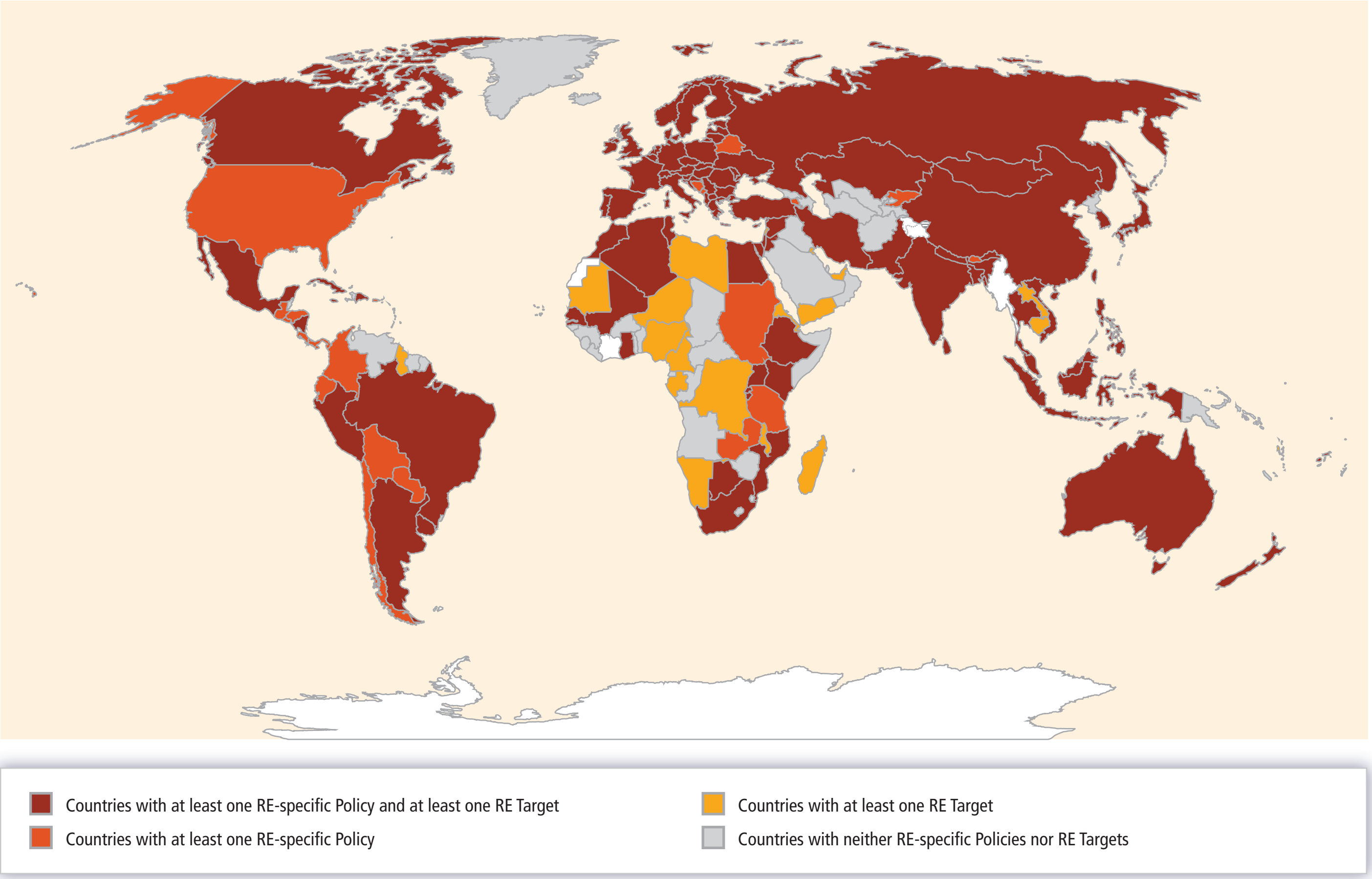

Figure TS.11.1 | Countries with at least one RE target and/or at least one RE-specific policy, in mid-2005 and in early 2011. This figure includes only national-level targets and policies (not municipal or state/provincial) and is not necessarily all-inclusive. [Figure 11.1]

Barriers related to policy implementation include conflicts with existing regulations; lack of skilled workers; and/or lack of institutional capacity to implement RE policies. [11.4.2]

Barriers to financing include a lack of awareness among financiers and lack of timely and appropriate information; issues related to financial structure and project scale; issues related to limited track records; and, in some countries, institutional weakness, including imperfect capital markets and insufficient access to affordable financing, all of which increase perceived risk and thus increase costs and/or make it more difficult to obtain RE project financing. Most importantly, many RE technologies are not economically competitive with current energy market prices, making them financially unprofitable for investors absent various forms of policy support, and thereby restricting investment capital. [11.4.3]

11.5 Experience with and assessment of policy options

Many policy options are available to support RE technologies, from their infant stages to demonstration and pre-commercialization, and through to maturity and wide-scale deployment. These include government R&D policies (supply-push) for advancing RE technologies, and deployment policies (demand-pull) that aim to create a market for RE technologies. Policies could be categorized in a variety of ways and no globally-agreed list of RE policy options or groupings exists. For the purpose of simplification, R&D and deployment policies have been organized within the following categories [11.5]:

- **Fiscal incentive:** actors (individuals, households, companies) are allowed a reduction of their contribution to the public treasury via income or other taxes or are provided payments from the public treasury in the form of rebates or grants.

