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Renewable Energy and Climate Change

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Executive Summary

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, 85% of current primary energy driving global economies comes from the combustion of fossil fuels and consumption of fossil fuels accounts for 56.6% of all anthropogenic GHG emissions.

Renewable energy 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 renewable energy (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.

GHG emissions associated with the provision of energy services are a major cause of climate change. The IPCC Fourth Assessment Report (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 greenhouse gas concentrations." Concentrations of CO_2 have continued to grow and by the end of 2010 had reached 390 ppm CO_2 or 39% above pre-industrial levels.

The long-term baseline scenarios reviewed for the AR4 show that the expected decrease in the energy intensity will not be able to compensate for the effects of the projected increase in the global gross domestic product. As a result, most of the scenarios exhibit a strong increase in primary energy supply throughout this century. In the absence of any climate policy, the overwhelming majority of the baseline scenarios exhibit considerably higher emissions in 2100 compared to 2000, implying rising CO_2 concentrations and, in turn, enhanced global warming. Depending on the underlying socioeconomic scenarios and taking into account additional uncertainties, global mean temperature is expected to rise and to approach a level between 1.1°C and 6.4°C over the 1980 to 1999 average by the end of this century.

To avoid adverse impacts of such climate change on water resources, ecosystems, food security, human health and coastal settlements with potentially irreversible abrupt changes in the climate system, 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, GHG concentrations would need to be stabilized in the range of 445 to 490 ppm CO_2eq in the atmosphere.

There are multiple means for lowering GHG emissions from the energy system, while still providing desired energy services. 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. 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. Unlike fossil fuels, most forms of RE produce little or no CO_2 emissions.

The contribution RE will provide within the portfolio of low carbon technologies heavily depends on the economic competition between these technologies, their relative environmental burden (beyond climate change), as well as on security and societal aspects. 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. Even without a push for climate change mitigation, scenarios that are examined in this report find that the increasing demand for energy services is expected to drive RE to levels exceeding today's energy usage.

On a global basis, it is estimated that RE accounted for 12.9% of the total 492 EJ of 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.[1] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4%. In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE), biofuels contributed 2% of global road transport fuel supply, and traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat. The contribution of RE to primary energy supply varies substantially by country and region. Scenarios of future low greenhouse gas futures consider RE and RE in combination with nuclear, and coal and natural gas with carbon capture and storage.

While the RE share of global energy consumption is still relatively small, deployment of RE has been increasing rapidly in recent years. Of the approximately 300 GW of new electricity generating capacity added globally over the two-year period from 2008 to 2009, 140 GW came from RE additions. Collectively, developing countries hosted 53% of global RE power generation capacity in 2009. 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 fuels and other factors have supported the continuing increase in the use of RE. These developments suggest the possibility that RE could play a much more prominent role in both developed and developing countries over the coming decades.

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

The theoretical potential for RE greatly exceeds all the energy that is used by all economies on Earth. 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.

Some RE, including wind and solar power, are variable and may not always be available for dispatch when needed. The energy density of some RE is also relatively lower, so that reducing the delivered energy needed to supply end-use energy services is especially important for RE even though benefiting all forms of energy.

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, regional variations in cost and performance and differing discount rates.

RE may provide a number of opportunities and can not only address climate change mitigation but may also address sustainable and equitable economic development, energy access, secure energy supply and local environmental and health impacts. Market failures, up-front costs, financial risk, lack of data as well as capacities and public and institutional awareness, perceived social norms and value structures, present infrastructure and current

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

energy market regulation, inappropriate intellectual property laws, trade regulations, lack of amenable policies and programs, lower power of RE and land use conflicts are amongst existing barriers and issues to expanding the use of RE.

Some governments have successfully introduced a variety of RE policies, motivated by a variety of factors, to address these various components of RE integration into the energy system. These policies have driven escalated growth in RE technologies in recent years. These policies can be categorized as fiscal incentives, public finance and regulation. They typically address two market failures: 1) the external cost of GHG emissions are not priced at an appropriate level; and 2) RE creates benefits to society beyond those captured by the innovator, leading to under-investment in such efforts. Several studies have concluded that some feed-in tariffs have been effective and efficient at promoting RE electricity. Quota policies can be effective and efficient if designed to reduce risk. An increasing number of governments are adopting fiscal incentives for RE heating and cooling. In the transportation sector, RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Policies have influenced the development of an international biofuel 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 trade-offs. RE technologies can play a greater role if they are implemented in conjunction with ‘enabling’ policies.

1.1 Background

1.1.1 Introduction

All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, communication) and to serve productive processes. The quality of energy is important to the development process (Cleveland et al., 1984; Brookes, 2000; Kaufmann, 2004). 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, including GHG emissions.

The IPCC Fourth Assessment Report (AR4) reported that fossil fuels provided 85% of the total primary energy in 2004 (Sims et al., 2007),[2] which is the same value as in 2008 (IEA 2010a; Table A.II.1). Furthermore, the combustion of fossil fuels accounted for 56.6% of all anthropogenic GHG emissions (CO_2eq) in 2004 (Rogner et al., 2007).[3] To maintain both a sustainable economy that is capable of providing essential goods and services to the citizens of both developed and developing countries, and to maintain a supportive global climate system, requires a major shift in how energy is produced and utilized (Nfah et al., 2007; Kankam and Boon, 2009). However, renewable energy technologies, which release much lower amounts of CO_2 than fossil fuels are growing. Chapter 10 examines more than 100 scenarios in order to explore the potential for RE to contribute to the development of a low-carbon future.

1.1.2 The Special Report on Renewable Energy Sources and Climate Change Mitigation

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. It consists of 11 chapters (Figure 1.1). Chapter 1 provides an overview of RE and climate change; Chapters 2 through 7 provide information on six types of RE technologies (biomass, solar, geothermal, hydro, ocean and wind)

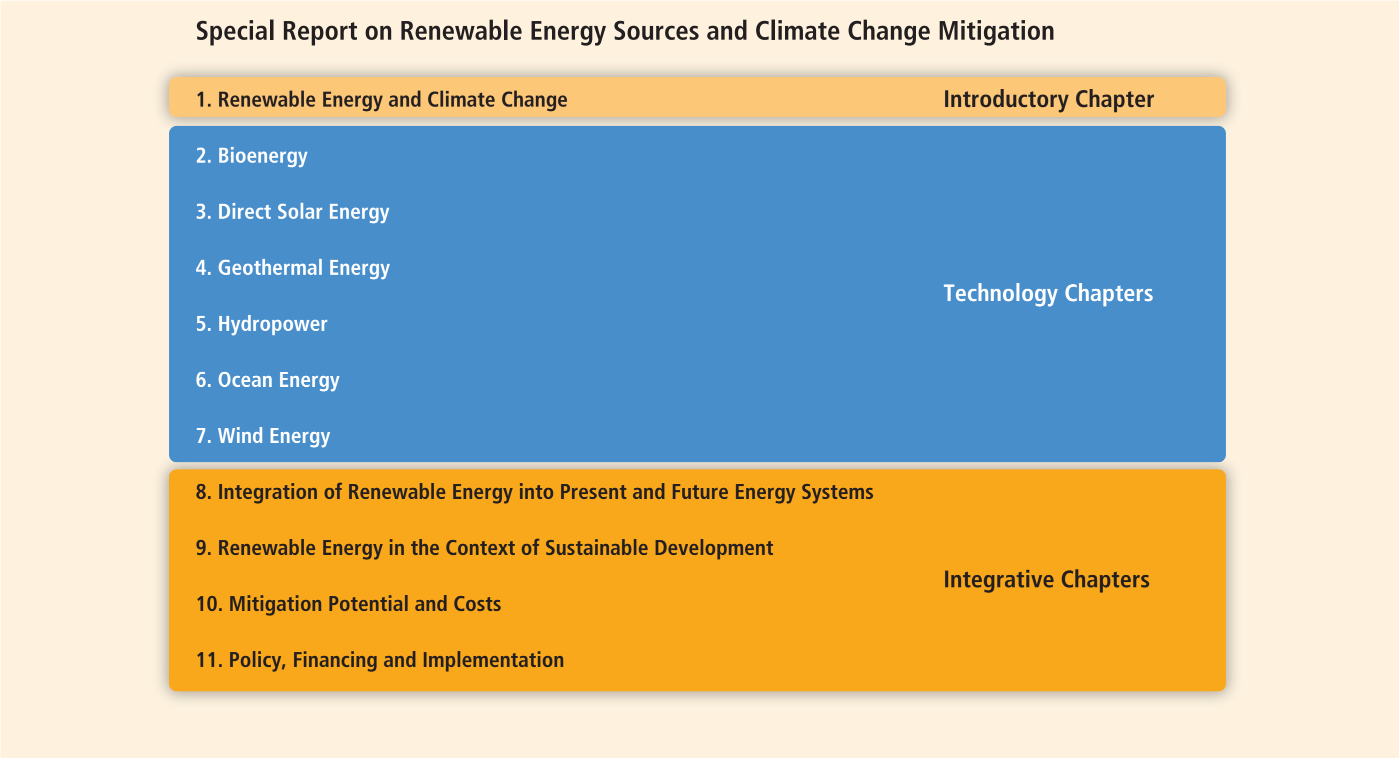

Figure 1.1 | Structure of the report.

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[2] The number from the 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.

[3] The contributions from other sources and/or gases (see Figure 1.1b in Rogner et al., 2007) 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%). For further information on sectoral emissions, including from forestry, see also Figure 1.3b in Rogner et al. (2007) and associated footnotes.

while Chapters 8 through 11 deal with integrative issues (integration of RE into present and future energy systems; RE in the context of sustainable development; mitigation potential and costs; and policy, financing and implementation). The report communicates uncertainty where relevant.[4] It provides the following information on the potential for renewable energy sources to meet GHG reduction goals:

- Identification of RE resources and available technologies and impacts of climate change on these resources (Chapters 2 through 7);
- Technology and market status, future developments and projected rates of deployment (Chapters 2 through 7 and 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 develoment (Chapter 9);
- Impacts on secure energy supply (Chapter 9);
- Economic and environmental costs, benefits, risks and impacts of deployment (Chapters 9 and 10);
- Mitigation potential of RE sources (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).

1.1.3 Climate change

GHG emissions associated with the provision of energy services are 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 greenhouse gas concentrations." (IPCC, 2007a). Concentrations of CO_2 have continued to grow since the AR4 to about 390 ppm CO_2 or 39% above pre-industrial levels by the end of 2010 (IPCC, 2007b; NOAA, 2010). The global average temperature has increased by 0.76°C (0.57°C to 0.95°C) between 1850 to 1899 and 2001 to 2005, and the warming trend has increased significantly over the last 50 years (IPCC, 2007b). While this report focuses on the energy sector, forest clearing and burning and land use change, and the release of non-CO_2 gases from industry, commerce and agriculture also contribute to global warming (IPCC, 2007b).

An extensive review of long-term scenarios (Fisher et al., 2007) revealed that economic growth is expected to lead to a significant increase in gross domestic product (GDP) during the 21st century (see Figure 1.2 left panel), associated with a corresponding increase in the demand for energy services. Historically, humankind has been able to reduce the primary energy input required to produce one GDP unit (the so-called primary energy intensity) and is expected to do so further in the future (see Figure 1.2 right panel).

Within the considered scenarios, the increase in energy efficiency is more than compensated for by the anticipated economic growth. In the

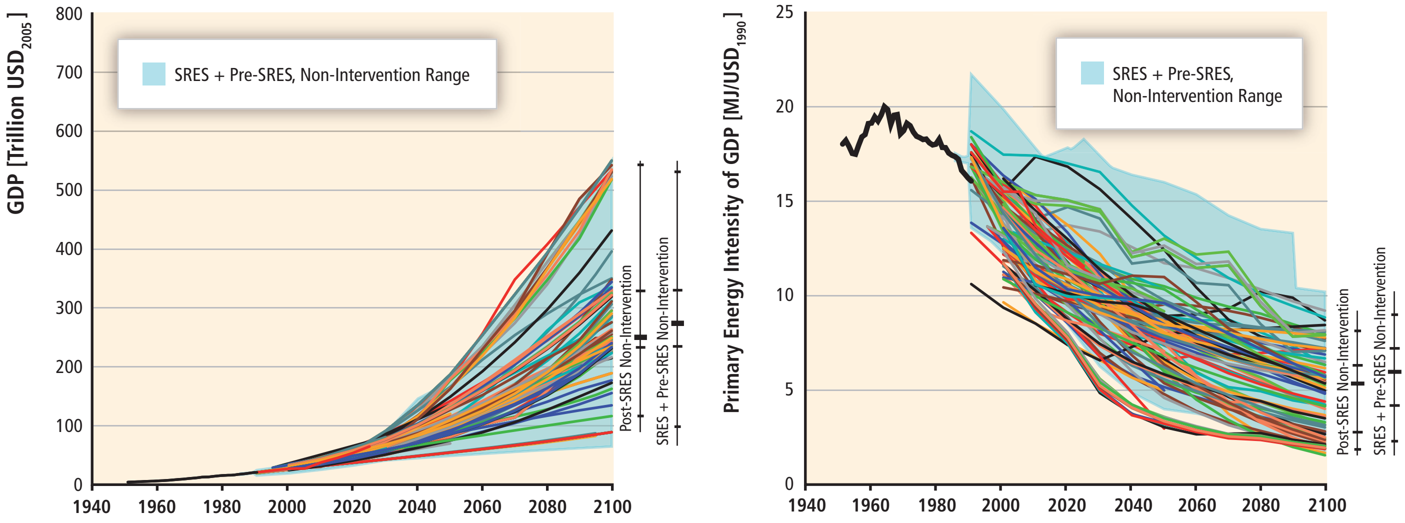

Figure 1.2 | Left panel: Comparison of GDP projections in post-SRES (Special Report on Emission Scenarios) emissions scenarios with those used in previous scenarios. The median of the new scenarios is about 7% below the median of the pre-SRES and SRES scenario literature. The two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. Right panel: Development of primary energy intensity of GDP: historical development and projections from SRES and pre-SRES scenarios compared to post-SRES scenarios. Adapted from Fisher et al., 2007, pp. 180 and 184.

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[4] 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.

business-as-usual case, the demand for global primary energy therefore is projected to increase substantially during the 21st century (see Figure 1.3 left panel).

Similarly to the behaviour of primary energy intensity, carbon intensity (the amount of CO_2 emissions per unit of primary energy) is—with few exceptions—expected to decrease as well (see Figure 1.3 right panel). Despite the substantial associated decarbonization, the overwhelming majority of the non-intervention emission projections exhibit considerably higher emissions in 2100 compared with those in 2000 (see the shaded area in Figure 1.4 left panel). Because emission rates substantially exceed natural removal rates, concentrations will continue to increase, which will raise global mean temperature. Figure 1.4 right panel shows the respective changes for representative emission scenarios (so-called SRES (Special Report on Emissions Scenarios) scenarios; see IPCC (2000a)) taken from the set of emissions scenarios shown in Figure 1.4 left panel.

In the absence of additional climate policies, the IPCC (2007a; see Figure 1.4) projected that global average temperature will rise over this century by between 1.1°C and 6.4°C over the 1980 to 1999 average, depending on socioeconomic scenarios (IPCC, 2000a). This range of uncertainty arises from uncertainty about the amount of GHGs that will be emitted in the future, and from uncertainty about the climate sensitivity. In addition to an investigation of potentially irreversible abrupt changes in the climate system, the IPCC assessed the adverse impacts of such climate change (and the associated sea level rise and ocean acidification) on water supply, ecosystems, food security, human health and coastal settlements (IPCC, 2007c).

The Cancun Agreements (2010) call for limiting global average temperature rise to no more than 2°C above pre-industrial values, and agreed to consider a goal of 1.5°C. The analysis shown in Figure 1.5 concludes that 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 in the range of 445 to 490 ppm CO_2eq. 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 (IPCC, 2007a). Note that there is a considerable range of probable temperature outcomes at this concentration range. Additional scenario analysis and mitigation costs under various GHG concentration stabilization levels are analyzed in Chapter 10. This report does not analyze the economic cost of damages from climate change.

1.1.4 Drivers of carbon dioxide emissions

Since about 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, both replacing many traditional uses of bioenergy and providing new services. The rapid rise in fossil fuel combustion (including gas flaring) has produced a corresponding rapid growth in CO_2 emissions (Figure 1.6).

The amount of carbon in fossil fuel reserves and resources (unconventional oil and gas resources as well as abundant coal) not yet burned has the potential to add quantities of CO_2 to the atmosphere—if burned over coming centuries—that would exceed the range of any of the scenarios considered in Figure 1.5 or in Chapter 10 (Moomaw et al., 2001; Knopf et al., 2010). Figure 1.7 summarizes current estimates of fossil fuel resources and reserves in terms of carbon content, and compares them with the amount already released to the atmosphere as CO_2. Reserves refer to what is extractable with today's technologies at current energy

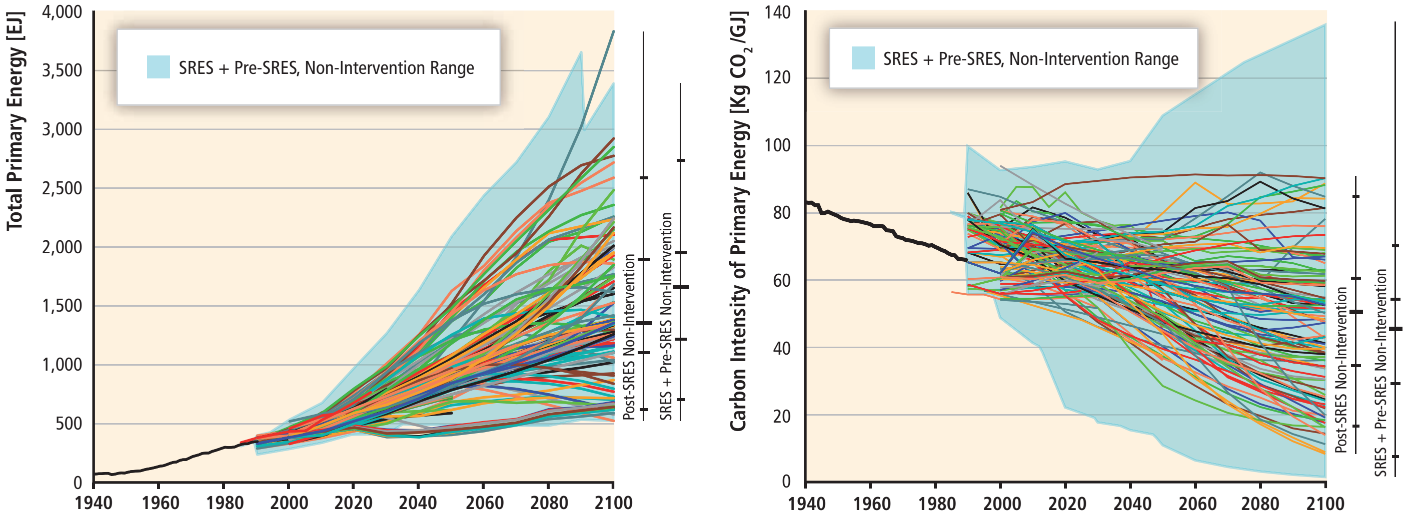

Figure 1.3 | Left panel: Projected increase in primary energy supply. Comparison of 153 SRES and pre-SRES baseline energy scenarios in the literature compared with the 133 more recent, post-SRES scenarios. The ranges are comparable, with small changes in the lower and upper boundaries. Right panel: Expected carbon intensity changes. Historical development and projections from SRES and pre-SRES scenarios compared to post-SRES scenarios. Adapted from Fisher et al., 2007, pp. 183 and 184.

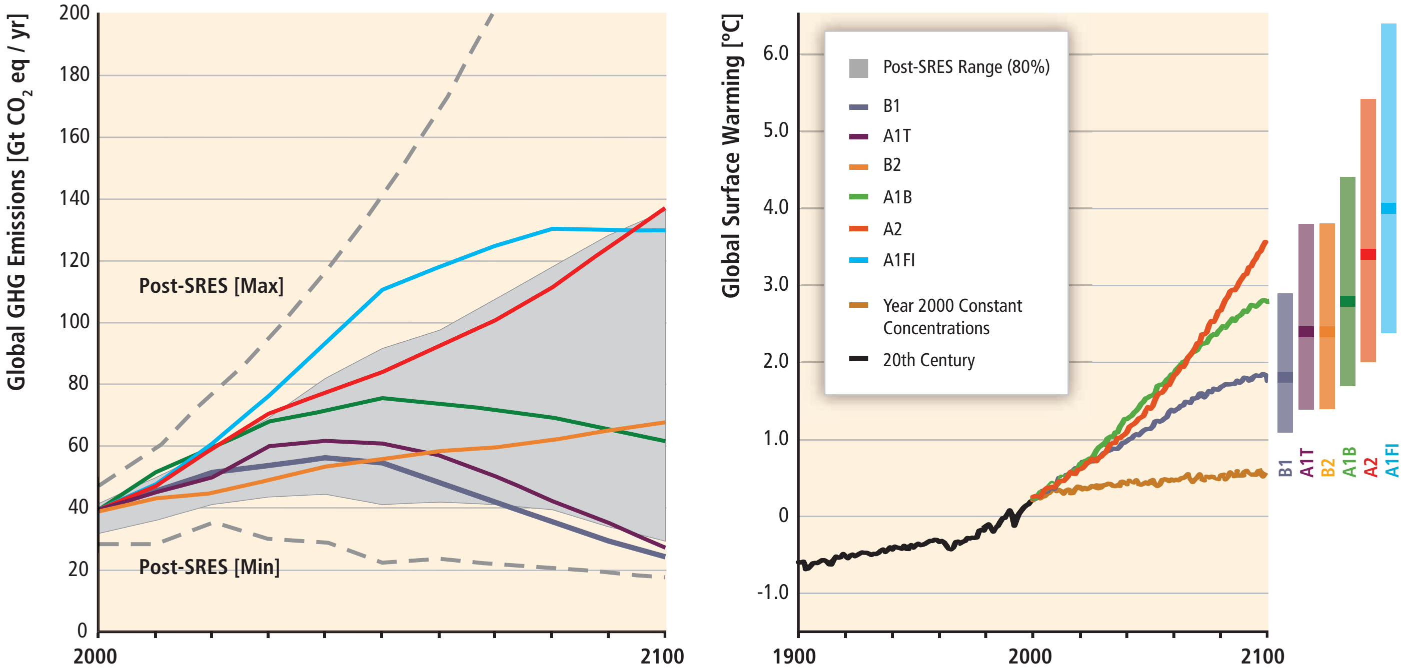

Figure 1.4 | Left panel: Global GHG emissions (Gt CO$_2$eq) in the absence of climate policies: six illustrative SRES marker scenarios (coloured lines) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (grey shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include CO$_2$, methane (CH$_4$), nitrous oxide (N$_2$O) and fluorinated gases. Right panel: Solid lines are multi-model global averages of projected surface warming for SRES scenarios A2, A1B and B1, shown as continuations of the 20th-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The brown line is not a scenario, but is for atmosphere-ocean general circulation model simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios for 2090 to 2099. All temperatures are relative to the period 1980 to 1999 (IPCC, 2007a, Figure SPM 5, page 7).

prices. Resources represent the total amount estimated to be available without regard to the technical or economic feasibility of extracting it (IEA, 2005).

In developing strategies for reducing CO$_2$ emissions it is useful to consider the Kaya identity that analyzes energy-related CO$_2$ emissions as a function of four factors: 1) Population; 2) GDP per capita; 3) energy intensity (i.e., total primary energy supply (TPES) per GDP); and 4) carbon intensity (i.e., CO$_2$ emissions per TPES) (Ehrlich and Holdren, 1971; Kaya, 1990).

The Kaya identity is then:
CO$_2$ emissions = Population x (GDP/population) x (TPES/GDP) x (CO$_2$/ TPES)

This is sometimes referred to as:
CO$_2$ emissions = (Population x Affluence x Energy intensity x Carbon intensity)

Renewable energy supply sources are effective in lowering CO$_2$ emissions because they have low carbon intensity with emissions per unit of energy output typically 1 to 10% that of fossil fuels (see Figure 1.13 and Chapter 10). Further reductions can also be achieved by lowering the energy intensity required to provide energy services. The role of these two strategies and their interaction is discussed in more detail in Section 1.2.6.

The absolute (a) and percentage (b) annual changes in global CO$_2$ emissions are shown in terms of the Kaya factors in Figure 1.8 (Edenhofer et al., 2010).

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.[5] In recent years (2000 to 2007), increases in carbon intensity have mainly been driven by the expansion of coal use by both developed and developing countries, although coal and petroleum use have fallen slightly since 2007. 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 (Edenhofer et al., 2010).

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

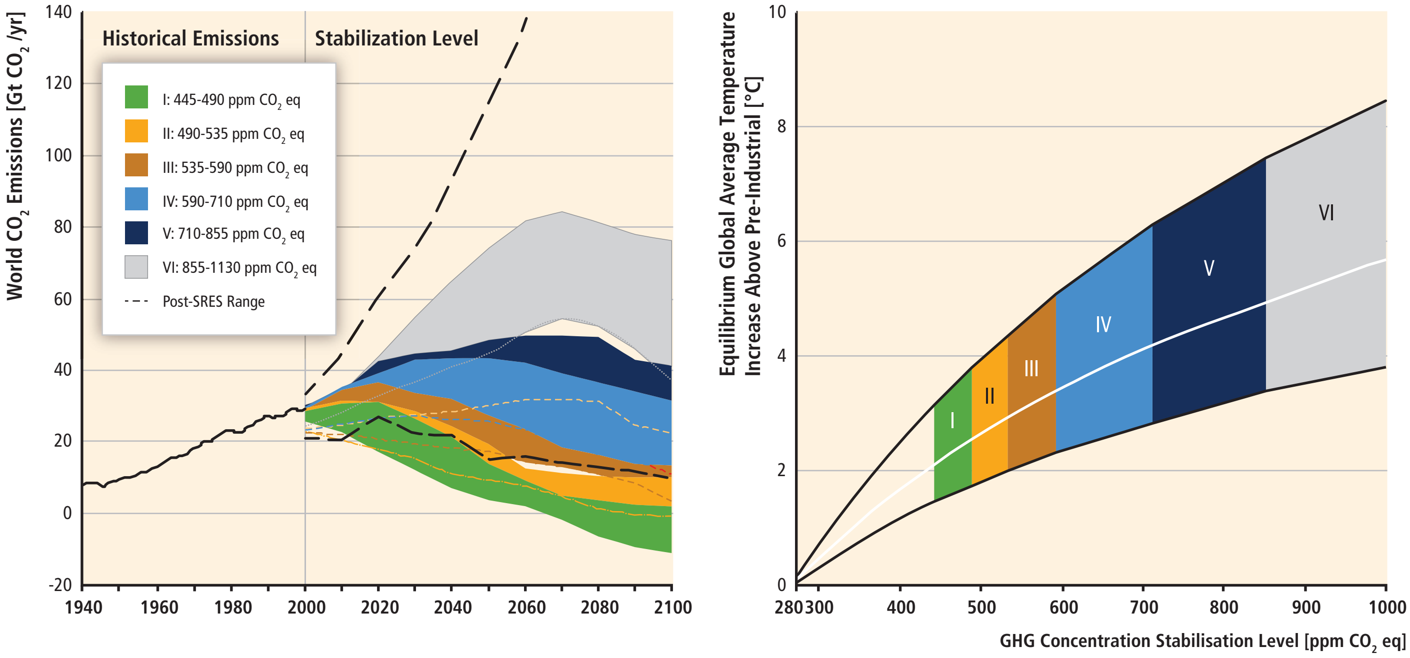

Figure 1.5 | Global CO$_2$ emissions from 1940 to 2000 and emissions ranges for categories of stabilization scenarios from 2000 to 2100 (left panel); and the corresponding relationship between the stabilization target and the likely equilibrium global average temperature increase above pre-industrial (right panel). Coloured shadings show stabilization scenarios grouped according to different targets (stabilization categories I to VI). The right panel shows ranges of global average temperature change above pre-industrial, using (i) 'best estimate' climate sensitivity of 3°C (line in middle of shaded area); (ii) upper bound of likely range of climate sensitivity of 4.5°C (line at top of shaded area); and (iii) lower bound of likely range of climate sensitivity of 2°C (line at bottom of shaded area) (IPCC, 2007a, Figure SPM-11, page 21).

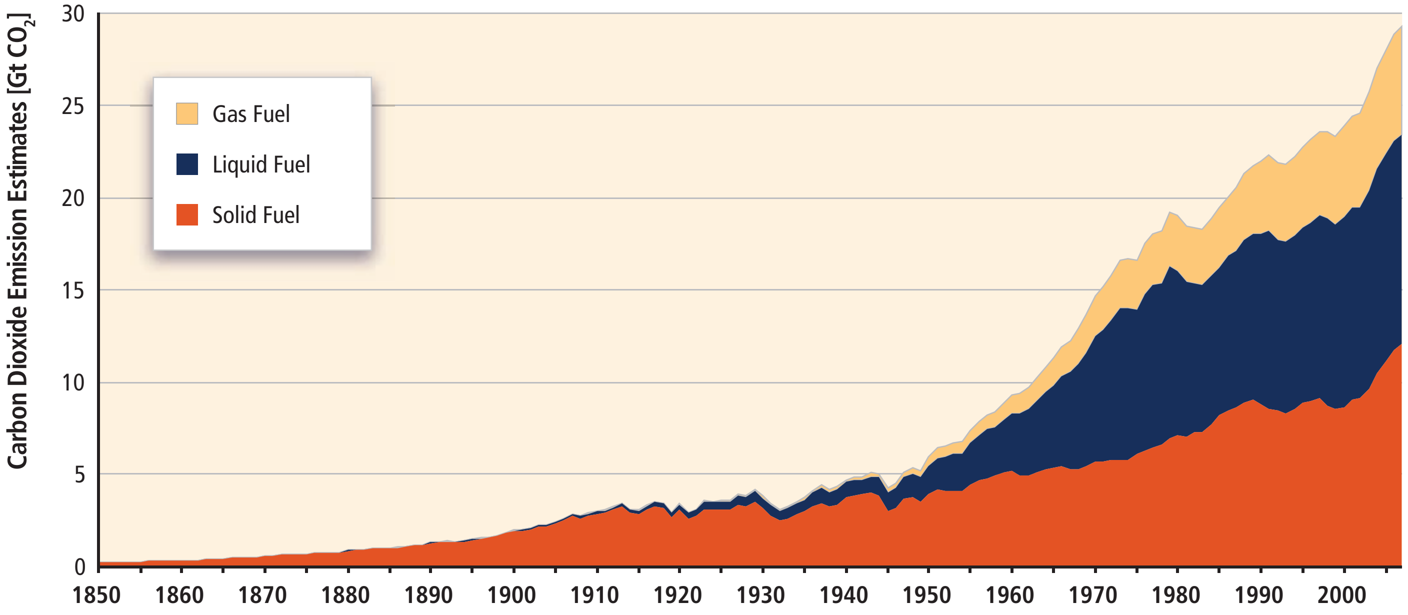

Figure 1.6 | Global CO$_2$ emissions from fossil fuel burning, 1850 to 2007. Gas fuel includes flaring of natural gas. All emission estimates are expressed in Gt CO$_2$. Data Source: (Boden and Marland, 2010).

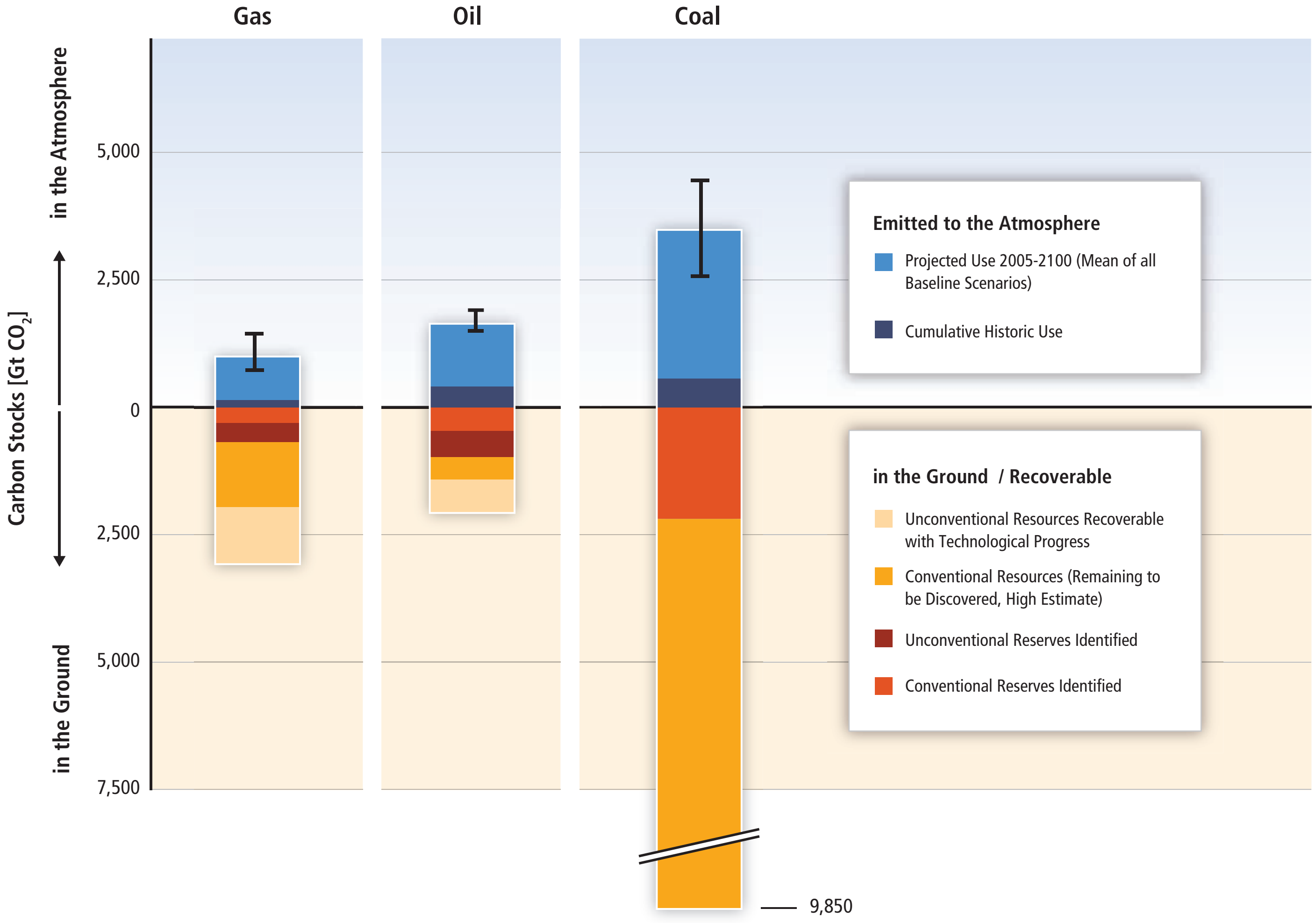

Figure 1.7 | CO_2 released to the atmosphere (above zero) and stocks of recoverable carbon from fossil fuels in the ground (below zero, converted to CO_2). Estimates of carbon stocks in the ground are taken from IPCC (2000a, Table 3-5). Estimates of carbon stocks remaining are provided by BGR (2009), cumulative historic carbon consumption (1750 to 2004) is from Boden et al. (2009) and estimated future consumption (2005 to 2100) from the mean of the baseline scenarios of the energy-economic and integrated assessment models considered in the analysis of Chapter 10 (Table 10.1). Only those scenarios where the full data set until 2100 was available were considered (i.e., 24 scenarios from 12 models). The light blue stacked bar shows the mean and the black error bars show the standard deviation of the baseline projections. Fossil energy stocks were converted to CO_2 emissions by using emission factors from IPCC (2006). Adapted from Knopf et al. (2010).

Historically, developed countries have contributed the most to cumulative global CO_2 emissions, and still have the highest total historical emissions and largest emissions per capita (World Bank, 2009). Recently, developing country annual emissions have risen to more than half of the total, and China surpassed the USA in annual emissions in 2007 (IEA, 2010f). Figure 1.9 examines the annual change in absolute emissions by country and country groups between 1971 and 2008 (Edenhofer et al., 2010).

1.1.5 Renewable energy as an option to mitigate climate change

On a global basis, it is estimated that RE accounted for 12.9% of the total 492 EJ of primary energy supply in 2008 (IEA, 2010a). 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.[6] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4% (Figure 1.10).

RE's contribution to electricity generation is summarized in Figure 1.11. In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE). Global electricity production in 2008 was 20,181 TWh (or 72.65 EJ) (IEA, 2010a).

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 fuels and other factors have supported the continuing increase

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[6] In addition, biomass use estimated to amount to 20 to 40% is not reported in official databases, such as dung, unaccounted production of charcoal, illegal logging, fuelwood gathering, and agricultural residue use (Section 2.1).