- **Public finance:** public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee); and

- **Regulation:** rule to guide or control conduct of those to whom it applies.

Although targets are a central component of policies, policies in place may not need specific targets to be successful. Further, targets without policies to deliver them are unlikely to be met. [11.5]

The success of policy instruments is determined by how well they are able to achieve various objectives or criteria, including:

- **Effectiveness:** extent to which intended objectives are met;

- **Efficiency:** ratio of outcomes to inputs, or RE targets realized for economic resources spent;

- **Equity:** the incidence and distributional consequences of a policy; and

- **Institutional feasibility:** the extent to which a policy instrument is likely to be viewed as legitimate, gain acceptance, and be adopted and implemented, including the ability to implement a policy once it has been designed and adopted. [11.5.1]

Most literature focuses on effectiveness and efficiency of policies. Elements of specific policy options make them more or less apt to achieve the various criteria, and how these policies are designed and implemented can also determine how well they meet these criteria. The selection of policies and details of their design ultimately will depend on the goals and priorities of policymakers. [11.5.1]

11.5.1 Research and development policies for renewable energy

R&D, innovation, diffusion and deployment of new low-carbon technologies create benefits to society beyond those captured by the innovator, resulting in under-investment in such efforts. Thus, government R&D can play an important role in advancing RE technologies. Not all countries can afford to support R&D with public funds, but in the majority of countries where some level of support is possible, public R&D for RE enhances the performance of nascent technologies so that they can meet the demands of initial adopters. Public R&D also improves existing technologies that already function in commercial environments. [11.5.2]

Government R&D policies include fiscal incentives, such as academic R&D funding, grants, prizes, tax credits, and use of public research centres; as well as public finance, such as soft or convertible loans, public equity stakes, and public venture capital funds. Investments falling under the rubric of R&D span a wide variety of activities along the technology development lifecycle, from RE resource mapping to improvements in commercial RE technologies. [11.5.2]

The success of R&D policies depends on a number of factors, some of which can be clearly determined, and others which are debated in the literature. Successful outcomes from R&D programmes are not solely related to the total amount of funding allocated, but are also related to the consistency of funding from year to year. On-off operations in R&D are detrimental to technical learning, and learning and cost reductions depend on continuity, commitment and organization of effort, and where and how funds are directed, as much as they rely on the scale of effort. In the literature, there is some debate as to the most successful approach to R&D policy in terms of timing: bricolage (progress via research aiming at incremental improvements) versus breakthrough (radical technological advances) with arguments favouring either option or a combination of both. Experience has shown that it is important that subsidies for R&D (and beyond) are designed to have an 'exit-strategy' whereby the subsidies are progressively phased out as the technology commercializes, leaving a functioning and sustainable sector in place. [11.5.2.3]

One of the most robust findings, from both the theoretical literature and technology case studies, is that R&D investments are most effective when complemented by other policy instruments—particularly, but not limited to, policies that simultaneously enhance demand for new RE technologies. Relatively early deployment policies in a technology's development accelerate learning, whether learning through R&D or learning through utilization (as a result of manufacture) and cost reduction. Together, R&D and deployment policies create a positive feedback cycle, inducing private sector investment in R&D (See Figure TS.11.2). [11.5.2.4]

11.5.2 Policies for deployment

Policy mechanisms enacted specifically to promote deployment of RE are varied and can apply to all energy sectors. They include fiscal incentives (grants, energy production payments, rebates, tax credits, reductions and exemptions, variable or accelerated depreciation); public finance (equity investment, guarantees, loans, public procurement); and regulations (quotas, tendering/bidding, FITs, green labelling and green energy purchasing, net metering, priority or guaranteed access, priority dispatch). While regulations and their impacts vary quite significantly from one end-use sector to another, fiscal incentives and public finance apply generally to all sectors. [11.5.3.1]

Fiscal incentives can reduce the costs and risks of investing in RE by lowering the upfront investment costs associated with installation, reducing the cost of production, or increasing the payment received for RE generated. Fiscal incentives also compensate for the various market failures that leave RE at a competitive disadvantage compared to fossil fuels and nuclear energy, and help to reduce the financial burden of investing in RE. [11.5.3.1]

Fiscal incentives tend to be most effective when combined with other types of policies. Incentives that subsidize production are generally preferable to investment subsidies because they promote the desired outcome—energy generation. 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 or when the technology is applied at a small scale (e.g., small