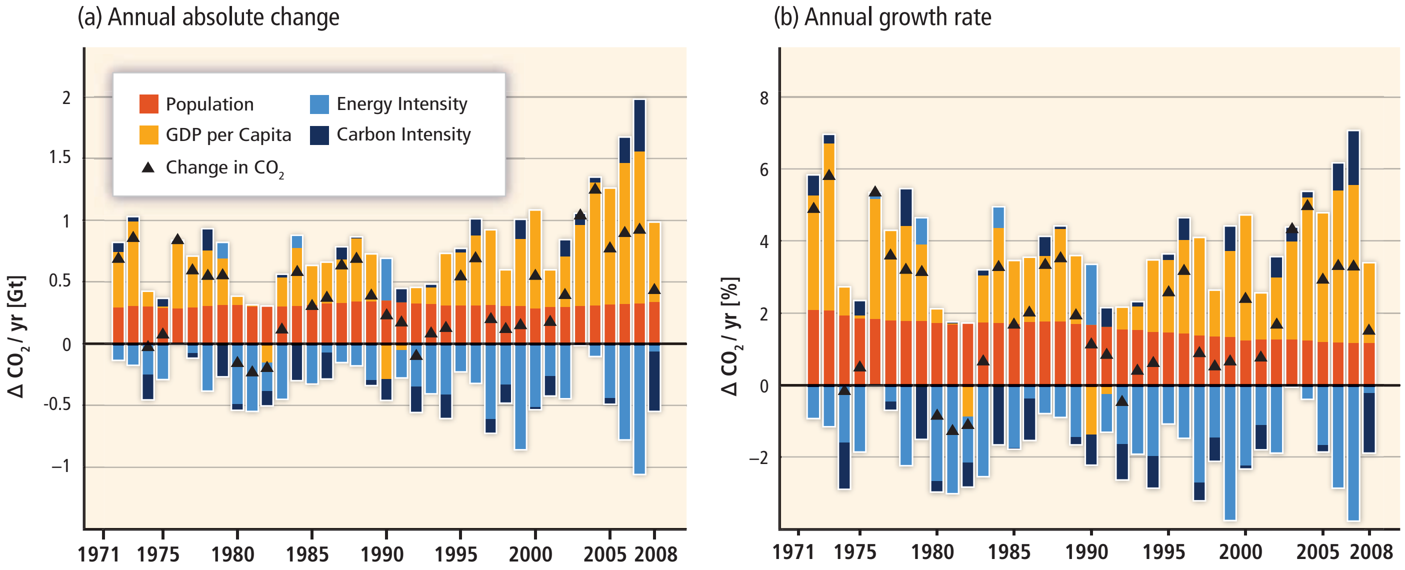

Figure 1.8 | Decomposition of (a) annual absolute change and (b) annual growth rate in global energy-related CO_2 emissions by the factors in the Kaya identity; population (red), GDP per capita (orange), energy intensity (light blue) and carbon intensity (dark blue) from 1971 to 2008. The colours show 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. Data source: IEA (2010a).

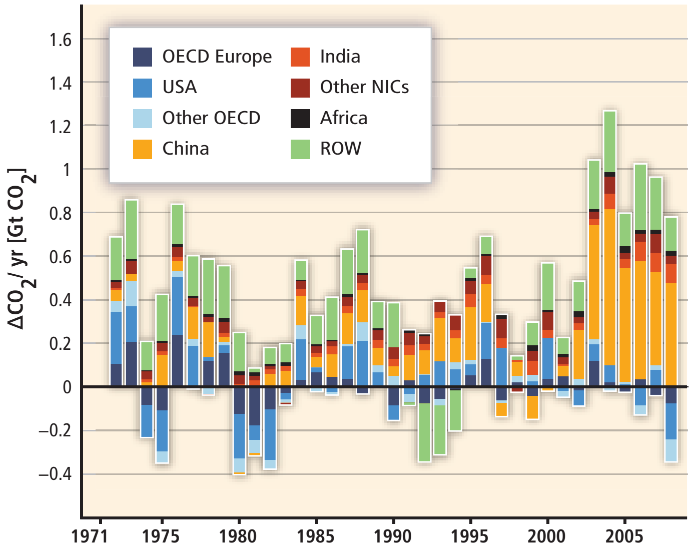

Figure 1.9 | Influence of selected countries and country groups on global changes in CO_2 emissions from 1971 to 2008. ROW: rest of world. Data source: IEA (2010a).

Note: "OECD" is the Organisation for Economic Co-operation and Development; "Other Newly Industrializing Countries (NICs)" include Brazil, Indonesia, the Republic of Korea, Mexico and South Africa; "Other OECD" does not include the Republic of Korea and Mexico; and "Africa" does not include South Africa.

in the use of RE (see Section 1.5.1 and Chapter 11). While RE is still relatively small, its growth has accelerated in recent years, as shown in Figure 1.12. 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), and solar hot water/heating (21%, 31 GW_{th}) (REN21, 2010). Biofuels accounted for 2% of global road transport fuel demand in 2008 and nearly 3% in 2009 (IEA, 2010c). 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 over the two-year period from 2008 to 2009, 140 GW came from RE additions. Collectively, by the end of 2009 developing countries hosted 53% of global RE power generation capacity (including all sizes of hydropower), with China adding more 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 markets included modern biomass (270 GW_{th}), solar (180 GW_{th}) and geothermal (60 GW_{th}). The use of RE (excluding traditional biomass) in meeting rural energy needs is also increasing, including small hydropower stations, various modern bioenergy options, and household or village PV, wind or hybrid systems that combine multiple technologies (REN21, 2010).

UNEP found that in 2008, despite a decline in overall energy investments, global investment in RE power generation rose by 5% to USD 140 billion (USD_{2005} 127 billion), which exceeded the 110 billion (USD_{2005} 100 billion) invested in fossil fuel generation capacity (UNEP, 2009).

These developments suggest the possibility that RE could play a much more prominent role in both developed and developing countries over the coming decades (Demirbas, 2009). New policies, especially in the USA, China and the EU, are supporting this effort (Chapter 11).

Estimates of the lifecycle CO_2 intensity for electric power-producing renewable energy technologies relative to fossil fuels and nuclear power are shown in Figure 1.13 and are discussed in more detail in Chapter 9. Renewable energy and nuclear technologies produce one to two orders of

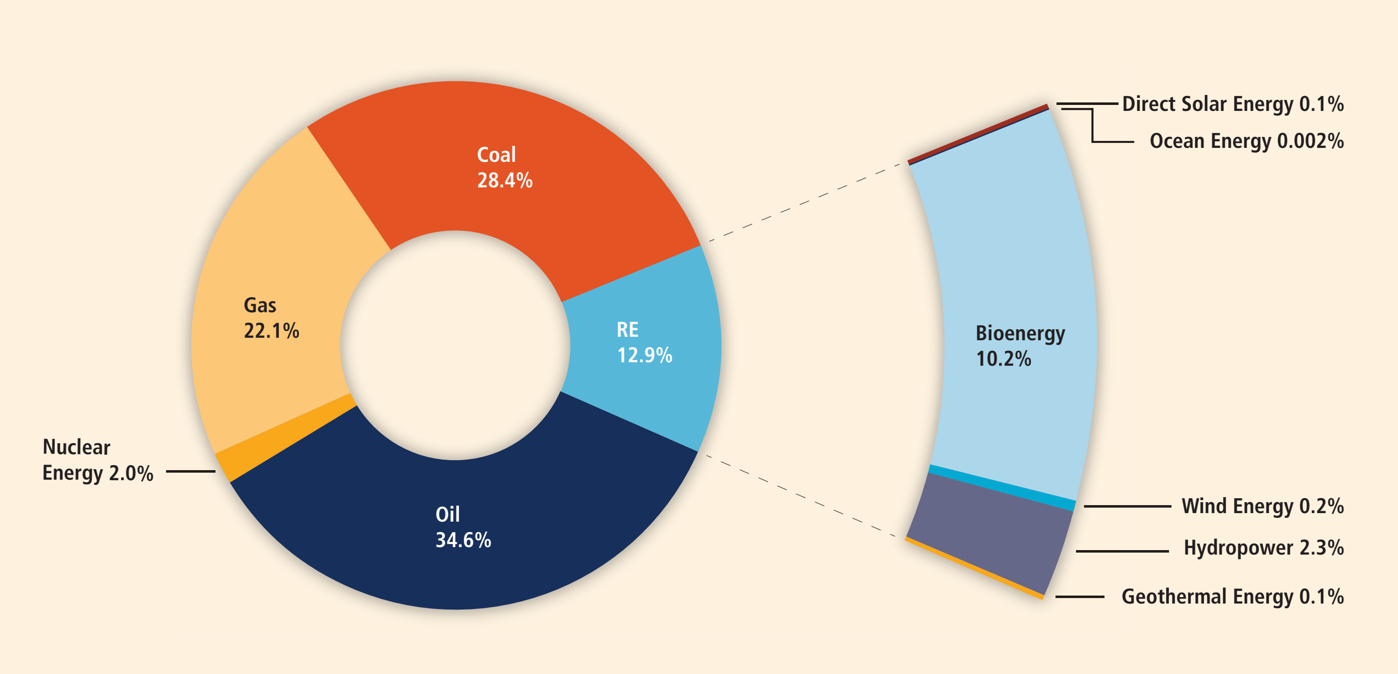

Figure 1.10 | Shares of energy sources in total global primary energy supply in 2008 (492 EJ). Modern biomass contributes 38% to the total biomass share. Data source: IEA (2010a).

Notes: Underlying data for figure have been converted to the direct equivalent method of accounting for primary energy supply (Annex II.4).

magnitude lower CO_2 emissions than fossil fuels in grams of CO_2 per kWh of electricity produced (Weisser, 2007; Sovacool, 2008; Jacobson, 2009).

Most RE technologies have low specific emissions of CO_2 into the atmosphere relative to fossil fuels, which makes them useful tools for addressing climate change (see Figure 1.13). For a RE resource to be sustainable, it must be inexhaustible and not damage the delivery of environmental goods and services including the climate system. For example, to be sustainable, biofuel production should not increase net CO_2 emissions, should not adversely affect food security, or require excessive use of water and chemicals or threaten biodiversity. To be sustainable, energy must also be economically affordable over the long term; it must meet societal needs and be compatible with social norms now and in the future. Indeed, as use of RE technologies accelerates, a balance will have to be struck among the several dimensions of sustainable development. It is important to assess the entire lifecycle of each energy source to ensure that all of the dimensions of sustainability are met (Sections 1.4.1.4 and 9.3.4).

1.1.6 Options for mitigation

There are multiple means for lowering GHG emissions from the energy system while still providing energy services (Pacala and Socolow, 2004; IPCC, 2007d). Energy services are the tasks to be performed using energy. Many options and combinations are possible for reducing emissions. In order to assess the potential contribution of RE to mitigating global climate change, competing mitigation options therefore must be considered as well (Chapter 10).

Chapter 4 of AR4 (Sims et al., 2007) identified a number of ways to lower heat-trapping emissions from energy sources while still providing energy services. They include:

- 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, lighting) (see also von Weizsäcker et al., 2009).
- 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 (Chapters 2 through 7).
- Utilize carbon 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 burned (see also IPCC, 2005).
- Change behaviour to better manage energy use or to use fewer carbon- and energy-intensive goods and services (see also Dietz et al., 2009).

Two additional means of reducing GHGs include enhancing the capacity of forests, soils and grassland sinks to absorb CO_2 from the atmosphere (IPCC, 2000b), and reducing the release of black carbon aerosols and particulates

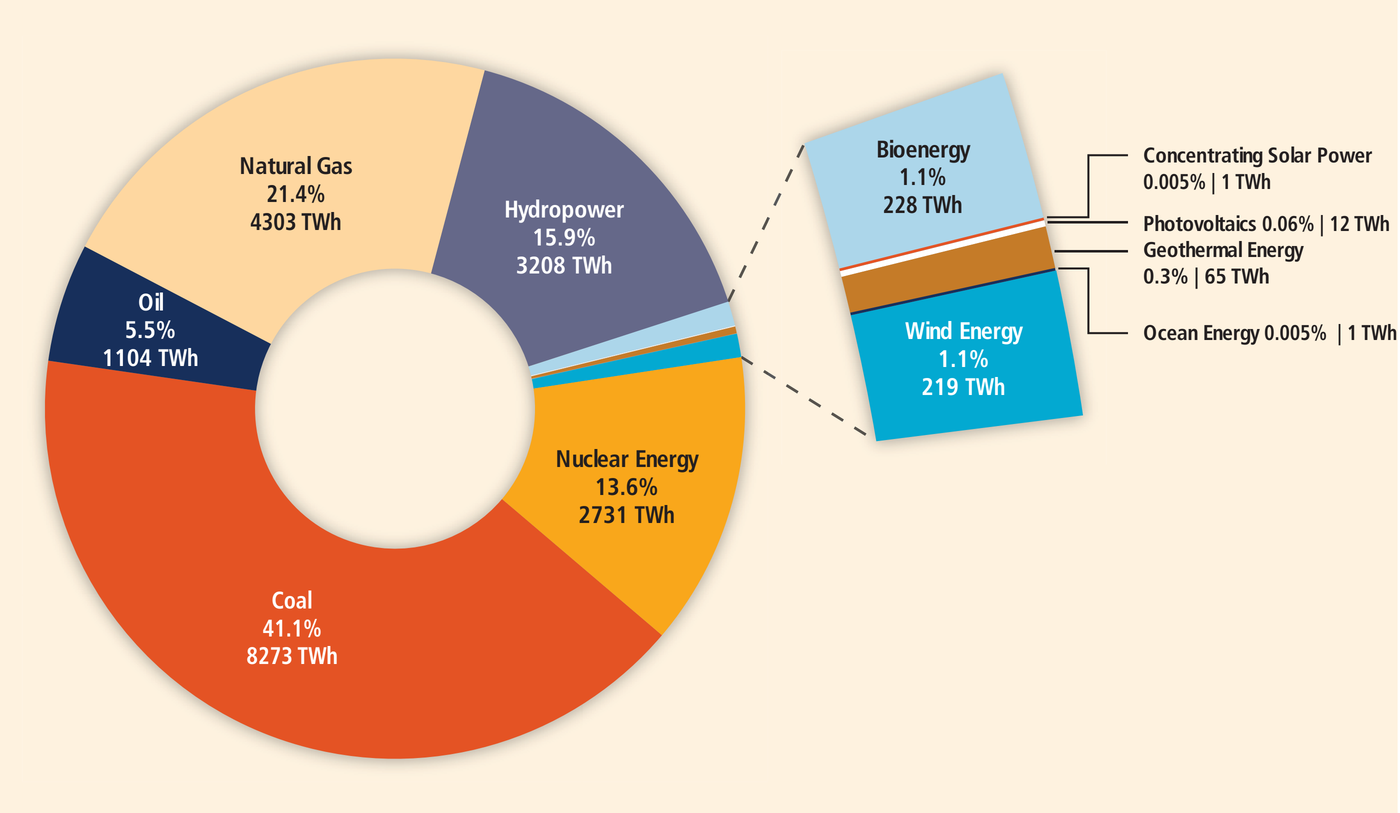

Figure 1.11 | Share of primary energy sources in world electricity generation in 2008. Data for renewable energy sources from IEA (2010a); for fossil and nuclear from IEA (2010d).

from diesel engines, biomass fuels and from the burning of agricultural fields (Bond and Sun, 2005). Additional reductions in non-CO_2 heat-trapping GHGs (CH_4, N_2O, hydrofluorocarbons, sulphur hexafluoride) can also reduce global warming (Moomaw et al., 2001, their Appendix; Sims et al., 2007).

Geoengineering solutions have been proposed to address other aspects of climate change, including altering the heat balance of the Earth by increasing surface albedo (reflectivity), or by reflecting incoming solar radiation with high-altitude mirrors or with atmospheric aerosols. Enhanced CO_2 absorption from the atmosphere through ocean fertilization with iron has also been proposed and tested (Robock et al., 2009; Royal Society, 2009).

There are multiple combinations of these means that can reduce the extent of global warming. 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. This report focuses on substitution of fossil fuels with low-carbon RE to reduce GHGs, and examines the competition between RE and other options to address global climate change (see Figure 1.14).

Setting a climate protection goal in terms of the admissible change in global mean temperature broadly defines (depending on the assumed climate sensitivity) a corresponding atmospheric CO_2 concentration limit and an associated carbon budget over the long term (see Figure 1.5, right panel) (Meinshausen et al., 2009). This budget, in turn, can be broadly translated into a time-dependent emission trajectory that serves as an upper bound or (if the remaining time flexibility is taken into account) in an associated corridor of admissible emissions (Figure 1.5, left panel). Subtracting any expected CO_2 emissions from land use change and land cover change constrains the admissible CO_2 emissions that could be realized by freely emitting carbon fuels (i.e., coal, oil, and gas burned without applying carbon capture technologies).

The corresponding fossil fuel supply is part of the total primary energy supply (see Figure 1.14). The remainder of the TPES is provided by zero- or low-carbon energy technologies, such as RE, nuclear or the combustion of fossil fuels combined with CCS (Clarke et al., 2009).

Whereas the admissible amount of freely emitting fossil fuels is mainly fixed by the climate protection goal, the complementary contribution of zero- or low-carbon energies to the primary energy supply is influenced by the 'scale' of the requested energy services and the overall efficiency with which these services can be provided.

As Figure 1.2 right panel clearly shows, the energy intensity is already expected to decrease significantly in the non-intervention scenarios. Technical improvements and structural changes are expected to result in considerably lower emissions than otherwise would be projected. As many low-cost options to improve the overall energy efficiency are

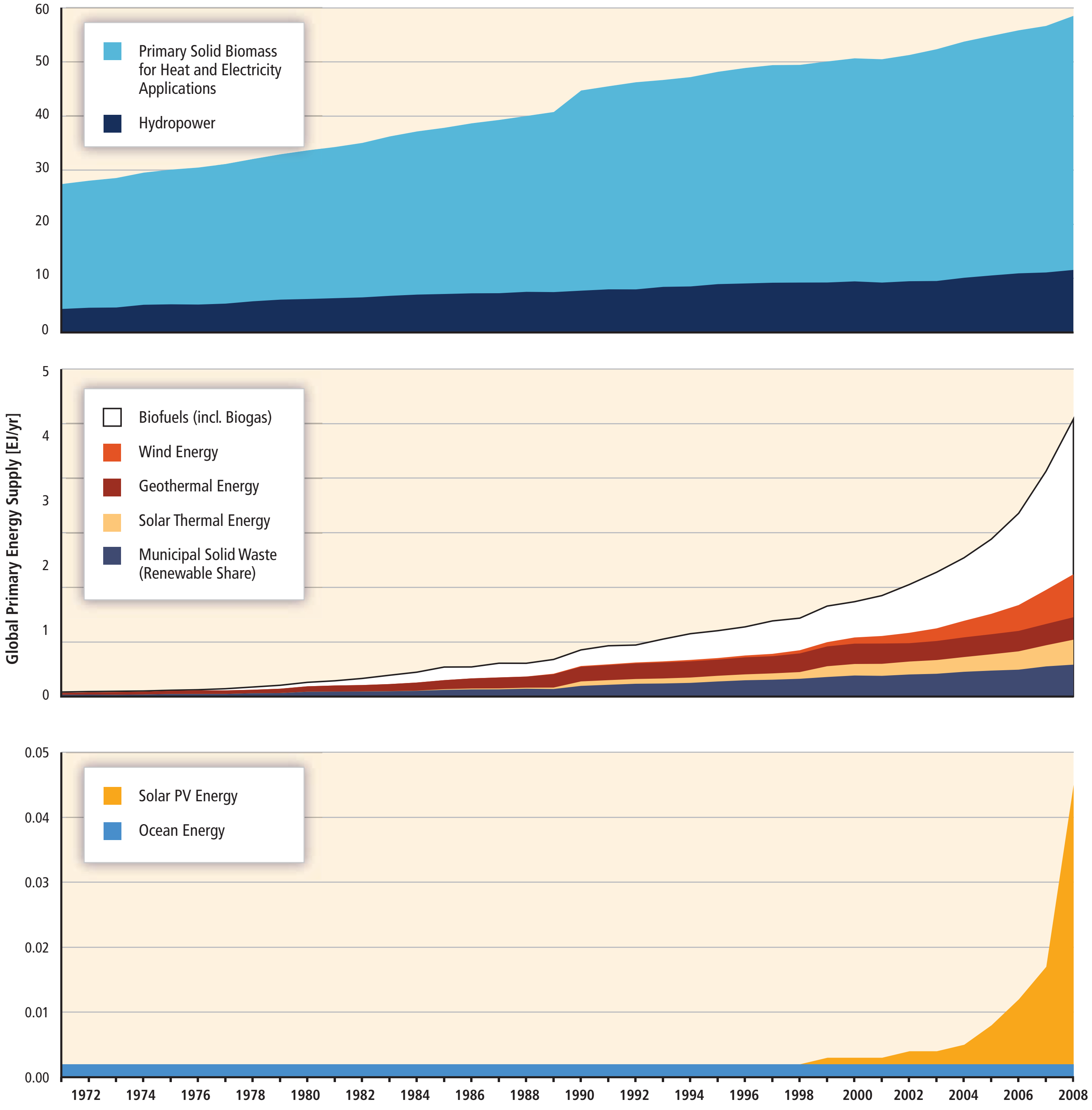

Figure 1.12 | Historical development of global primary energy supply from renewable energy from 1971 to 2008. Data Source: IEA (2010a).

Note: Technologies are referenced to separate vertical units for display purposes only. Underlying data for figure have been converted to the 'direct equivalent' method of accounting for primary energy supply (Section 1.1.9 and 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 (Sections 2.3 and 2.4)).

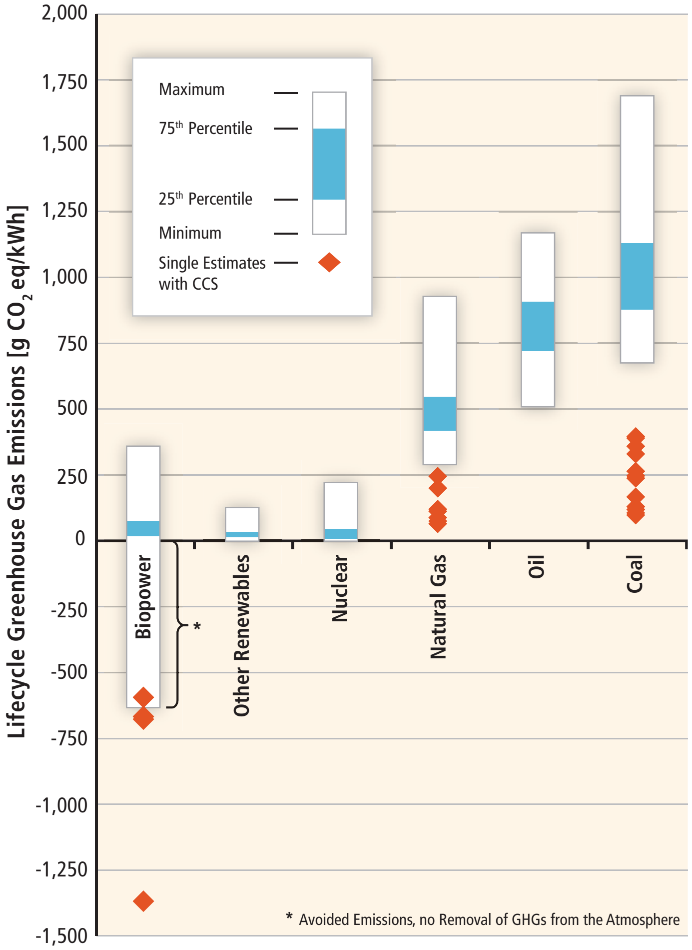

Figure 1.13 | Lifecycle GHG emissions of renewable energy, nuclear energy and fossil fuels (Chapter 9, Figure 9.8).

already part of the non-intervention scenarios (Fisher et al., 2007), the *additional* opportunities to decrease energy intensity in order to mitigate climate change are limited (Bruckner et al., 2010). In order to achieve ambitious climate protection goals, for example, stabilization below the aforementioned 2°C global mean temperature change, energy efficiency improvements alone do not suffice. In addition, low-carbon technologies become imperative.

Chapter 10 includes a comprehensive analysis of over 100 scenarios of energy supply and demand to assess the costs and benefits of RE options to reduce GHG emissions and thereby mitigate climate change. The contribution RE will provide within the portfolio of these low-carbon technologies heavily depends on the economic competition between these technologies (Chapter 10), a comparison of the relative environmental burdens (beyond climate change) associated with them, as well as secure energy supply and societal aspects (Figure 1.14). However, even without a push for climate change mitigation, scenarios that are examined in this report find that the increasing demand for energy services is expected to drive RE to levels exceeding today's energy usage. There are large uncertainties in projections, including economic and population growth, development and deployment of higher efficiency technologies, the ability of RE technologies to overcome initial cost barriers, preferences, environmental considerations and other barriers.

1.1.7 Trends in international policy on renewable energy

The international community's discussions of RE began with the fuel crises of the 1970s, when many countries began exploring alternative energy sources. Since then, RE has featured prominently in the United Nations agenda on environment and development through various initiatives and actions (WIREC, 2008; Hirschl, 2009).

The 1981 UN Conference on New and Renewable Sources of Energy adopted the Nairobi Programme of Action. The 1992 UN Conference on Environment and Development, and Action Plan for implementing sustainable development through sustainable energy and protection of the atmosphere was reinforced by the 2002 World Summit on Sustainable Development where several RE Partnerships were signed. 'Energy for Sustainable Development' highlighted the importance of RE at the 2001 UN Commission on Sustainable Development (CSD, 2001). Major RE meetings were held in Bonn in 2004, Beijing in 2005 and in Washington, DC, in 2008.

The International Energy Agency (IEA) has provided a forum for discussing energy issues among OECD countries, and provides annual reports on all forms of energy including RE. The IEA also prepares scenarios of alternative futures utilizing differing combinations of primary energy

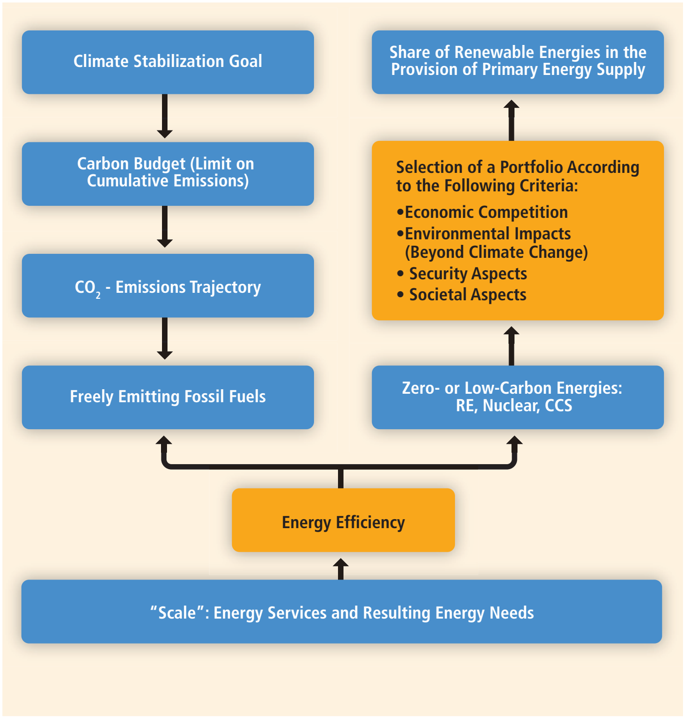

Figure 1.14 | The role of renewable energies within the portfolio of zero- or low-carbon mitigation options (qualitative description).

sources, energy efficiency and CO_2 emissions. REN 21, a nongovernmental organization, compiles recent data on RE resources based upon industrial and governmental reports. A new international organization, the International Renewable Energy Agency (IRENA), was also established in 2009 and has 149 signatories and 57 member countries[7].

1.1.8 Advancing knowledge about renewable energy

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.

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.

Though not comprehensive, a broad and selective listing of areas of anticipated present and future knowledge advancement is provided in Table 1.1.

1.1.9 Metrics and definitions

A glossary of terms is provided in Annex I. Conventions, conversion factors and methodologies are described in Annex II. A cost table for RE technologies is provided in Annex III.

To have a common comparison for all low-carbon sources, primary energy is measured according to the direct equivalent method rather than the physical content method favoured by IEA. The two methods treat all combustion technologies the same, but the direct equivalent method only counts the electric or thermal energy that is produced as primary energy for nuclear power or geothermal power, while the physical content method counts the total heat that is released. See Box 1.1 and Annex II where the differences between these methods are described in further detail.

1.2 Summary of renewable energy resources

1.2.1 Definition, conversion and application of renewable energy

Renewable energy 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 and 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.

There is a multi-step process whereby primary energy is converted into an energy carrier (heat, electricity or mechanical work), and then into an energy service. 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 1.16).

Since it is energy services and not energy that people need, the goal is to meet those needs in an efficient manner that requires less primary energy consumption with low-carbon technologies that minimize CO_2 emissions (Haas et al., 2008). Thermal conversion processes to produce electricity (including from 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 (Jacobson, 2009; LLNL, 2009; Sterner, 2009). 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 through 7). To better compare low-carbon sources that produce electricity over time, this report has adopted the *direct equivalent method* in which primary energy of *all non-combustible sources* is defined as one unit of secondary energy, for example, electricity,

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[7] See www.irena.org/

Table 1.1 | Select areas of possible future knowledge advancement

Future cost and timing of RE deployment	• Cost of emerging and non-electricity RE technologies, in diverse regional contexts • Future cost reduction given uncertainty in research and development (R&D)-driven advances and deployment-oriented learning • Cost of competing conventional and low-carbon energy technologies • Ability to analyze variable and location-dependent RE technologies in large-scale energy models, including the contribution of RE towards sustainable development and energy access • Further assessments of RE deployment potentials at global, regional and local scales • Analysis of technology-specific mitigation potential through comparative scenario exercises considering uncertainties • Impacts of policies, barriers and enabling environments on deployment volume and timing
Realizable technical potential for RE at all geographic scales	• Regional/local RE resource assessments • Improved resource assessments for emerging technologies and non-electricity RE technologies • Future impacts of climate change on RE technical potential • Competition for RE resources, such as biomass, between RE technologies and other human activities and needs • Location of RE resources relative to the location of energy demand (i.e., population centres)
Technical and institutional challenges and costs of integrating diverse RE technologies into energy systems and markets	• Comparative assessment of the short- and long-term technical/institutional solutions and costs of integrating high penetrations of RE • Specific technical/institutional challenges of integrating variable RE into electricity markets that differ from those of the OECD, for RE resources other than wind, and the challenges and costs of cycling coal and nuclear plants • Benefits and costs of combining multiple RE sources for the purpose of integration into energy markets • Institutional and technical barriers to integrating RE into heating and transport networks • Impacts of possible future changes in energy systems (including more or less centralization or decentralization, degree of demand response, and the level of integration of the electricity sector with the presently distinct heating and transport sectors) on integration challenges and cost
Comprehensive assessment of socioeconomic and environmental aspects of RE and other energy technologies	• Net lifecycle carbon emissions of certain RE technologies (e.g., some forms of bioenergy, hydropower) • Assessment of local and regional impacts on ecosystems and the environment • Assessment of local and regional impacts on human activities and well-being • Balancing widely varying positive and negative impacts over different geographic and temporal scales • Policies to effectively minimize and manage negative impacts, and realize positive benefits • Understanding and methods to address public acceptance concerns of local communities
Opportunities for meeting the needs of developing countries with sustainable RE services	• Impacts of RE deployment on multiple indicators of sustainable development • Regional/local RE resource assessments in developing countries • Advantages and limitations of improving energy access with decentralized forms of RE • Local human resource needs to ensure effective use of RE technologies • Financing mechanisms and investment tools to ensure affordability • Effective capacity building, as well as technology and knowledge transfer
Policy, institutional and financial mechanisms to enable cost-effective deployment of RE in a wide variety of contexts	• The combination of policies that are most efficient and effective for deploying different RE technologies in different countries. • How to address equity concerns while encouraging significant increases in RE investment. • How to design a policy such that potential co-benefits of RE deployment are maximized, for example security, equity and environmental benefits • Optimizing the balance of design and of timing of RE-specific versus carbon-pricing policies to take best advantage of the synergies between these two policy types. • Finding the most effective way to overcome the inherent advantage of current energy technologies including regulations and standards that lock-out RE technologies and what needs to change in order to allow RE to penetrate the energy system

Box 1.1 | Implications of different primary energy accounting conventions for energy and emission scenarios.

Primary energy for combustible energy sources is defined as the heat released when it is burned in air. As discussed in Annex II (A.II.4) and Table 1.A.1, there is no single, unambiguous accounting method for calculating primary energy from non-combustible energy sources such as nuclear energy and all RE sources with the exception of bioenergy. The *direct equivalent method* is used throughout this report. The direct equivalent method treats all non-combustible energy sources in an identical way by counting one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. Depending on the type of secondary energy produced, this may lead to an understatement of the contribution of non-combustible RE and nuclear compared to bioenergy and fossil fuels by a factor of roughly 1.2 up to 3 (using indicative fossil fuel to electricity and heat conversion efficiencies of 38 and 85%, respectively). The implications of adopting the direct equivalent method in contrast to the other two most prominent methods—the physical energy content method and the substitution method—are illustrated in Figure 1.15 and Table 1.2 based on a selected climate stabilization scenario. The scenario is from Loulou et al. (2009) and is referred to as 1B3.7MAX in that publication. CO_2-equivalent concentrations of the Kyoto gases reach 550 ppm by 2100.

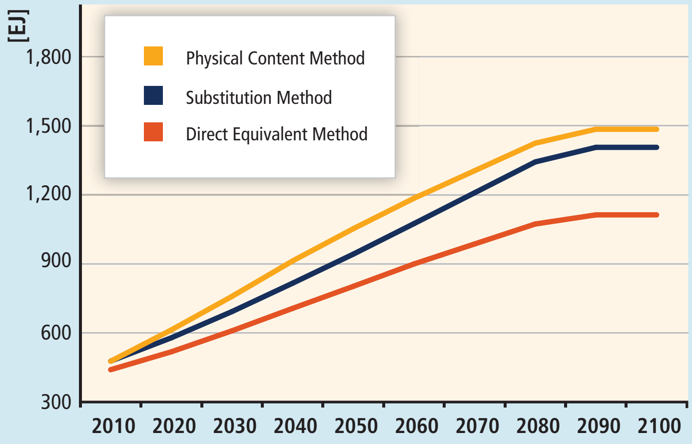

Figure 1.15 | Comparison of global total primary energy supply between 2010 and 2100 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario.

Differences from applying the three accounting methods to current energy consumption remain limited. However, substantial differences arise when applying the methods to long-term scenarios when RE reaches higher shares. For the selected scenario, the accounting gap between methods grows substantially over time, reaching about 370 EJ by 2100. There are significant differences in the accounting for individual non-combustible sources by 2050, and even the share of total renewable primary energy supply varies between 24 and 37% across the three methods. The biggest absolute gap for a single source is geothermal energy, with about 200 EJ difference between the direct equivalent and the physical energy content method. The gaps for hydro and nuclear energy remain considerable. For more details on the different approaches, see Annex II.

Table 1.2 | Comparison of global total primary energy supply in 2050 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario.

	Physical content method		Direct equivalent method		Substitution method	
	EJ	%	EJ	%	EJ	%
Fossil fuels	586.56	55.24	581.56	72.47	581.56	61.71
Nuclear	81.10	7.70	26.76	3.34	70.43	7.47
RE	390.08	37.05	194.15	24.19	290.37	30.81
Bioenergy	119.99	11.40	119.99	14.95	119.99	12.73
Solar	23.54	2.24	22.04	2.75	35.32	3.75
Geothermal	217.31	20.64	22.88	2.85	58.12	6.17
Hydro	23.79	2.26	23.79	2.96	62.61	6.64
Ocean	0.00	0.00	0.00	0.00	0.00	0.00
Wind	5.45	0.52	5.45	0.68	14.33	1.52
Total	1,052.75	100.00	802.47	100.00	942.36	100.00

instead of wind kinetic energy, geothermal heat, uranium fuel or solar radiation (Macknick, 2009; Nakicenovic et al., 1998). Hence any losses between the original sources and electricity are not counted in the amount of primary energy from these non-combustible sources (Annex II, A.II.4). Hence, primary energy requirements to produce a unit of electricity or other work from these sources are generally lower than for fossil fuels or biomass combustion processes.

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 RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment. The overview of RE technologies and applications in Table 1.3 provides an abbreviated list of the major renewable primary energy sources and technologies, the status of their development and the typical or primary distribution method (centralized network/grid required or decentralized, local standalone supply). The list is not considered to be comprehensive, for example, domestic animals and obtaining energy from plant biomass provide an important energy service in transportation and agriculture in many cultures but are not considered in this report. The table is constructed from the information and findings in the respective technology chapters.

1.2.2 Theoretical potential of renewable energy

The theoretical potential of RE is much greater than all of the energy that is used by all the economies on Earth. The challenge is to capture it and utilize it to provide desired energy services in a cost-effective manner. Estimated annual fluxes of RE and a comparison with fossil fuel reserves and 2008 annual consumption of 492 EJ are provided in Table 1.4.