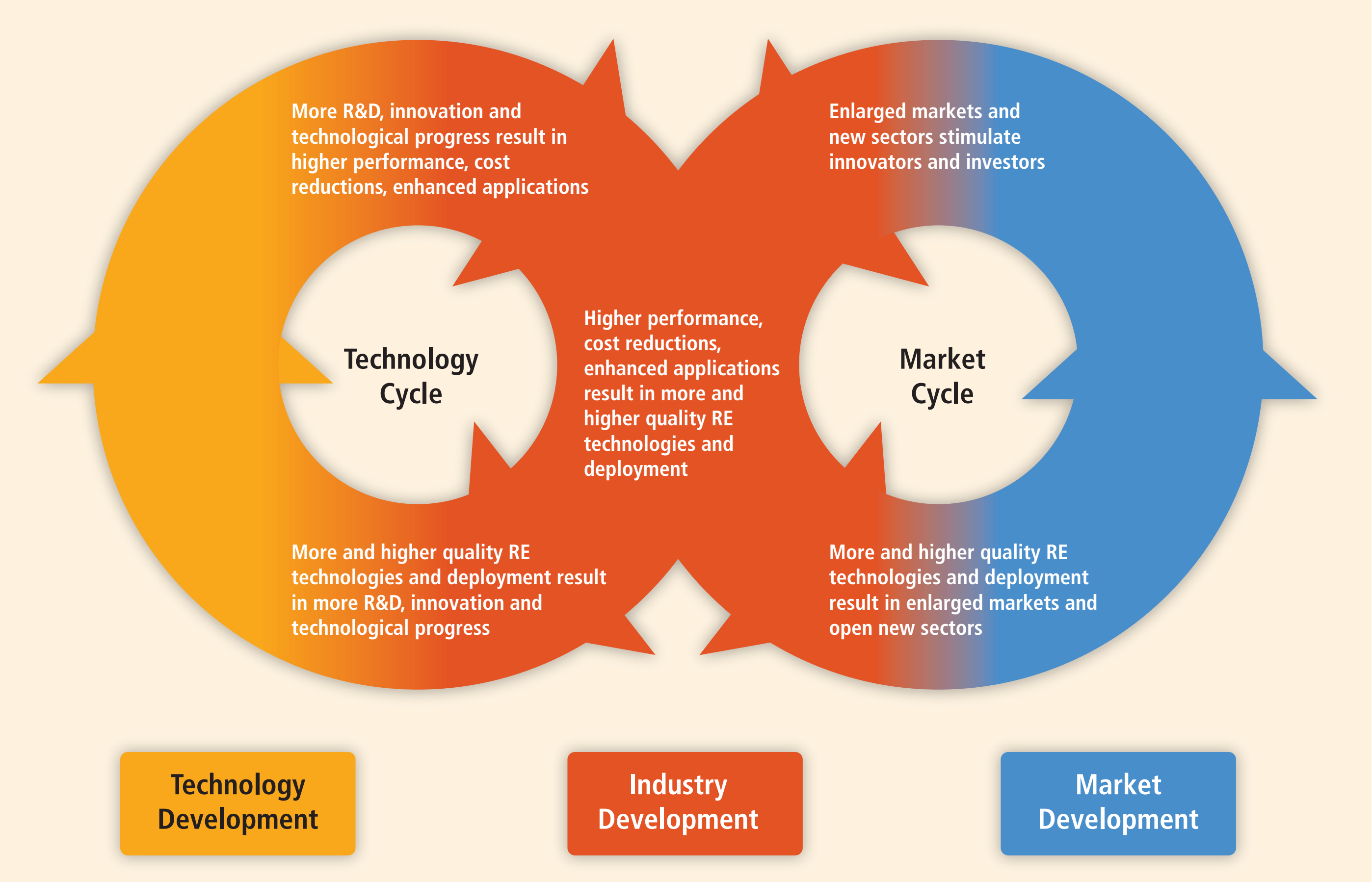

Figure TS.11.2 | The mutually-reinforcing cycles of technology development and market deployment drive down technology costs. [Figure 11.5] rooftop solar systems), particularly if they are paired with technology standards and certification to ensure minimum quality of systems and installation. Experience with wind energy policies suggests that production 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. 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). Tax-based incentives have historically tended to be used to promote only the most mature and cheapest available technologies. Generally, tax credits work best in countries where there are numerous profitable, tax-paying private sector firms that are in a position to take advantage of them. [11.5.3.1]

Public finance mechanisms have a twofold objective: to directly mobilize or leverage commercial investment into RE projects, and to indirectly create scaled-up and commercially sustainable markets for these technologies. In addition to the more traditional public finance policies such as soft loans and guarantees, a number of innovative mechanisms are emerging at various levels of government, including the municipal level. These include financing of RE projects through long-term loans to property owners that allow repayment to be matched with energy savings (for example, Property Assessed Clean Energy in California), and the 'recycling' of government funds for multiple purposes (e.g., using public funds saved through energy efficiency improvements for RE projects). [11.5.3.2]