1.2.3 Technical potential of renewable energy technologies

Technical potential is defined as the amount of RE output obtainable by full implementation of demonstrated and likely to develop technologies or practices.[8] The literature related to the technical potential of the different RE types assessed in this report varies considerably (Chapters 2 through 7 contain details and references). Among other things, this variation is due to methodological differences among studies, variant definitions of technical potential and variation due to differences between authors about how technologies and resource capture techniques may change over time. The global technical potential of RE sources will not limit continued market growth. A wide range of estimates is

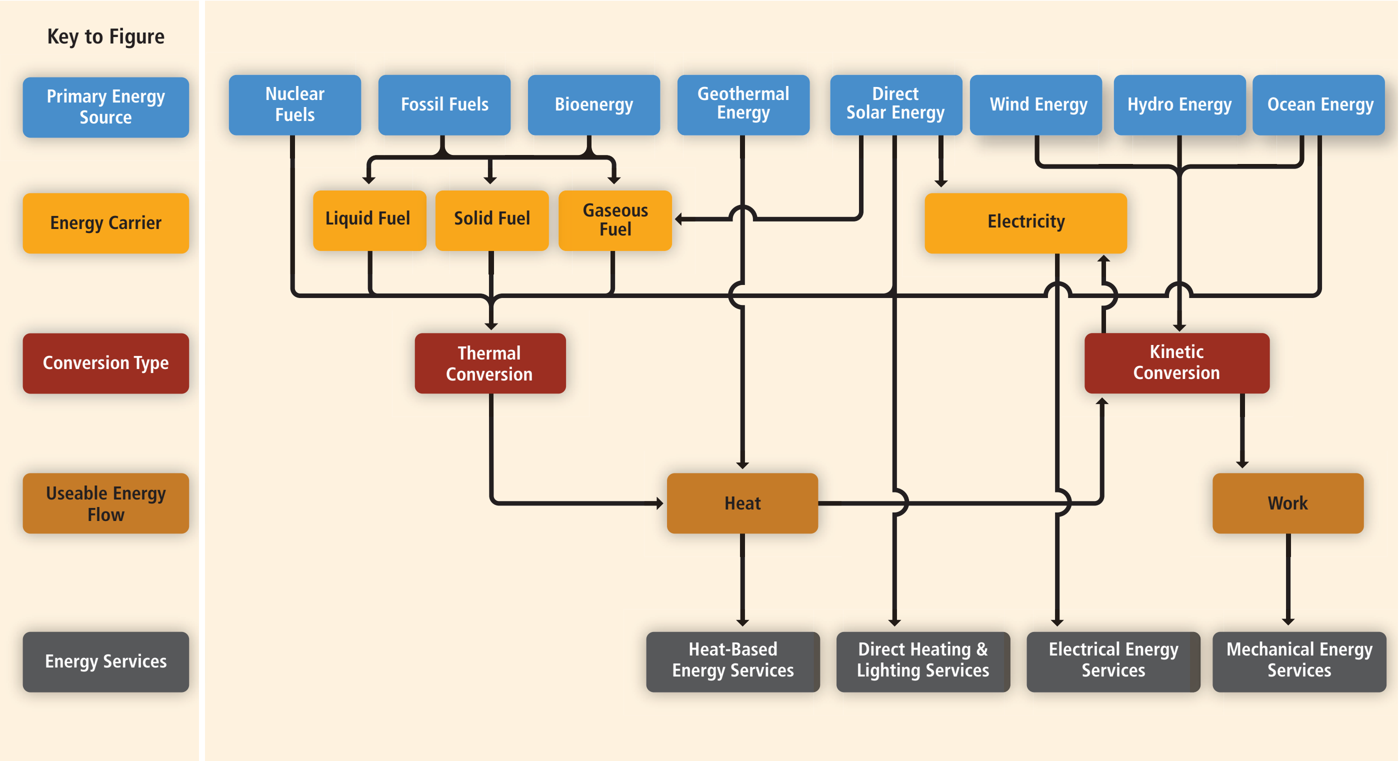

Figure 1.16 | Illustrative paths of energy from source to service. All connected lines indicate possible energy pathways. The energy services delivered to the users can be provided with differing amounts of end-use energy. This in turn can be provided with more or less primary energy from different sources,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

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[8] The Glossary (Annex I) provides a more comprehensive definition of this term and of economic and market potential.

Table 1.3 | Overview of renewable energy technologies and applications (Chapters 2 through 7)

Renewable Energy Source	Select Renewable Energy Technologies	Primary Energy Sector (Electricity, Thermal, Mechanical, Transport)[1]	Technology Maturity[2]				Primary Distribution Method[3]	
			R & D	Demo & Pilot Project	Early-Stage Com'l	Later-Stage Com'l	Centralized	Decentralized
Bioenergy[4]	Traditional Use of Fuelwood/Charcoal	Thermal				●		●
	Cookstoves (Primitive and Advanced)	Thermal				●		●
	Domestic Heating Systems (pelletbased)	Thermal				●		●
	Small- and Large-Scale Boilers	Thermal				●	●	●
	Anaerobic Digestion for Biogas Production	Electricity/Thermal/Transport				●	●	●
	Combined Heat and Power (CHP)	Electricity/Thermal				●	●	●
	Co-firing in Fossil Fuel Power Plant	Electricity				●	●	
	Combustion-based Power Plant	Electricity				●	●	●
	Gasification-based Power Plant	Electricity			●		●	●
	Sugar- and Starch-Based Crop Ethanol	Transport				●	●	
	Plant- and Seed Oil-Based Biodiesel	Transport				●	●	
	Lignocellulose Sugar-Based Biofuels	Transport		●			●	
	Lignocellulose Syngas-Based Biofuels	Transport			●		●	
	Pyrolysis-Based Biofuels	Transport		●			●	
	Aquatic Plant-Derived Fuels	Transport	●				●	
	Gaseous Biofuels	Thermal				●	●	
Direct Solar	Photovoltaic (PV)	Electricity				●	●	●
	Concentrating PV (CPV)	Electricity			●		●	●
	Concentrating Solar Thermal Power (CSP)	Electricity			●		●	●
	Low Temperature Solar Thermal	Thermal				●		●
	Solar Cooling	Thermal		●				●
	Passive Solar Architecture	Thermal				●		●
	Solar Cooking	Thermal			●			●
	Solar Fuels	Transport	●				●	
Geothermal	Hydrothermal, Condensing Flash	Electricity				●	●	
	Hydrothermal, Binary Cycle	Electricity				●	●	
	Engineered Geothermal Systems (EGS)	Electricity		●			●	
	Submarine Geothermal	Electricity	●				●	
	Direct Use Applications	Thermal				●	●	●
	Geothermal Heat Pumps (GHP)	Thermal				●		●
Hydropower	Run-of-River	Electricity/Mechanical				●	●	●
	Reservoirs	Electricity				●	●	●
	Pumped Storage	Electricity				●	●	
	Hydrokinetic Turbines	Electricity/Mechanical		●			●	●
Ocean Energy	Wave	Electricity		□			□	
	Tidal Range	Electricity				□	□	
	Tidal Currents	Electricity		□			□	
	Ocean Currents	Electricity	□				□	
	Ocean Thermal Energy Conversion	Electricity/Thermal		□			□	
	Salinity Gradients	Electricity		□			□	

Continued next Page →

Renewable Energy Source	Select Renewable Energy Technologies	Primary Energy Sector (Electricity, Thermal, Mechanical, Transport)[1]	Technology Maturity[2]				Primary Distribution Method[3]	
			R & D	Demo & Pilot Project	Early-Stage Com'l	Later-Stage Com'l	Centralized	Decentralized
Wind Energy	Onshore, Large Turbines	Electricity				●	●	
	Offshore, Large Turbines	Electricity			●		●	
	Distributed, Small Turbines	Electricity				●		●
	Turbines for Water Pumping / Other Mechanical	Mechanical				●		●
	Wind Kites	Transport		●				●
	Higher-Altitude Wind Generators	Electricity	●				●	

Notes: 1. Primary energy sector as used here is intended to refer to the primary current or expected use(s) of the RE technology. In practice, RE-generated fuels may be used to meet a variety of energy service needs (not only transportation); electricity can be used to meet thermal and transportation needs; etc. 2. The highest level of maturity within each technology category is identified in the table; less mature technologies exist within some technology categories. 3. Centralized refers to energy supply that is distributed to end users through a network; decentralized refers to energy supply that is created onsite. Categorization is based on the 'primary' distribution method, recognizing that virtually all technologies can, in some circumstances, be used in both a centralized and decentralized fashion. 4. Bioenergy technologies can also be combined with CCS, though CCS technology is at an earlier stage of maturity.

Table 1.4 | Renewable energy theoretical potential expressed as annual energy fluxes of EJ/yr compared to 2008 global primary energy supply.

Renewable source	Annual Flux (EJ/yr)	Ratio (Annual energy flux/ 2008 primary energy supply)	Total reserve
Bioenergy	1,548[d]	3.1	—
Solar Energy	3,900,000[a]	7,900	—
Geothermal Energy	1,400[c]	2.8	—
Hydropower	147[a]	0.30	—
Ocean Energy	7,400[a]	15	—
Wind Energy	6,000[a]	12	—
Annual Primary energy source	**Annual Use 2008 (EJ/yr)**	**Lifetime of Proven Reserve (years)**	**Total Reserve (EJ)**
Total Fossil	418[b]	112	46,700
Total Uranium	10[b]	100–350	1,000–3,500
Total RE	64[b]	—	—
Primary Energy Supply	492 (2008)[b]	—	—

Sources: a. Rogner et al. (2000); b. IEA (2010c) converted to direct equivalent method (Annex II; IEA, 2010d); c. Pollack et al. (1993); d. Smeets et al. (2007).

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. Figure 1.17 summarizes the ranges of technical potential for the different RE technologies based on the respective chapter discussions. These ranges are compared to a comprehensive literature review by Krewitt et al. (2009) in Table 1.A.1 including more detailed notes and explanations in the Appendix to this chapter.[9] The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all forms of RE. According to the definition of technical potential in the Glossary (Annex I), many of the studies summarized in Table 1.A.1 to some extent take into account broader economic and socio-political considerations. For example, for some technologies, land suitability or other sustainability factors are included, which result in lower technical potential estimates. However, the absolute size of the global technical potential for RE as a whole is unlikely to constrain RE deployment.

Taking into account the uncertainty of the technical potential estimates, Figure 1.17 and Table 1.A.1 provide a perspective for the reader to understand the relative technical potential of the RE resources in the context of current global electricity and heat demand as well as of global primary energy supply. Aspects related to technology evolution, sustainability, resource availability, land use and other factors that relate to this technical potential are explored in the various

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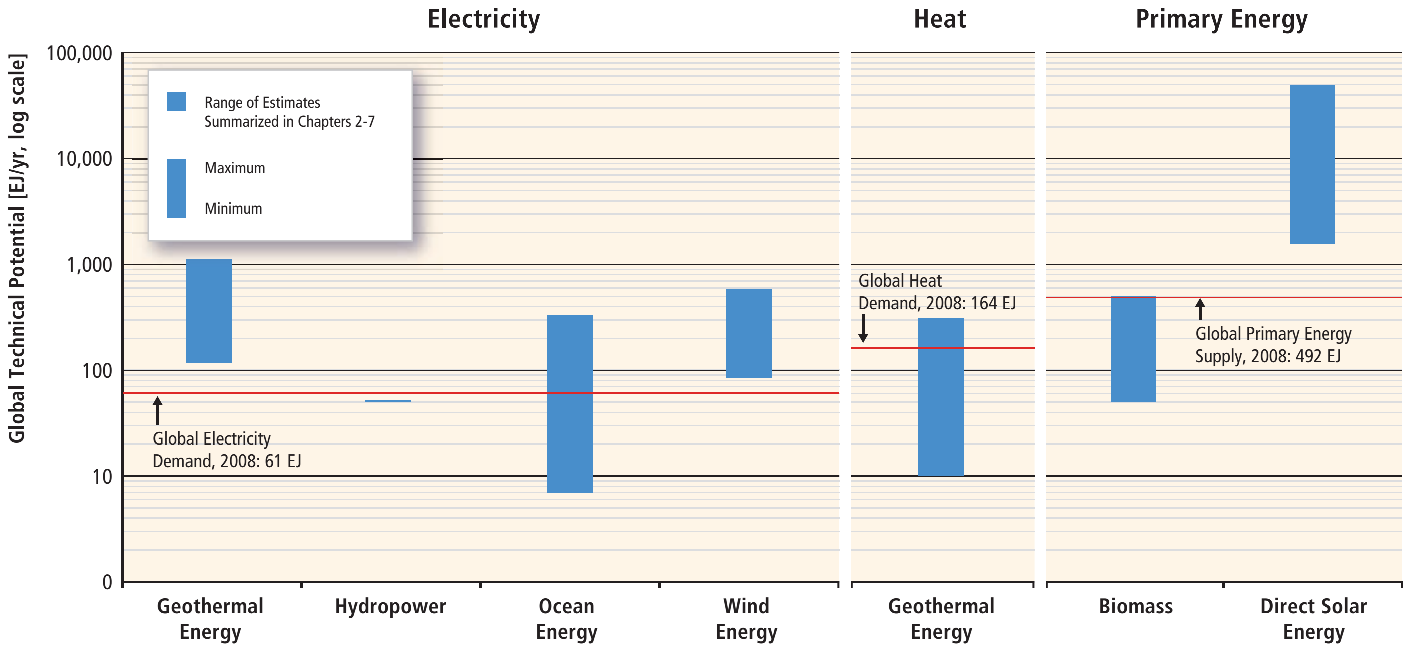
[9] The definition of technical potential in Loulou et al. (2009) is similar but not identical to the definition here in that it is bounded by local/geographical availability and technological limitations associated with conversion efficiencies and the capture and transfer of the energy. See footnotes to Table 1.A.1.



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 1.17 | 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.

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 1.A.1 (as well as the underlying chapters).

chapters. The regional distribution of technical potential is addressed in Chapter 10.

Note also that the various types of energy cannot necessarily be added together to estimate a total, because each type was estimated independently of the others (e.g., the assessment did not take into account land use allocation; for example, PV and concentrating solar power cannot occupy the same space even though a particular site is suitable for either of them).

In addition to the theoretical and technical potential discussions, this report also considers the economic potential of RE sources that takes into account all social costs and assumes perfect information (covered in Section 10.6) and the market potential of RE sources that depends upon existing and expected real-world market conditions (covered in Section 10.3) shaped by policies, availability of capital and other factors, each of which is discussed in AR4 and defined in Annex I.

1.2.4 Special features of renewable energy with regard to integration

The costs and challenges of integrating increasing shares of RE into an existing energy supply system depend on the system characteristics, the current share of RE, the RE resources available and how the system evolves and develops in the future. Whether for electricity, heating, cooling, gaseous fuels or liquid fuels, RE integration is contextual, site specific and complex. The characteristics of RE specific to integration in existing energy networks are discussed in detail in Chapter 8.

RE can be integrated into all types of electricity systems from large, interconnected continental-scale grids (Section 8.2.1) down to small autonomous buildings (Section 1.3.1, 8.2.5). System characteristics are important, including the generation mix, network infrastructure, energy market designs and institutional rules, demand location, demand profiles, and control and communication capability. Combined with the location, distribution, variability and predictability of the RE resources, these characteristics determine the scale of the integration challenge. Partially dispatchable wind and solar energy can be more difficult to integrate than fully dispatchable hydropower, bioenergy and geothermal energy. Partly because of the geographical distribution and fixed remote locations of many RE resources, 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 (Section 8.2.1).

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 hydropower), and modified institutional arrangements including regulatory and market mechanisms (Section 8.2.1).

Integration of RE into district heating and cooling networks (Section 8.2.2), gas distribution grids (Section 8.2.3) and liquid fuel systems (Section 8.2.4) has different system requirements and challenges than those of electrical power systems. Storage is an option for heating and cooling networks that incorporate variable RE sources. For RE integration into gas distribution grids, it is important that appropriate gas quality standards are met. Various RE technologies can also be utilized directly in all end-use sectors (such as first-generation biofuels, building-integrated solar water heaters and wind power) (Section 8.3).

The full utilization of variable renewable sources such as wind and solar power can be enhanced by energy storage. Storing energy as heat is commonly practised today, and multiple means of storing electricity have been developed. Pumped water storage is a well-developed technology that can utilize existing dams to provide electricity when variable sources are not providing. Other technologies include flywheel storage of kinetic energy, compressed air storage and batteries. Battery and other storage technologies are discussed in Chapter 8. If electric vehicles become a major fraction of the fleet, it is possible to utilize their batteries in a vehicle-to-grid system for managing the variability of RE supply (Moomaw, 1991; Kempton and Tomic, 2005; Hawken et al., 2010).

1.2.5 Energy efficiency and renewable energy

Energy services are the tasks to be performed using energy. A specific energy service can be provided in many ways. Lighting, for example, may be provided by daylight, candles or oil lamps or by a multitude of different electric lamps. The efficiency of the multiple conversions of energy from primary source to final output may be high or low, and may involve the release of large or small amounts of CO_2 (under a given energy mix). Hence there are many options as to how to supply any particular service. In this report, some specific definitions for different dimensions of efficiency are utilized.

Energy efficiency is the ratio of useful energy or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to its energy input (measured as kWh/kWh, tonnes/kWh or any other physical measure of useful output like tonne-km transported, etc.). Energy efficiency can be understood as the reciprocal of energy intensity. Hence the fraction of solar, wind or fossil fuel energy that can be converted to electricity is the conversion efficiency. There are fundamental limitations on the efficiency of conversions of heat to work in an automobile engine or a steam or gas turbine, and the attained conversion efficiency is always significantly below these limits. Current supercritical coal-fired steam turbines seldom exceed a 45% conversion of heat to electric work (Bugge et al., 2006), but a combined-cycle steam and gas turbine operating at higher temperatures has achieved 60% efficiencies (Pilavachi, 2000; Najjar et al., 2004).

Energy intensity is the ratio of energy use to output. If output is expressed in physical terms (e.g., tonnes of steel output), energy intensity is the reciprocal of energy productivity or energy efficiency. Alternatively (and often more commonly), output is measured in terms of populations (i.e., per capita) or monetary units such as contribution to gross domestic product (GDP) or total value of shipments or similar terms. At the national level, energy intensity is the ratio of total domestic primary (or final) energy use to GDP. Energy intensity can be decomposed as a sum of intensities of particular activities weighted by the activities' shares of GDP. At an aggregate macro level, energy intensity stated in terms of energy per unit of GDP or in energy per capita is often used for a sector such as transportation, industry or buildings, or to refer to an entire economy.

Energy savings arise from decreasing energy intensity by changing the activities that demand energy inputs. For example, turning off lights when not needed, walking instead of taking vehicular transportation, changing the controls for heating or air conditioning to avoid excessive heating or cooling or eliminating a particular appliance and performing a task in a less energy intensive manner are all examples of energy savings (Dietz et al., 2009). Energy savings can be realized by technical, organizational, institutional and structural changes and by changed behaviour.

Studies suggest that 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 to perform a specific energy service may lead to utilization of more energy services. Rebound effects can be distinguished at the micro and macro level. At the micro level, a successful energy efficiency measure may be expected to lead to lower energy costs for the entity subject to the measure because it uses less energy. However, the full energy saving may not occur because a more efficient vehicle reduces the cost of operation per kilometre, so the user may drive more kilometres. Or a better-insulated home may not achieve the full saving because it is now possible to achieve greater comfort by using some of the saved energy. The analysis of this effect is filled with many methodological difficulties (Guerra and Sancho, 2010), but 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 OECD countries, and is very small for more efficient appliances and water heating (Sorrell et al., 2009). An efficiency measure that is successful in lowering economy-wide energy demand, however, lowers the price of energy as well. This leads to a decrease in economy-wide energy costs leading to additional cost savings for the entities that are subject to the efficiency measure (lower energy price and less energy use) as well as cost savings for the rest of the economy that may not be subject to the measure but benefits from the lower energy price. Studies that examine changes in energy intensity in OECD countries find that at the macro level, there is a reduction that appears related to energy efficiency gains, and any rebound effect is small (Schipper and Grubb, 2000). One analysis suggests that when all effects of lower energy prices are taken into account, there are offsetting factors that can outweigh a positive rebound effect (Turner, 2009). It is expected that the rebound effect may be greater in developing countries and among poor consumers (Orasch and Wirl, 1997). These analyses of the rebound effect do not examine whether an energy user might spend his economic savings on something other than the energy use whose efficiency was just improved (i.e., on other activities that involve either higher or lower energy intensity than the saved energy service), nor do there appear to be studies of corporate efficiency, where the savings might pass through to the bottom profit line. For climate change, the main concern with any rebound effect is its influence on CO_2 emissions, which can be addressed effectively with a price on carbon (Chapter 11).

The role of energy efficiency in combination with RE is somewhat more complex and less studied. It is necessary to examine the total cost of end-use efficiency measures plus RE technology, and then determine whether there is rebound effect for a specific case.