Public procurement of RE technologies and energy supplies is a frequently cited but not often utilized mechanism to stimulate the market for RE. Governments can support RE development by making commitments to purchase RE for their own facilities or encouraging clean energy options for consumers. The potential of this mechanism is significant: in many nations, governments are the largest consumer of energy, and their energy purchases represent the largest components of public expenditures. [11.5.3.2]

Regulatory policies include quantity- and price-driven policies such as quotas and FITs; quality aspects and incentives; and access instruments such as net metering. Quantity-driven policies set the quantity to be achieved and allow the market to determine the price, whereas price-driven policies set the price and allow the market to determine quantity. Quantity-driven policies can be used in all three end-use sectors in the form of obligations or mandates. Quality incentives include green energy purchasing and green labelling programmes (occasionally mandated by governments, but not always), which provide information to consumers about the quality of energy products to enable consumers to make voluntary decisions and drive demand for RE. [11.5.3.3]

Policies for deployment: Electricity

To date, far more policies have been enacted to promote RE for electricity generation than for heating and cooling or transport. These include fiscal incentives and public finance to promote investment in and generation of RE electricity, as well as a variety of electricity-specific regulatory policies. Although governments use a variety of policy types to promote RE electricity, the most common policies in use are FITs and quotas or Renewable Portfolio Standards (RPS). [11.5.4]

There is a wealth of literature assessing quantity-based (quotas, RPS; and tendering/bidding policies) and price-based (fixed-price and premium-price FITs) policies, primarily quotas and FITs, and with a focus on effectiveness and efficiency criteria. A number of historical studies, including those carried out for the European Commission, have concluded that 'well-designed' and 'well–implemented' FITs have to date been the most efficient (defined as comparison of total support received and generation cost) and effective (ability to deliver an increase in the share of RE electricity consumed) support policies for promoting RE electricity. [11.5.4]

One main reason for the success of well-implemented FITs is that they usually guarantee high investment security due to the combination of long-term fixed-price payments, network connection, and guaranteed grid access for all generation. Well-designed FITs have encouraged both technological and geographic diversity, and have been found to be more suitable for promoting projects of varying sizes. The success of FIT policies depends on the details. The most effective and efficient policies have included most or all of the following elements [11.5.4.3]:

- Utility purchase obligation;
- Priority access and dispatch;
- Tariffs based on cost of generation and differentiated by technology type and project size, with carefully calculated starting values;
- Regular long-term design evaluations and short-term payment level adjustments, with incremental adjustments built into law in order to reflect changes in technologies and the marketplace, to encourage innovation and technological change, and to control costs;
- Tariffs for all potential generators, including utilities;
- Tariffs guaranteed for a long enough time period to ensure an adequate rate of return;
- Integration of costs into the rate base and shared equally across country or region;
- Clear connection standards and procedures to allocate costs for transmission and distribution;
- Streamlined administrative and application processes; and
- Attention to preferred exempted groups, for example, major users on competitiveness grounds or low-income and other vulnerable customers.

Experiences in several countries demonstrate 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 that mute (if not eliminate) price volatility and reduce risk. However, they have been found to benefit the most mature, least-cost technologies. This effect can be addressed in the design of the policy if different RE options are distinguished or are paired with other incentives. The most effective and efficient quantity-based mechanisms have included most if not all of the following elements, particularly those that help to minimize risk [11.5.4.3]:

- Application to large segment of the market (quota only);
- Clearly defined eligibility rules including eligible resources and actors (applies to quotas and tendering/bidding);
- Well-balanced supply-demand conditions with a clear focus on new capacities—quotas should exceed existing supply but be achievable at reasonable cost (quota only);
- Long-term contracts/specific purchase obligations and end dates, and no time gaps between one quota and the next (quota only);
- Adequate penalties for non-compliance, and adequate enforcement (applies to quotas and tendering/bidding);
- Long-term targets, of at least 10 years (quota only);
- Technology-specific bands or carve-outs to provide differentiated support (applies to quotas and tendering/bidding); and
- Minimum payments to enable adequate return and financing (applies to quotas and tendering/bidding).

Net metering enables small producers to 'sell' into the grid, at the retail rate, any renewable electricity that they generate in excess of their total demand in real time as long as that excess generation is compensated for by excess customer load at other times during the designated netting period. It 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, while also benefiting providers by improving load factors if RE electricity is produced during peak demand periods. On its own, however, it is generally insufficient to stimulate significant growth of less competitive technologies like PV at least where generation costs are higher than retail prices. [11.5.4]

Policies for deployment: Heating and cooling

An increasing number of governments are adopting incentives and mandates to advance RE heating and cooling (H/C) technologies. Support for RE H/C presents policymakers with a unique challenge due to the often distributed nature of heat generation. Heating and cooling services can be provided via small- to medium-scale installations that service a single dwelling, or can be used in large-scale applications to provide district heating and cooling. Policy instruments for both RE heating (RE-H) and cooling (RE-C) need to specifically address the more heterogeneous characteristics of resources, including their wide 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. [11.5.5]