Furthermore, carbon leakage may also reduce the effectiveness of carbon reduction policies. Carbon leakage is defined as the increase in CO_2 emissions outside of the countries taking domestic mitigation action divided by the reduction in the emissions of these countries. If carbon reduction policies are not applied uniformly across sectors and political jurisdictions, then it is possible for carbon-emitting activities that are controlled in one place to move to another sector or country where such activities are not restricted (Kallbekken, 2007; IEA, 2008a). Recent research suggests, however, that estimates of carbon leakage are too high (Paltsev, 2001; Barker et al., 2007; Di Maria and van der Werf, 2008).

Reducing energy needed at the energy services delivery stage is an important means of reducing the primary energy required for all energy supply fuels and technologies. Because RE sources usually have a lower power density than fossil or nuclear fuels, energy savings at the end-use stage are often required to utilize a RE technology for a specific energy service (Twidell and Weir, 2005). For example, it may not be possible to fuel all vehicles on the planet with biofuels at their current low engine efficiencies, but if vehicle fuel efficiency were greater, a larger fraction of vehicles could be run on biofuels. Similarly, by lowering demand, the size and cost of a distributed solar system may become competitive (Rezaie et al., 2011). The importance of end-use efficiency in buildings in order for renewable technology to be a viable option has been documented (Frankl et al., 1998). Furthermore, electricity distribution and management is simplified and system balancing costs are lower if the energy demands are smaller (see Chapter 8). Energy efficiency at the end-use stage thus facilitates the use of RE.

Often the lowest cost option is to reduce end-use energy demand through efficiency measures, which include both new technologies and more efficient practices (Hamada et al., 2001; Venema and Rehman, 2007; Ambrose, 2009; Harvey, 2009). Examples can be found in efficient appliances for lighting, as well as heating and cooling in the building sector. For example, compact fluorescent or light-emitting diode lamps use much less electricity to produce a lumen of light than does a traditional incandescent lamp (Mehta et al., 2008). Properly sized variable-speed electric motors and improved efficiency compressors for refrigerators, air conditioners and heat pumps can lower primary energy use in many applications (Ionel, 1986; Sims et al., 2007; von Weizsäcker et al., 2009). Efficient houses and small commercial buildings such as the Passivhaus design from Germany are so air tight and well insulated that they require only about one-tenth the energy of more conventional dwellings (Passivhaus, 2010). Energy efficient design of high-rise buildings in tropical countries could reduce emissions from cooling at a substantial cost savings (Ossen et al., 2005; Ambrose, 2009).

Examples from the transportation sector include utilizing engineering improvements in traditional internal combustion engines to reduce fuel consumption rather than enhancing acceleration and performance (Ahman and Nilsson, 2008). Significant efficiency gains and substantial CO_2 emission reductions have also been achieved through the use of hybrid electric systems, battery electric systems and fuel cells (see Section 8.3.1). Biofuels become more economically feasible for aircraft as engine efficiency improves (Lee, 2010). Examples that raise energy efficiency in the power supply and industrial sectors include combined heat and power systems (Casten, 2008; Roberts, 2008), and recovery of otherwise wasted thermal or mechanical energy (Bailey and Worrell, 2005; Brown et al., 2005) thereby avoiding burning additional fuel for commercial and industrial heat. These latter examples are also applicable to enhancing the overall delivery of energy from RE such as capturing and utilizing the heat from PV or biomass electricity systems, which is done frequently in the forest products industry.

1.3 Meeting energy service needs and current status

1.3.1 Current renewable energy flows

Global renewable energy flows from primary energy through carriers to end uses and losses in 2008 (IEA, 2010a) are shown in Figure 1.18. 'RE' here includes combustible biomass, forest and crop residues and renewable municipal waste as well as the other types of RE considered in this report: direct solar (PV and solar thermal) energy, geothermal energy, hydropower, and ocean and wind energy.

'Other sectors' include agriculture, commercial and residential buildings, public services and non-specified other sectors. The 'transport sector' includes international aviation and international marine bunkers. Data for the renewable electricity and heat flows to the end-use sectors are not available. Considering that most of the renewable electricity is grid-connected, they are estimated on the assumption that their allocations to industries, transport and other sectors are proportional to those of the total electricity and heat, which are available from the IEA (IEA, 2010a).

At the global level, on average, RE supplies increased by 1.8% per annum between 1990 and 2007 (IEA, 2009b), nearly matching the growth rate in total primary energy consumption (1.9%).

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 (IEA, 2010a). 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 (IEA, 2010c).

1.3.2 Current cost of renewable energy

While the resource is obviously large and could theoretically supply all energy needs long into the future, the levelized cost of energy (LCOE) for many RE technologies is currently higher than existing energy prices,

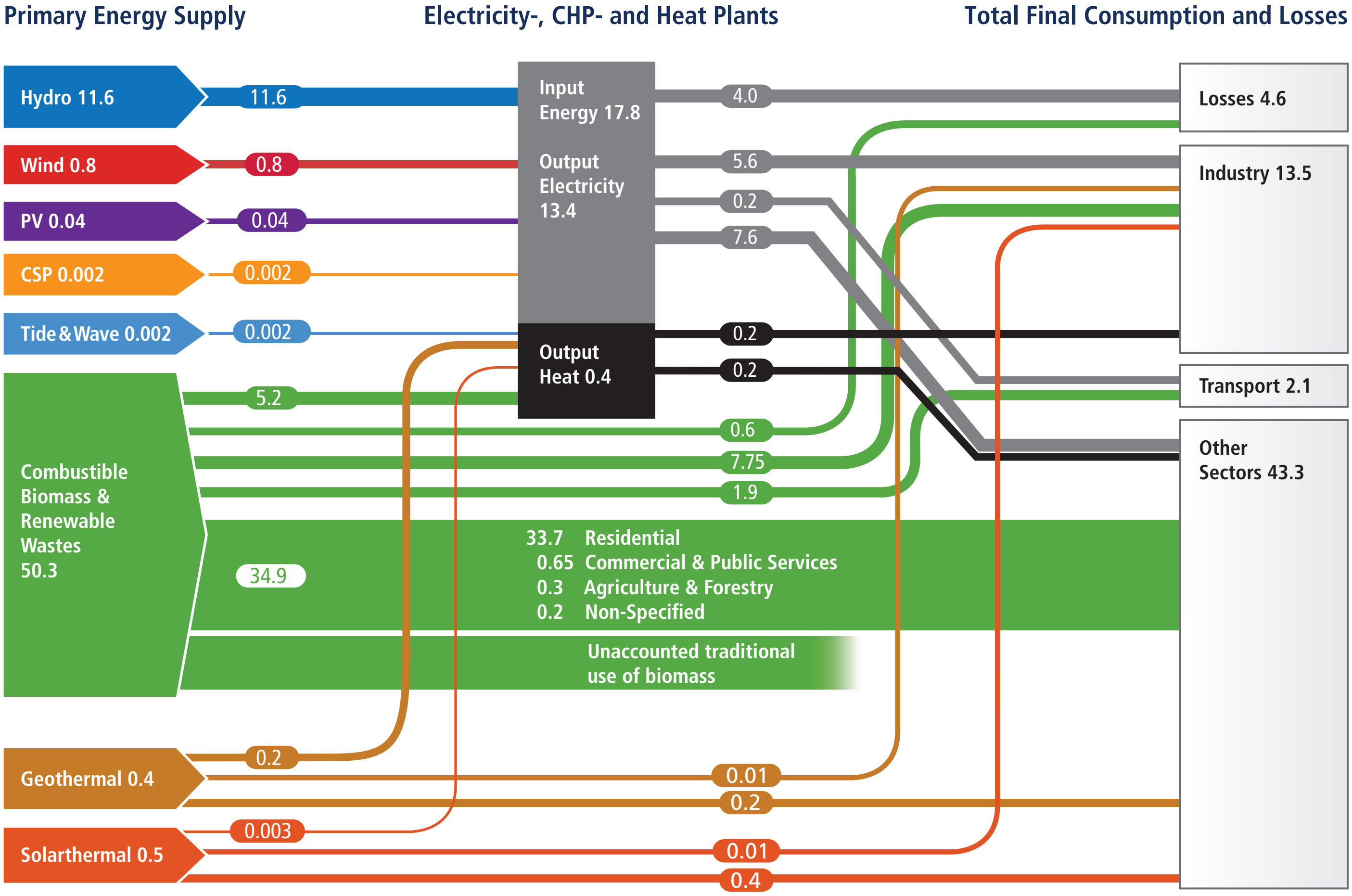


Figure 1.18 | Global energy flows (EJ) in 2008 from primary RE through carriers to end uses and losses. Data Source: (IEA, 2010a).

though in various settings RE is already economically competitive. Even though the LCOE of a particular energy technology is not the sole determinant of its value or economic competitiveness, ranges of recent LCOE are provided in this report as one of several benchmark values.[10] Figures 1.19, 1.20 and 1.21 provide a comparison of LCOE ranges associated with selected RE technologies that are currently commercially available to provide electricity, heat and transportation fuels, respectively. The ranges of recent LCOE for some of these RE technologies are wide and depend, inter alia, on technology characteristics, regional variations in cost and performance, and differing discount rates.

These cost ranges in these figures are broad and do not resolve the significant uncertainties surrounding the costs, if looked at from a very general perspective. Hence, as with the technical potential described above, the data are meant to provide context only (as opposed to precise comparison).

The levelized costs of identical technologies can vary across the globe, depending on services rendered, RE quality and local costs of investment, financing, operation and maintenance. The breadth of the ranges can be narrowed if region-, country-, project- and/or investor-specific conditions are taken into account. Chapters 2 through 7 provide some detail on the sensitivity of LCOE to such framework conditions; Section 10.5 shows the effect of the choice of the discount rate on levelized costs; and Annex III provides the full set of data and additional sensitivity analysis.

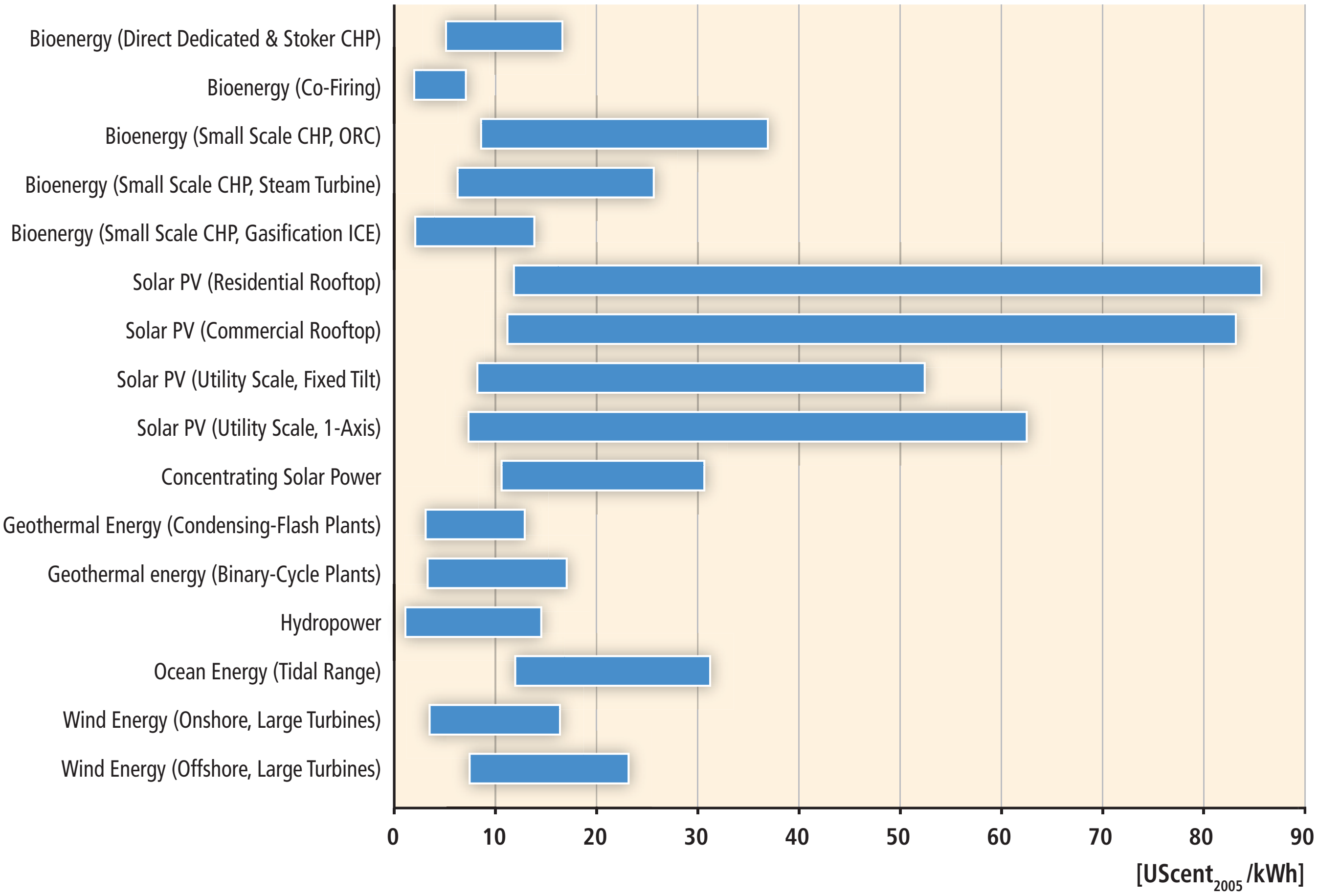


Figure 1.19 | Levelized cost of electricity (LCOE) for commercially available RE technologies covering a range of different discount rates. The LCOE estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on a 3% discount rate applied to 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 a 10% discount rate applied to 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.

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[10] Cost and performance data were gathered by the authors of Chapters 2 through 7 from a variety of sources in the available literature. They are based on the most recent information available in the literature. Details can be found in the respective chapters and are summarized in a data table in Annex III. All costs were assessed using standard discounting analysis at 3, 7 and 10% as described in the Annex II. A number of default assumptions about costs and performance parameters were made to define the levelized cost if data were unavailable and are also laid out in Annex III.

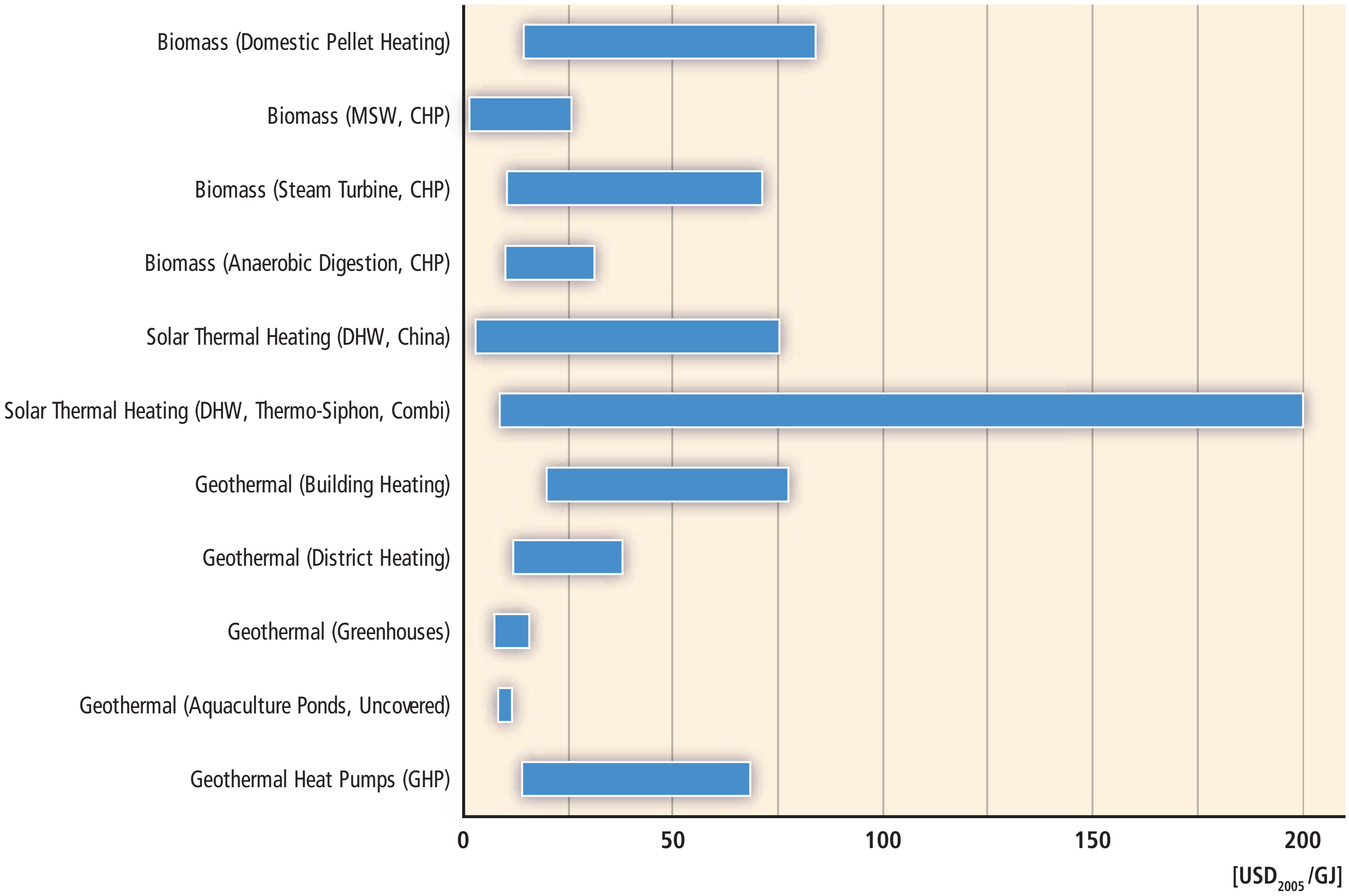

Figure 1.20 | Levelized cost of heat (LCOH) for commercially available RE technologies covering a range of different discount rates. The LCOH estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on a 3% discount rate applied to 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 a 10% discount rate applied to 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.

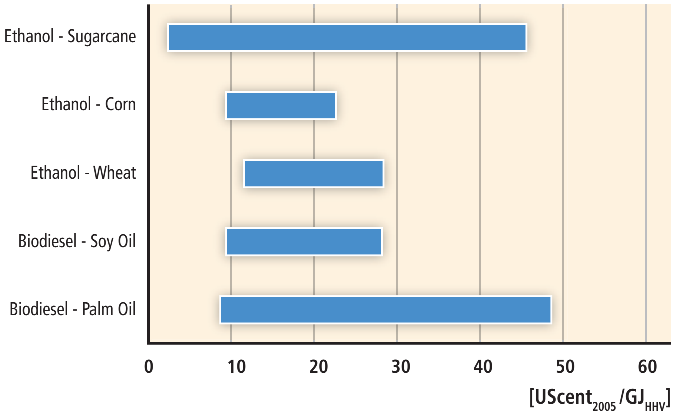

Figure 1.21 | Levelized Cost of Fuels (LCOF) for commercially available biomass conversion technologies covering a range of different discount rates. LCOF estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on a 3% discount rate applied to the low ends of the ranges of investment, operations and maintenance (O&M) and feedstock cost. The higher bound of the levelized cost range is accordingly based on a 10% discount rate applied to 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. HHV stands for 'higher heating value'. For data and supplementary information see Annex III.

Given favourable conditions, however, the lower ends of the ranges indicate that some RE technologies are broadly competitive at existing energy prices (see also Section 10.5). Monetizing the external costs of energy supply would improve the relative competitiveness of RE. The same applies if market prices increase due to other reasons (see Section 10.6). That said, these graphs provide no indication of the technical potential that can be utilized. Section 10.4 provides more information in this regard, for example, in discussing the concept of energy supply curves.

Furthermore, the levelized cost for a technology is not the sole determinant of its value or economic competitiveness. The attractiveness of a specific energy supply option depends also on broader economic as well as environmental and social aspects and the contribution that the technology makes to meeting specific energy services (e.g., peak electricity demands) or imposes in the form of ancillary costs on the energy system (e.g., the costs of integration). Chapters 8 to 11 offer important complementary perspectives on such cost issues covering, for example, the cost of integration, external costs and benefits, economy-wide costs and costs of policies.

The costs of most RE technologies have declined and additional expected technical advances would result in further cost reductions. Significant advances in RE technologies and associated long-term cost reductions have been demonstrated over the last decades, though periods of rising prices have sometimes been experienced (due to, for example, increasing demand for RE in excess of available supply) (see Section 10.5). The contribution of different drivers (e.g., R&D, economies of scale, deployment-oriented learning and increased market competition among RE suppliers) is not always understood in detail (see Sections 2.7, 3.8, 7.8, and 10.5).

Historical and potential future cost drivers are discussed in most of the technology chapters (Chapters 2 through 7) as well as in Chapter 10, including in some cases an assessment of historical learning rates and the future prospects for cost reductions under specific framework conditions. Further cost reductions are expected, resulting in greater potential deployment and consequent climate change mitigation. Examples of important areas of potential technological advancement include: new and improved feedstock production and supply systems; biofuels produced via new processes (also called next-generation or advanced biofuels, e.g., lignocellulosic) and advanced biorefining (Section 2.6); advanced PV and CSP technologies and manufacturing processes (Section 3.7); enhanced geothermal systems (EGS) (Section 4.6); multiple emerging ocean technologies (Section 6.6); and foundation and turbine designs for offshore wind energy (Section 7.7). Further cost reductions for hydropower are expected 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 locations and to improve the technical performance of new and existing projects (Sections 5.3, 5.7, and 5.8).

1.3.3 Regional aspects of renewable energy

The contribution of RE to primary energy supply varies substantially by country and region. Geographic distribution of RE manufacturing, use and export is now being diversified from the developed world to other developing regions, notably Asia including China (UNStats, 2010). In China, growing energy needs for solar cooking and hot water production have promoted RE development. China is now the leading producer, user and exporter of solar thermal panels for hot water production, and has been rapidly expanding its production of solar PV, most of which is exported, and has recently become the leading global producer. In terms of capacity, in 2008, China was the largest investor in thermal water heating and third in bioethanol production (REN21, 2009). China has been doubling its wind turbine installations every year since 2006, and was second in the world in installed capacity in 2009. India has also become a major producer of wind turbines and now is among the top five countries in terms of installation. In terms of installed renewable power capacity, China now leads the world followed by the USA, Germany, Spain and India (REN21, 2009, 2010).

As noted earlier, RE is more evenly distributed than fossil fuels. There are countries or regions rich in specific RE resources. Twenty-four countries utilize geothermal heat to produce electricity. The share of geothermal energy in national electricity production is above 15% in El Salvador, Kenya, the Philippines and Iceland (Bromley et al., 2010). More than 60% of primary energy is supplied by hydropower and geothermal energy in Iceland (IEA, 2010a). In some years, depending on the level of precipitation, Norway produces more hydroelectricity than it needs and exports its surplus to the rest of Europe. Brazil, New Zealand and Canada also have a high share of hydroelectricity in total electricity: 80, 65 and 60%, respectively (IEA, 2010c). Brazil relies heavily on and is the second-largest producer of bioethanol, which it produces from sugarcane (EIA, 2010; IEA, 2010e).

As regards biomass as a share of regional primary energy consumption, Africa is particularly high, with a share of 48.0%, followed by India at 26.5%, non-OECD Asia excluding China and India at 23.5%, and China at 10% (IEA, 2010a). Heat pump systems that extract stored solar energy from the air, ground or water have penetrated the market in developed countries, sometimes in combination with renewable technologies such as PV and wind. Heat pump technology is discussed in Chapter 4.

Sun-belt areas such as deserts and the Mediterranean littoral are abundant in direct normal radiation (cloudless skies) and suitable for concentrated solar thermal power plants. Export of solar- and wind-generated electricity from the countries rich in these resources could become important in the future (Desertec, 2010).

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, which is described in Section 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, heat from the earth or biomass—furthermore, technologies that can harness these forms of energy are available and are improving rapidly (Asif and Muneer, 2007). While the opportunities seem great and are discussed in Section 1.4.1, there are barriers (Section 1.4.2) and issues (Section 1.4.3) that slow the introduction of RE into modern economies.

1.4.1 Opportunities

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 (and laid out below) but that are not intentionally targeted. There are four major opportunity areas that RE is well suited to address, and these are briefly described here and in more detail in Section 9.2.2. The four areas are social and economic development, energy access, energy security, and climate change mitigation and the reduction of environmental and health impacts.

1.4.1.1 Social and economic development

Globally, per capita incomes as well as broader indicators such as the Human Development Index 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. As economic activity expands and diversifies, demands for more sophisticated and flexible energy sources arise. Economic development has therefore been associated with a shift from direct combustion of fuels to higher quality electricity (Kaufmann, 2004; see Section 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 (Kaygusuz, 2007; UNDP, 2007). Because of their decentralized nature, RE technologies can play an important role in fostering rural development (see Section 1.4.1.2).

The creation of (new) employment opportunities is seen as a positive long-term effect of RE both in developed and developing countries and was stressed in many national green-growth strategies. Also, policymakers have supported the development of domestic markets for RE as a means to gain competitive advantage in supplying international markets (see Sections 9.3.1.4 and 11.3.4).

1.4.1.2 Energy access

In 2009, more than 1.4 billion people globally lacked access to electricity, 85% of them in rural areas, and the number of people relying on traditional biomass for cooking was estimated to be around 2.7 billion (IEA, 2010c). By 2015, almost 1.2 billion more people will need access to electricity and 1.9 billion more people will need access to modern fuels to meet the Millennium Development Goal of halving the proportion of people living in poverty (UNDP/WHO, 2009).

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. Various initiatives, some of them based on RE, particularly in the developing countries, aim at improving universal access to modern energy services through increased access to electricity and cleaner cooking facilities (REN 21, 2009; see Sections 9.3.2 and 11.3.2). 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 (IEA, 2010d).

For electricity, small and standalone configurations of RE technologies such as PV (Chapter 3), hydropower (Chapter 5), and bioenergy (Chapter 2) can often meet energy needs of rural communities more cheaply than fossil fuel alternatives such as diesel generators. For example, PV is attractive as a source of electric power to provide basic services, such as lighting and clean drinking water. For greater local demand, small-scale hydropower or biomass combustion and gasification technologies may offer better solutions (IEA, 2010d). For bioenergy, the progression implies moving from the use of, for example, firewood, cow dung and agricultural residues to, for example, liquid propane gas stoves, RE-based advanced biomass cookstoves or biogas systems (Clancy et al., 2007; UNDP, 2005; IEA, 2010d; see Sections 2.4.2 and 9.3.2).

1.4.1.3 Energy security

At a general level, energy security can best be understood as robustness against (sudden) disruptions of energy supply. More specifically, availability and distribution of resources, as well as variability and reliability of energy supply can be identified as the two main themes.

Current energy supplies are dominated by fossil fuels (petroleum and natural gas) whose price volatility can have significant impacts, in particular for oil-importing developing countries (ESMAP, 2007). National security concerns about the geopolitical availability of fuels have also been a major driver for a number of countries to consider RE. For example, in the USA, the military has led the effort to expand and diversify fuel supplies for aviation and cites improved energy supply security as the major driving force for sustainable alternative fuels (Hileman et al., 2009; Secretary of the Air Force, 2009; USDOD, 2010).

Local RE options can contribute to energy security goals by means of diversifying energy supplies and diminishing dependence on limited suppliers, although RE-specific challenges to integration must be considered. In addition, the 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. This may be particularly important for oil-importing developing countries with high import shares (Sections 9.3.3, 9.4.3 and 11.3.3).

1.4.1.4 Climate change mitigation and reduction of environmental and health impacts

Climate change mitigation is one of the key driving forces behind a growing demand for RE technologies (see Section 11.3.1). In addition to reducing GHG emissions, RE technologies can also offer benefits with respect to air pollution and health compared to fossil fuels (see Section 9.3.4). Despite these important advantages of RE, no large-scale technology deployment comes without trade-offs, such as, for example, induced land use change. This mandates an assessment of the overall burden from the energy system on the environment and society, taking account of the broad range of impact categories with the aim of identifying possible trade-offs and potential synergies.

Lifecycle assessments facilitate a quantitative comparison of 'cradle to grave' emissions across different energy technologies (see Section 9.3.4.1). Figure 1.22 illustrates the lifecycle structure for CO_2 emission analysis, and qualitatively indicates the relative GHG implications for RE, nuclear power and fossil fuels. Alongside the commonly known CO_2 production pathways from fossil fuel combustion, natural gas production (and transportation) and coal mines are a source of methane, a potent greenhouse gas, and uncontrolled coal mine fires release significant amounts of CO_2 to the atmosphere.

Traditional biomass use results in health impacts from the high concentrations of particulate matter and carbon monoxide, among other pollutants. Long-term exposure to biomass smoke increases the risk of a child developing an acute respiratory infection and is a major cause of morbidity and mortality in developing countries (WEC/FAO, 1999).

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 impacts on sustainable development, including local and indoor air pollution, GHG emissions, deforestation and forest degradation (see Sections 2.5.4, 9.3.4.2, 9.3.4.3 and 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 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 (see Section 9.3.4.4). 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 lead 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 hydropower (which can also release methane from submerged vegetation), wind energy and biofuels (see Section 9.3.4.5).

Since a degree of climate change is now inevitable, adaptation to climate change is an essential component of sustainable development (IPCC, 2007e). Adaptation can be either anticipatory or reactive to an altered climate. Some RE technologies may assist in adapting to change, and are usually anticipatory in nature. AR4 includes a chapter on the linkage between climate mitigation (reducing emissions of GHGs) and climate adaptation including the potential to assist adaptation to climate change (Klein et al., 2007a, b).

- Active and passive solar cooling of buildings helps counter the direct impacts on humans of rising mean temperatures (Chapter 3);

- Dams (used for hydropower) may also be important in managing the impacts of droughts and floods, which are projected to increase with climate change. Indeed, this is one of reasons for building such dams in the first place (Section 5.10; see also World Commission on Dams (WCD, 2000);

- Solar PV and wind require no water for their operation, and hence may become increasingly important as droughts and high river temperatures limit the power output of thermal power plants (Section 9.3.4);

- Water pumps in rural areas remote from the power grid can utilize PV (Chapter 3) or wind (Chapter 7) for raising agricultural productivity during climate-induced increases in dry seasons and droughts; and

- Tree planting and forest preservation along coasts and riverbanks is a key strategy for lessening the coastal erosion impacts of climate change. With suitable choice of species and silvicultural practices, these plantings can also yield a sustainable source of biomass for energy, for example, by coppicing (Section 2.5).

1.4.2 Barriers

A barrier was defined in the AR4 as 'any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy, programme or measure'(IPCC, 2007d; Verbruggen et al., 2010). For example, the technology as currently available may not suit the desired scale of application. This barrier could be attenuated in principle by a program of technology development (R&D).

This section describes some of the main barriers and issues to using RE for climate change mitigation, adaptation and sustainable development. As throughout this introductory chapter, the examples are illustrative and not comprehensive. Section 1.5 (briefly) and Section 11.4 (in more

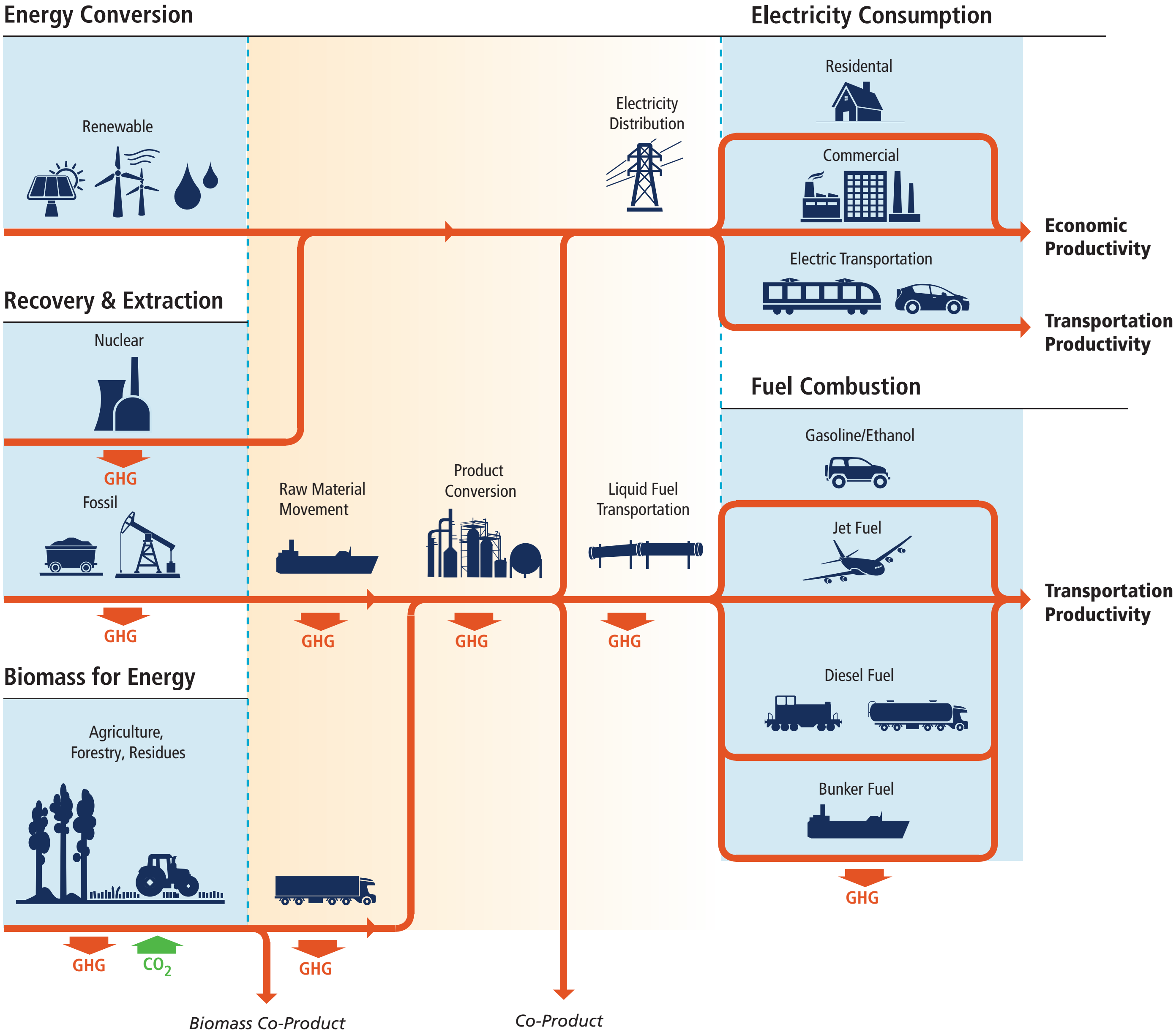

Figure 1.22 | Illustrative system for energy production and use illustrating the role of RE along with other production options. A systemic approach is needed to conduct lifecycle systems analysis.

detail) look at policies and financing mechanisms that may overcome them. When a barrier is particularly pertinent to a specific technology, it is examined in the appropriate technology chapter (i.e., Chapters 2 to 7).

The various barriers are categorized as 1) market failures and economic barriers, 2) information and awareness barriers, 3) socio-cultural barriers and 4) institutional and policy barriers (see Table 1.5). This categorization is somewhat arbitrary since, in many cases, barriers extend across several categories. More importantly, for a particular project or set of circumstances it will usually be difficult to single out one particular barrier. They are interrelated and need to be dealt with in a comprehensive manner.

1.4.2.1 Market failures and economic barriers

Market Failures

In economics a distinction is often made between *market failures* and *barriers*. With reference to the theoretical ideal market conditions (Debreu, 1959; Becker, 1971), all real-life markets fail to some degree (Bator, 1958; Meade, 1971; Williamson, 1985), evidenced by losses in welfare. Market failures (imperfections) are often due to externalities or 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. Externalities may be negative (external costs) or positive (external benefits). External benefits lead to an undersupply of beneficial

Table 1.5 | A categorization of barriers to RE deployment

Section	Type of barrier	Some potential policy instruments (see Chapter 11)
1.4.2.1	Market failures and economic barriers	Carbon taxes, emission trading schemes, public support for R&D, economic climate that supports investment, microfinance
1.4.2.2	Information and awareness barriers	Energy standards, information campaigns, technical training
1.4.2.3	Socio-cultural barriers	Improved processes for land use planning
1.4.2.4	Institutional and policy barriers	Enabling environment for innovation, revised technical regulations, international support for technology transfer (e.g., under the UNFCCC), liberalization of energy industries

activities (e.g., public goods) from a societal point of view because the producer is not fully rewarded. External costs lead to a too-high demand for harmful activities because the consumer does not bear the full (societal) cost. Another market failure is rent appropriation by monopolistic entities. In the case of RE deployment, these may appear as:

- Underinvestment in invention and innovation in RE technologies because initiators cannot benefit from exclusive property rights for their efforts (Margolis and Kammen, 1999; Foxon and Pearson, 2008).

- Un-priced environmental impacts and risks of energy use when economic agents have no obligation to internalize the full costs of their actions (Beck, 1995; Baumol and Oates, 1998). The release of GHG emissions and the resulting climate change is a clear example (Stern, 2007; Halsnaes et al., 2008), but the impacts and risks of some RE projects and of other low-carbon technologies (nuclear, CCS) may not always be fully priced either.

- The occurrence of monopoly (one seller) or monopsony (one buyer) powers in energy markets limits competition among suppliers or demanders and reduces opportunities for free market entry and exit (see Section 1.4.2.4). Monopoly and oligopoly power may be due to deliberate concentration, control and collusion. Regulated interconnected network industries (e.g., electric, gas and heat transmission grids) within a given area are natural monopolies because network services are least-cost when provided by a single operator (Baumol et al., 1982, p.135).

Characterizing these imperfections as market failures, with high likelihoods of welfare losses and of the impotence of market forces in clearing the imperfections, provides strong economic arguments for public policy intervention to repair the failures (Coase, 1960; Bromley, 1986). On top of imperfections classified as market failures, various factors affect the behaviour of market agents, and are categorized here as other types of barriers.