The number of policies to support RE sources of heating and cooling has increased in recent years, resulting in increasing generation of RE H/C. However, a majority of support mechanisms have been focused on RE-H. Policies in place to promote RE-H include fiscal incentives such as rebates and grants, tax reductions and tax credits; public finance policies like loans; regulations such as use obligations; and educational efforts. [11.5.5.1–11.5.5.3, 11.6]

To date, fiscal incentives have been the prevalent policy in use, with grants being the most commonly applied. Tax credits available after the installation of a RE-H system (i.e., ex-post) may be logistically advantageous over, for example, grants requiring pre-approval before installation, though there is limited experience with this option. Regulatory mechanisms like use obligations and quotas have attracted increased interest for their potential to encourage growth of RE-H independent of public budgets, though there has been little experience with these policies to date. [11.5.5]

Similar to RE electricity and RE transport, RE H/C policies will be better suited to particular circumstances/locations if, in their design, consideration is given to the state of maturity of the particular technology, of the existing markets and of the existing supply chains. Production incentives are considered be more effective for larger H/C systems, such as district heating grids, than they are for smaller, distributed onsite H/C generation installations for which there are few cost-effective metering or monitoring procedures. [11.5.5]

Though there are some examples of policies supporting RE-C technologies, in general policy aiming to drive deployment of RE-C solely is considerably less well-developed than that for RE-H. Many of the mechanisms described in the above paragraphs could also be applied to RE-C, generally with similar advantages and disadvantages. The lack of experience with deployment policies for RE-C is probably linked to the early levels of technological development of many RE-C technologies. R&D support as well as policy support to develop the early market and supply chains may be of particular importance for increasing the deployment of RE-C technologies in the near future. [11.5.5.4]

Policies for deployment: Transportation

A range of policies has been implemented to support the deployment of RE for transport, though the vast majority of these policies and related experiences have been specific to biofuels. Biofuel support policies aim to promote domestic consumption via fiscal incentives (e.g., tax exemptions for biofuel at the pump) or regulations (e.g., blending mandates), or to promote domestic production via public finance (e.g., loans) for production facilities, via feedstock support or tax incentives (e.g., excise tax exemptions). Most commonly, governments enact a combination of policies. [11.5.6]

Tax incentives are commonly used to support biofuels because they change their cost-competitiveness relative to fossil fuels. They can be installed along the whole biofuel value chain, but are most commonly provided to either biofuel producers (e.g., excise tax exemptions/credits) and/or to end consumers (e.g., tax reductions for biofuels at the pump). [11.5.6]

However, several European and other G8+5 countries have begun gradually shifting from the use of tax breaks for biofuels to blending mandates. It is difficult to assess the level of support under biofuel mandates because prices implied by these obligations are generally not public (in contrast to the electricity sector, for example). While mandates are key drivers in the development and growth of most modern biofuels industries, they are found to be less appropriate for the promotion of specific types of biofuel because fuel suppliers tend to blend low-cost biofuels. By nature, mandates need to be carefully designed and accompanied by further requirements in order to reach a broader level of distributional equity and to minimize potential negative social and environmental impacts. Those countries with the highest share of biofuels in transport fuel consumption have had hybrid systems that combine mandates (including penalties) with fiscal incentives (tax exemptions foremost). [11.5.6]

Synthesis

Some policy elements have been shown to be more effective and efficient in rapidly increasing RE deployment and enabling governments and society to achieve specific targets. The details of policy design and implementation can be as important in determining effectiveness and efficiency as the specific policies that are used. Key policy elements include [11.5.7]:

- Adequate value derived from subsidies, FITs, etc. to cover cost such that investors are able to recover their investment at a rate of return that matches their risk.

- Guaranteed access to networks and markets or at a minimum clearly defined exceptions to that guaranteed access.

- Long-term contracts to reduce risk thereby reducing financing costs.

- Provisions that account for diversity of technologies and applications. RE technologies are at varying levels of maturity and with different characteristics, often facing very different barriers. Multiple RE sources and technologies may be needed to mitigate climate change, and some that are currently less mature and/or more costly than others could play a significant role in the future in meeting energy needs and reducing GHG emissions.

- Incentives that decline predictably over time as technologies and/or markets advance.

- Policy that is transparent and easily accessible so that actors can understand the policy and how it works, as well as what is required to enter the market and/or to be in compliance. Also includes longer-term transparency of policy goals, such as medium- and long-term policy targets.

- Inclusive, meaning that the potential for participation is as broad as possible on both the supply side (traditional producers, distributors of technologies or energy supplies, whether electricity, heat or fuel), and the demand side (businesses, households, etc.), which can 'self-generate' with distributed RE, enabling broader participation that unleashes more capital for investment, helps to build broader public support for RE, and creates greater competition.

- Attention to preferred exempted groups, for example, major users on competitiveness grounds or low-income and vulnerable customers on equity and distributional grounds.

It is also important to recognize that there is no one-size-fits-all policy, and policymakers can benefit from the ability to learn from experience and adjust programmes as necessary. Policies need to respond to local political, economic, social, ecological, cultural and financial needs and conditions, as well as factors such as the level of technological maturity, availability of affordable capital, and the local and national RE resource base. In addition, a mix of policies is generally needed to address the various barriers to RE. Policy frameworks that are transparent and sustained—from predictability of a specific policy, to pricing of carbon and other externalities, to long-term targets for RE—have been found to be crucial for reducing investment risks and facilitating deployment of RE and the evolution of low-cost applications. [11.5.7]

Macroeconomic impacts of renewable energy policies

Payment for supply-push type RE support tends to come from public budgets (multinational, national, local), whereas the cost of demand-pull mechanisms often lands on the end users. For example, if a renewable electricity policy is added to a countries' electricity sector, this additional cost is often borne by electricity consumers, although exemptions or re-allocations can reduce costs for industrial or vulnerable customers where necessary. Either way, there are costs to be paid. If the goal is to transform the energy sector over the next several decades, then it is important to minimize costs over this entire period; it is also important to include all costs and benefits to society in that calculation. [11.5.7.2]

Conducting an integrated analysis of costs and benefits of RE is extremely demanding because so many elements are involved in determining net impacts. Effects fall into three categories: direct and indirect costs of the system as well as benefits of RE expansion; distributional effects (in which economic actors or groups enjoy benefits or suffer burdens as a result of RE support); and macroeconomic aspects such as impacts on GDP or employment. For example, RE policies provide opportunities for potential economic growth and job creation, but measuring net effects is complex and uncertain because the additional costs of RE support create distributional and budget effects on the economy. Few studies have examined such impacts on national or regional economies; however, those that have been carried out have generally found net positive economic impacts. [11.3.4, 11.5.7.2]

Interactions and potential unintended consequences of renewable energy and climate policies

Due to overlapping drivers and rationales for RE deployment and overlapping jurisdictions (local, national, international) substantial interplay may occur among policies at times with unintended consequences. Therefore, a clear understanding of the interplay among policies and the cumulative effects of multiple policies is crucial. [11.3, 11.5.7, 11.6.2]

If not applied globally and comprehensively, both carbon pricing and RE policies create risks of 'carbon leakage', where RE policies in one jurisdiction or sector reduce the demand for fossil fuel energy in that jurisdiction or sector, which *ceteris paribus* reduces fossil fuel prices globally and hence increases demand for fossil energy in other jurisdictions or sectors. Even if implemented globally, suboptimal carbon prices and RE policies could potentially lead to higher carbon emissions. For example, if fossil fuel resource owners fear more supportive RE deployment policies in the long term, they could increase resource extraction as long as RE support is moderate. Similarly, the prospect of future carbon price increases may encourage owners of oil and gas wells to extract resources more rapidly, while carbon taxes are lower, undermining policymakers' objectives for both the climate and the spread of RE technology. The conditions of such a 'green paradox' are rather specific: carbon pricing would have to begin at low levels and increase rapidly. Simultaneously, subsidized RE would have to remain more expensive than fossil fuel-based technologies. However, if carbon prices and RE subsidies begin at high levels from the beginning, such green paradoxes become unlikely. [11.5.7]

The cumulative effect of combining policies that set fixed carbon prices, like carbon taxes, with RE subsidies is largely additive: in other words, extending a carbon tax with RE subsidies decreases emissions and increases the deployment of RE. However, the effect on the energy system of combining endogenous-price policies, like emissions trading and/or RE quota obligations, is usually not as straightforward. Adding RE policies on top of an emissions trading scheme usually reduces carbon prices which, in turn, makes carbon-intensive (e.g., coal-based) technologies more attractive compared to other non-RE abatement options such as natural gas, nuclear energy and/or energy efficiency improvements. In such cases, although overall emissions remain fixed by the cap, RE policies reduce the costs of compliance and/or improve social welfare only if RE technologies experience specific externalities and market barriers to a greater extent than other energy technologies. [11.5.7]

Finally, RE policies alone (i.e., without carbon pricing) are not necessarily an efficient instrument to reduce carbon emissions because they do not provide enough incentives to use all available least-cost mitigation options, including non-RE low-carbon technologies and energy efficiency improvements. [11.5.7]

11.6 Enabling environment and regional issues

RE technologies can play a greater role in climate change mitigation if they are implemented in conjunction with broader 'enabling' policies that can facilitate change in the energy system. An 'enabling' environment encompasses different institutions, actors (e.g., the finance community, business community, civil society, government), infrastructures (e.g., networks and markets), and political outcomes (e.g., international agreements/cooperation, climate change strategies) (see Table TS.11.1). [11.6]

A favourable or 'enabling' environment for RE can be created by encouraging innovation in the energy system; addressing the possible interactions of a given policy with other RE policies as well as with other non-RE policies; easing the ability of RE developers to obtain finance and to successfully site a project; removing barriers for access to networks and markets for RE installations and output; enabling technology transfer and capacity building; and by increasing education and awareness raising at the institutional level and within communities. In turn, the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. [11.6.1–11.6.8]

A widely accepted conclusion in innovation literature is that established socio-technical systems tend to narrow the diversity of innovations because the prevailing technologies develop a fitting institutional environment. This may give rise to strong path dependencies and exclude (or lock out) rivalling and potentially better-performing alternatives. For these reasons, socio-technical system change takes time, and it involves change that is systemic rather than linear. RE technologies are being integrated into an energy system that, in much of the world, was constructed to accommodate the existing energy supply mix. As a result, infrastructure favours the currently dominant fuels, and existing lobbies and interests all need to be taken into account. Due to the intricacies of technological change, it is important that all levels of government (from local through to international) encourage RE development through policies, and that nongovernmental actors also be involved in policy formulation and implementation. [11.6.1]

Government policies that complement each other are more likely to be successful, and the design of individual RE policies will also affect the success of their coordination with other policies. Attempting to actively promote the complementarities of policies across multiple sectors—from energy to agriculture to water policy, etc.—while also considering the independent objectives of each, is not an easy task and may create win-win and/or win-lose situations, with possible trade-offs. This implies a need for strong central coordination to eliminate contradictions and conflicts among sectoral policies and to simultaneously coordinate action at more than one level of governance. [11.6.2]

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 project. The cost of financing and access to it depends on the broader financial market conditions prevalent at the time of investment, and on the specific risks of a project, technology, and actors involved. Beyond RE-specific policies, broader conditions can

Table TS.11.1 | Factors and participants contributing to a successful RE governance regime. [Table 11.4]

Dimensions of an Enabling Environment >> Factors and actors contributing to the success of RE policy	Section 11.6.2 Integrating Policies (national/ supranational policies)	Section 11.6.3 Reducing Financial and Investment Risk	Section 11.6.4 Planning and Permitting at the local level	Section 11.6.5 Providing infrastructures networks and markets for RE technology	Section 11.6.6 Technology Transfer and Capacity Building	Section 11.6.7 Learning from actors beyond government
Institutions	Integrating RE policies with other policies at the design level reduces potential for conflict among government policies	Development of financing institutions and agencies can aid cooperation between countries, provide soft loans or international carbon finance (CDM). Long-term commitment can reduce the perception of risk	Planning and permitting processes enable RE policy to be integrated with non-RE policies at the local level	Policymakers and regulators can enact incentives and rules for networks and markets, such as security standards and access rules	Reliability of RE technologies can be ensured through certification Institutional agreements enable technology transfer	Openness to learning from other actors can complement design of policies and enhance their effectiveness by working within existing social conditions
Civil society (individuals, households, NGOs, unions …)	Municipalities or cities can play a decisive role in integrating state policies at the local level	Community investment can share and reduce investment risk Public-private partnerships in investment and project development can contribute to reducing risks associated with policy instruments Appropriate international institutions can enable an equitable distribution of funds	Participation of civil society in local planning and permitting processes might allow for selection of the most socially relevant RE projects	Civil society can become part of supply networks through co-production of energy and new decentralized models.	Local actors and NGOs can be involved in technology transfer through new business models bringing together multi-national companies / NGOs / Small and Medium Enterprises	Civil society participation in open policy processes can generate new knowledge and induce institutional change Municipalities or cities may develop solutions to make RE technology development possible at the local level People (individually or collectively) have a potential for advancing energy-related behaviours when policy signals and contextual constraints are coherent
Finance and business communities		Public private partnerships in investment and project development can contribute to reducing risks associated with policy instruments	RE project developers can offer know-how and professional networks in : i) aligning project development with planning and permitting requirements ; ii) adapting planning and permitting processes to local needs and conditions Businesses can be active in lobbying for coherent and integrated policies	Clarity of network and market rules improves investor confidence	Financing institutions and agencies can partner with national governments, provide soft loans or international carbon finance (CDM).	Multi-national companies can involve local NGOs or SMEs as partners in new technology development (new business models) Development of corporations and international institutions reduces risk of investment
Infrastructures	Policy integration with network and market rules can enable development of infrastructure suitable for a low-carbon economy	Clarity of network and market rules reduces risk of investment and improves investor confidence		Clear and transparent network and market rules are more likely to lead to infrastructures complementary to a low-carbon future		City and community level frameworks for the development of long-term infrastructure and networks can sustain the involvement of local actors in policy development

Continued next Page →

Dimensions of an Enabling Environment >> Factors and actors contributing to the success of RE policy	Section 11.6.2 Integrating Policies (national/ supranational policies)	Section 11.6.3 Reducing Financial and Investment Risk	Section 11.6.4 Planning and Permitting at the local level	Section 11.6.5 Providing infrastructures networks and markets for RE technology	Section 11.6.6 Technology Transfer and Capacity Building	Section 11.6.7 Learning from actors beyond government
Politics (international agreements / cooperation, climate change strategy, technology transfer…)	Supra-national guidelines (e.g., EU on "streamlining", ocean planning, impact study) may contribute to integrating RE policy with other policies	Long-term political commitment to RE policy reduces investors risk in RE projects	Supra- national guidelines may contribute to evolving planning and permitting processes	Development cooperation helps sustain infrastructure development and allows easier access to low-carbon technologies	CDMs, Intellectual property rights (IPR) and patent agreements can contribute to technology transfer	Appropriate input from non-government institutions stimulates more agreements that are socially connected UNFCCC process mechanisms such as Expert Group on Technology Transfer (EGTT), the Global Environment Facility (GEF), and the Clean Development Mechanism (CDM) and Joint Implementation (JM) may provide guidelines to facilitate the involvement of non-state actors in RE policy development

include political and currency risks, and energy-related issues such as competition for investment from other parts of the energy sector, and the state of energy sector regulations or reform. [11.6.3]

The successful deployment of RE technologies to date has depended on a combination of favourable planning procedures at both national and local levels. Universal procedural fixes, such as 'streamlining' of permitting applications, are unlikely to resolve conflicts among stakeholders at the level of project deployment because they would ignore place- and scale-specific conditions. A planning framework to facilitate the implementation of RE might include the following elements: aligning stakeholder expectations and interests; learning about the importance of context for RE deployment; adopting benefit-sharing mechanisms; building collaborative networks; and implementing mechanisms for articulating conflict for negotiation. [11.6.4]

After a RE project receives planning permission, investment to build it is only forthcoming once its economic connection to a network is agreed; when it has a contract for the 'off-take' of its production into the network; and when its sale of energy, usually via a market, is assured. The ability, ease and cost of fulfilling these requirements is central to the feasibility of a RE project. Moreover, the methods by which RE is integrated into the energy system will have an effect on the total system cost of RE integration and the cost of different scenario pathways. In order to ensure the timely expansion and reinforcement of infrastructure for and connection of RE projects, economic regulators may need to allow 'anticipatory' or 'proactive' network investment and/or allow projects to connect in advance of full infrastructure reinforcement. [11.6.5, 8.2.1.3]

For many countries, a major challenge involves gaining access to RE technologies. Most low-carbon technologies, including RE technologies, are developed and concentrated in a few countries. It has been argued that many developing nations are unlikely to 'leapfrog' pollution-intensive stages of industrial development without access to clean technologies that have been developed in more advanced economies. However, technologies such as RE technologies typically do not flow across borders unless environmental policies in the recipient country provide incentives for their adoption. Further, technology transfer should not replace but rather should complement domestic efforts at capacity building. In order to have the capacity to adapt, install, maintain, repair and improve on RE technologies in communities without ready access to RE, investment in technology transfer must be complemented by investment in community-based extension services that provide expertise, advice and training regarding installation, technology adaptation, repair and maintenance. [11.6.6]

In addition to technology transfer, institutional learning plays an important role in advancing deployment of RE. Institutional learning is conducive to institutional change, which provides space for institutions to improve the choice and design of RE policies. It also encourages a stronger institutional capacity at the deeper, often more local, level where numerous decisions are made on siting and investments in RE projects. Institutional learning can occur if policymakers can draw on nongovernmental actors, including private actors (companies, etc.) and civil society for collaborative approaches in policymaking. Information and education are often emphasized as key policy tools for influencing energy-related behaviours. However, the effectiveness of education- and information-based policies is limited by contextual factors, which cautions against an over-reliance on information- and education-based policies alone. Changes in energy-related behaviours are the outcome of a process in which personal norms or attitudes interact with prices, policy signals, and the RE technologies themselves, as well as the social context in which individuals find themselves. These contextual factors point to the importance of collective action as a more effective, albeit more complex medium for change than individual action. This supports coordinated, systemic policies that go beyond narrow 'attitude-behaviour-change' policies if policymakers wish to involve individuals in the RE transition. [11.6.7, 11.6.8]

11.7 A structural shift

If decision makers intend to increase the share of RE and, at the same time, meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical. To achieve GHG concentration stabilization levels with high shares of RE, a structural shift in today's energy systems will be required over the next few decades. Such a transition to low-carbon energy differs from previous energy transitions (e.g., from wood to coal, or coal to oil) because the available time span is restricted to a few decades, and because RE must develop and integrate into a system constructed in the context of an existing energy structure that is very different from what might be required under higher penetration RE futures. [11.7]

A structural shift towards a world energy system that is mainly based on renewable energy might begin with a prominent role for energy efficiency in combination with RE. This requires, however, a reasonable carbon pricing policy in the form of a tax or emission trading scheme that avoids carbon leakage and rebound effects. Additional policies are required that extend beyond R&D to support technology deployment; the creation of an enabling environment that includes education and awareness raising; and the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning. [11.6, 11.7] The policy frameworks that induce the most RE investment are those designed to reduce risks and enable attractive returns, and to provide stability over a time frame relevant to the investment. [11.5] The appropriate and reliable mix of instruments is even more important where energy infrastructure is not yet developed and energy demand is expected to increase significantly in the future. [11.7]