Up-front Investment Cost

The initial investment cost of a unit of RE capacity may be higher than for a non-RE energy system. Because the cost of such systems is largely up-front, it would be unaffordable to most potential customers, especially in developing countries, unless a financial mechanism is established to allow them to pay for the RE energy service month by month as they do for kerosene. Even if the initial equipment is donated by an overseas agency, such a financial mechanism is still needed to pay for the technical support, spare parts and eventual replacement of the system. Failure to have these institutional factors properly set up has been a major inhibitor to the use of RE in the Pacific Islands, where small-scale PV systems would appear to be a natural fit to the scattered tropical island communities (Johnston and Vos, 2005; Chaurey and Kandpal, 2010).

Financial risk

All power projects carry financial risk because of uncertainty in future electricity prices, regardless of its source, making it difficult for a private or public investor to anticipate future financial returns on investment. Moreover, the financial viability of an RE system strongly depends on the availability of capital and its cost (interest rates) because the initial capital cost comprises most of the economic cost of an RE system. While the predictability of such costs is a relative advantage of RE systems, many RE technologies are still in their early development phase, so that the risks related to the first commercial projects are high. The private capital market requires higher returns for such risky investments than for established technologies, raising the cost of RE projects (Gross et al., 2010; Bazilian and Roques, 2008).

An example of financial risk from an RE system outside the power sector is the development of biofuels for aviation. In 2009, neither the potential bio-jet fuel refiners nor the airlines fully understood how to structure a transaction that was credit worthy and as a result might get financed if there were interested financial institutions. (Slade et al., 2009)

1.4.2.2 Informational and awareness barriers

Deficient data about natural resources

RE is widely distributed but is site-specific in a way that fossil fuel systems are not. For example, the output of a wind turbine depends strongly on the wind regime at that place, unlike the output of a diesel generator. While broad-scale data on wind is reasonably well available from meteorological records, it takes little account of local topography, which may mean that the output of a particular turbine could be 10 to 50 % higher on top of a local hill than in the valley a few hundred metres away (Petersen et al., 1998). To obtain such site-specific data requires onsite measurement for at least a year and/or detailed modelling. Similar data deficiencies apply to most RE resources, but can be attenuated by specific programs to better measure those resources (Hammer et al., 2003).

Skilled human resources (capacity)

To develop RE resources takes skills in mechanical, chemical and electrical engineering, business management and social science, as with other energy sources. But the required skill set differs in detail for different technologies and people require specific training. Developing the skills to operate and maintain the RE 'hardware' is exceedingly important for a successful RE project (Martinot, 1998). Where these barriers are overcome as in Bangladesh, significant installations of RE systems in developing countries has occurred (Barua et al., 2001; Ashden Awards for Sustainable Energy, 2008; Mondal et al., 2010). It is also important that the user of RE technology understand the specific operational aspects and availability of the RE source. One case where this is important is in the rural areas of developing countries. Technical support for dispersed RE, such as PV systems in the rural areas of developing countries, requires many people with basic technical skill rather than a few with high technical skill as tends to be the case with conventional energy systems. Training such people and ensuring that they have ready access to spare parts requires establishment of new infrastructure.

More generally, in some developing countries, the lack of an ancillary industry for RE (such as specialized consulting, engineering and procurement, maintenance, etc.) implies higher costs for project development and is an additional barrier to deployment.

Public and institutional awareness

The oil (and gas) price peaks of 1973, 1980, 1991 and 2008 made consumers, governments and industry in both industrialized and developing counties search for alternative sources of energy. While these price surges caused some shift to coal for power production, they also generated actions to adopt more RE, especially solar, wind and biomass (Rout et al., 2008; van Ruijven and van Vuuren, 2009; Chapter 7). There is, however, limited awareness of the technical and financial issues of implementing a sustained transition to alternative primary energy sources—especially RE (Henriques and Sadorsky, 2008). The economic and transactional costs of shifting away from vulnerable and volatile fossil fuels like oil are overestimated, and there is always a shift back to these fuels once price shocks abate. The reluctance to make a shift away from a known energy source is very high because of institutional, economic and social lock-in (Unruh and Carillo-Hermosilla, 2006). One means of motivation might be a realization that the economic welfare cost of high oil prices exceeds that of effective climate polices (Viguier and Vielle, 2007).

1.4.2.3 Socio-cultural barriers

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. Barriers may arise from inadequate attention to such socio-cultural concerns and may relate to impacts on 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 (see Section 9.5.1.1).

Farmers on whose land wind farms are built rarely object; in fact they usually see turbines as a welcome extra source of income either as owners (Denmark) or as leasers of their land (USA), as they can continue to carry on agricultural and grazing activities beneath the turbines. Other forms of RE, however, preclude multiple uses of the land (Kotzebue et al., 2010). Dams for hydropower compete for recreational or scenic use of rivers (Hynes and Hanley, 2006), and the reservoirs may remove land from use for agriculture, forests or urban development. Large-scale solar or wind may conflict with other values (Simon, 2009) and may conflict with other social values of land such as nature preserves or scenic vistas (Groothuis et al., 2008; Valentine, 2010). Specific projects may also have negative implications for poor populations (Mariita, 2002). Land use can be just as contentious in some developing countries. In Papua New Guinea, for example, villagers may insist on being paid for the use of their land, for example, for a mini-hydro system of which they are the sole beneficiaries (Johnston and Vos, 2005).

Hence, social acceptance is an important element in the need to rapidly and significantly scale up RE deployment to help meet climate change mitigation goals, as large-scale implementation can only be successfully undertaken with the understanding and support of the public. Social acceptance of RE is generally increasing; having domestic solar energy PV or domestic hot water systems on one's roof has become a mark of the owner's environmental commitment (Bruce et al., 2009). However, wind farms still have to battle local opposition before they can be established (Pasqualetti et al., 2002; Klick and Smith, 2010; Webler and Tuler, 2010) and there is opposition to aboveground transmission lines from larger-scale renewable generation facilities (as well as from conventional power sources) (Furby et al., 1988; Hirst and Kirby, 2001; Gerlach, 2004; Vajjhala and Fischbeck, 2007; Puga and Lesser, 2009).

To overcome such barriers may require dedicated communication efforts related to such subjective and psychological aspects as well as the more objective opportunities associated with wider-scale applications of RE technologies. At the same time, 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 (see Section 9.5.2). See Chapters 7 and 11 for more discussion of how such local planning issues impact the uptake of RE. Chapter 11 also includes a wider discussion of the enabling social and institutional environment required for the transition to RE systems. Opposition to unwanted projects can be influenced by policies but social acceptance may be slow to change.

1.4.2.4 Institutional and policy barriers

Existing industry, infrastructure and energy market regulation
Apart from constituting a market failure (see above), monopoly power can be perceived as an institutional barrier if not addressed adequately by energy market regulation.

The energy industry in most countries is based on a small number of companies (sometimes only one in a particular segment such as electricity or gas supply) operating a highly centralized infrastructure. These systems evolved as vertically integrated monopolies that may become committed to large conventional central power facilities supported by policies to ensure they deliver affordable and reliable electricity or gas. They are sometimes unreceptive to distributed smaller supply technologies (World Bank, 2006).

Therefore, regulations governing energy businesses in many countries are still designed around monopoly or near-monopoly providers and 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, and may therefore be unnecessarily restrictive for RE systems. In the process of historical development, most of the rules governing sea lanes and coastal areas were written long before offshore wind power and ocean energy systems were being developed and do not consider the possibility of multiple uses that include such systems (See Chapter 7).

Liberalization of energy markets occurred in several countries in the 1990s and more extensively in Europe in the past decade. Some of these changes in regulations allow independent power producers to operate, although in the USA many smaller proposed RE projects were often excluded due to the scales required by regulation (Markard and Truffer, 2006). In many countries, current regulations remain that protect the dominant centralized production, transmission and distribution system and make the introduction of alternative technologies, including RE, difficult. An examination and modification of existing laws and regulations is a first step in the introduction of RE technologies, especially for integrating them into the electric power system (Casten, 2008).

In addition to regulations that address the power generation sector, local building codes sometimes prevent the installation of rooftop solar panels or the introduction of wind turbines for aesthetic or historical preservation reasons (Bronin, 2009; Kooles, 2009).

Intellectual property rights
Intellectual property rights play a complex and conflicting role. Technological development of RE has been rapid in recent years, particularly in PV and wind power (Lior, 2010; see Chapters 8 and 11). Much of the basic technology is in the public domain, which can lead to underinvestment in the industry. Patents protect many of these new developments thereby promoting more private investment in R&D (Beck, 1995; Baumol and Oates, 1998). Countering this benefit are concerns that have been raised that patents may unduly restrict low-cost access to these new technologies by developing countries, as has happened with many new pharmaceuticals (Barton, 2007; Ockwell et al., 2010; Chapters 3 and 7). There are certainly circumstances where developing country companies need patent protection for their products as well.

Tariffs in international trade
Tariff barriers (import levies) and non-trade barriers imposed by some countries significantly reduce trade in some RE technologies. Discussions about lowering or eliminating tariffs on environmental goods and services including RE technologies have been part of the Doha round of trade negotiations since 2001. Many developing countries argue that reducing these tariffs would primarily benefit developed countries economically, and no resolution has been achieved so far. Developed countries have levied tariffs on imported biofuels, much of which originates in developing countries, thereby discouraging their wider use (Elobeid and Tokgoz, 2008; see Section 2.4.6.2).

Allocation of government financial support
Since the 1940s, governments in industrialized countries have spent considerable amounts of public money on energy-related research, development, and demonstration. By far the greatest proportion of this has been on nuclear energy systems (IEA, 2008b; see also Section 10.5). However, following the financial crisis of 2008 and 2009, some governments used part of their 'stimulus packages' to encourage RE or energy efficiency (Section 9.3.1.3). Tax write-offs for private spending have been similarly biased towards non-RE sources (e.g., in favour of oil exploration or new coal-burning systems), notwithstanding some recent tax incentives for RE (GAO, 2007; Lior, 2010). The policy rationale for government support for developing new energy systems is discussed in Section 1.5 and Chapter 11.

1.4.3 Issues

Issues are not readily amenable to policies and programs.

An issue is that the resource may be too small to be useful at a particular location or for a particular purpose. For example, the wind speed may be too low or too variable to produce reliable power, the topography may be either too flat or there may be insufficient flow to sustain low-head hydro or run-of-river systems for hydropower, or the demands of industry may be too large to be supplied by a local renewable source (Painuly, 2001).

Some renewable resources such as wind and solar are variable and may not always be available for dispatch when needed (Chapter 8). 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. Extensive planting for biomass production or building of large-area reservoirs can lead to displacement of forests with associated negative effects, such as the direct and indirect release of CO_2 and/or methane and soil loss (Melillo et al., 2009; Chapter 2 and Section 5.6.1).

1.5 Role of policy, research and development, deployment, scaling up 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 (Section 11.2). In addition to the reduction of CO_2 emissions, governments have enacted RE policies to meet a 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. In general, energy access has been the primary driver in developing countries whereas energy security and environmental concerns have been most important in developed countries (Chapter 9 and Section 11.3).

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, an issue that each technology chapter addresses. For example, while the use of biofuels can offset GHG emissions from fossil fuels, direct and indirect land use changes must be also be evaluated in order to determine net benefits.[11] In some cases, this may even result in increased GHG emissions, potentially overwhelming the gains from CO_2 absorption (Fargione et al., 2008; Scharlemann and Laurance, 2008; Searchinger et al., 2008; Krewitt et al., 2009; Melillo et al., 2009). A full discussion of this effect can be found in Sections 2.5.3 and 9.3.4.

Various policies have been designed to address every stage of the development chain, involving R&D, testing, deployment, commercialization, market preparation, market penetration, maintenance and monitoring, as well as integration into the existing system. These policies are designed and implemented to overcome the barriers and markets failures discussed above (Sections 1.4.2, 11.1.1, 11.4 and 11.5).

Two key market failures are typically addressed: 1) the external costs of GHG emissions are not priced at an appropriate level; and 2) deployment of low-carbon technologies such as RE creates benefits to society beyond those captured by the innovator, leading to under-investment in such efforts (Sections 11.1 and 11.4). Implementing RE policies (i.e., those promoting exclusively RE) in addition to climate change mitigation policies (i.e., encouraging low-carbon technologies in general) can be justified if a) the negative consequences of innovation market failures should be mitigated and/or b) other goals beyond climate protections are to be addressed.

1.5.1 Policy options: trends, experience and assessment

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 (Section 11.2.2).

Policy and decision makers approach the market in a variety of ways: level the playing field in terms of taxes and subsidies; create a regulatory environment for effective utilization of the resource; internalize externalities of all options or modify or establish prices through taxes and subsidies; create command and control regulations; provide government support for R&D; provide for government procurement priorities; or establish market oriented regulations, all of which shape the markets for new technologies. Some of these options, such as price, modify relative consumer preferences, provide a demand pull and enhance utilization for a particular technology. Others, such as government-supported R&D, attempt to create new products through supply push (Freeman and Soete, 2000; Sawin, 2001; Moore, 2002). 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 (Section 11.5):

- **Fiscal incentives:** 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.

Research and development, 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. A full discussion of R&D policy options can be found in Section 11.5.2.

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[11] Note that such land use changes are not restricted to biomass based RE. For example, wind generation and hydro developments as well as surface mining for coal and storage of combustion ash also incur land use impacts.

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. Together R&D and deployment policies create a positive feedback cycle, inducing private sector investment in R&D. Relatively early deployment policies in a technology's development accelerate learning through private R&D and/or through utilization and cost reduction (Section 11.5.2).The failure of many worthy technologies to move from R&D to commercialization has been coined the 'valley of death' for new products (Markham, 2002; Murphy and Edwards, 2003; IEA, 2009b; Section 11.5). Attempts to move renewable technology into mainstream markets following the oil price shocks failed in most developed countries (Roulleau and Loyd, 2008). Many of the technologies were not sufficiently developed or had not reached cost competitiveness and, once the price of oil came back down, interest in implementing these technologies faded. Solar hot water heaters were a technology that was ready for the market and with tax incentives many such systems were installed. But once the tax advantage was withdrawn, the market largely collapsed (Dixit and Pindyck, 1994).

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, and the mix of policies and their design and implementation vary regionally and depend on prevailing conditions. 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, availability of affordable capital, and the local and national RE resource base. Key policy elements include adequate value to cover costs and account for social benefits, inclusiveness and ease of administration. Further, the details of policy design and implementation—including flexibility to adjust as technologies, markets and other factors evolve—can be as important in determining effectiveness and efficiency as the specific policies that are used (Section 11.5). Transparent, sustained, consistent signals—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 the risk of investment sufficiently to enable appropriate rates of deployment and the evolution of low-cost applications (Sections 11.2, 11.4 and 11.5).

For deployment policies with a focus on RE electricity, there is a wealth of literature assessing quantity-based (quotas, renewable portfolio standards that define the degree to which electricity generated must be from renewable sources, and tendering/bidding policies) and price-based (fixed-price and premium-price feed-in tariffs (FIT)) policies, primarily quotas and FITs, and with a focus on effectiveness and efficiency criteria. Several studies have concluded that some FITs 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. A number of studies 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 (Ragwitz et al., 2005; Stern, 2007; de Jager and Rathmann, 2008; Section 11.5.4). Quota policies have been moderately successful in some cases. They 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. To date, fiscal incentives have been the prevalent policy in use to support RE heating and cooling, with grants the most commonly applied incentive. Obligations to use RE heat are gaining attention for their potential to encourage growth independent of public financial support (Section 11.5.5).

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. 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. Those countries with the highest share of biofuels in transport fuel consumption have had hybrid systems that combine mandates (including penalties) with fiscal incentives (foremost tax exemptions). Policies have influenced the development of an international biofuel trade (Section 11.5.6).

There is now considerable experience with several types of policies designed to increase the use of renewable technology. Denmark became a world leader in the manufacture and deployment of large-scale wind turbines by setting long-term contracts for renewably generated electricity production (REN21, 2009). Germany and Spain (among others) have used a similar demand-pull mechanism through FITs that assured producers of RE electricity sufficiently high rates for a long and certain time period. Germany is the world's leading installer of solar PV, and in 2008 had the largest installed capacity of wind turbines (REN21, 2009). The USA has relied mostly on government subsidies for RE technologies and this supply-push approach has been less successful than demand pull (Lewis and Wiser, 2007; Butler and Neuhoff, 2008). China has encouraged renewable technology for water heating, solar PV and wind turbines by investing in these technologies directly. China is already the leading producer of solar hot water systems for both export and domestic use, and is now the largest producer of PV technology (REN 21, 2009).

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 (Section 11.5.7). Impacts can be positive or negative, depending on policy choice, design and the level of implementation (local, regional, national or global). Negative effects would include the risk of carbon leakage and rebound effects, which need to be taken into account when designing policies. In the long term, enhancing knowledge for the implementers and regulators of RE supply technologies and processes can help reduce costs of mitigation, and putting a price on carbon can increase the competitiveness of RE (Sections 11.1.1 and 11.5.7).

1.5.2 Enabling environment

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; by understanding the ability of RE developers to obtain finance and planning permission to build and site a project; by removing barriers for access to networks and markets for RE installations and output; by increasing education and awareness raising; and by enabling technology transfer. In turn, existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE (Section 11.6).

1.5.2.1 Complementing renewable energy policies and non-renewable energy policies

Since all forms of RE capture and production involve spatial considerations, policies need to consider land use, employment, transportation, agricultural, water, food security, trade concerns, existing infrastructure and other sector-specific issues. 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-lose and/or win-win situations, with possible trade-offs.

1.5.2.2 Providing infrastructure, networks and markets for renewable energy

Advancing RE in the electric power sector, for example, will require policies to address its 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 (Quezada et al., 2006; Cossent et al., 2009) and the governance of the system may need to be adjusted to ease or harmonize access; current regulations and laws, designed to assure the reliability of the current centralized grid, may prevent the wide-scale introduction of renewable electric generating technology.

In the transport sector, issues exist related to the necessary infrastructure for biofuels, recharging hydrogen, battery or hybrid electric vehicles that are 'fuelled' by the electric grid or from off-grid renewable electrical production (Tomic and Kempton, 2007; Sections 1.4.2.4 and 11.6.5).

Brazil has been especially effective in establishing a rural agricultural development program around sugarcane. Bioethanol produced from sugarcane in Brazil is currently responsible for about 40% of the spark ignition travel and it has been demonstrated for use in diesel buses and even in a crop duster aircraft. The bagasse, which is otherwise wasted, is gasified and used to operate gas turbines for electricity production while the 'waste' heat is used in the sugar to bioethanol refining process (Pousa et al., 2007; Searchinger et al., 2008).

1.5.3 A structural shift

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. Some analyses conclude that large, low-carbon facilities such as nuclear power, or large coal (and natural gas) plants with CCS can be scaled up rapidly enough to meet CO_2 reduction goals if they are available (MIT, 2003, 2007, 2009). Alternatively, the expansion of natural gas-fired turbines during the past few decades in North America and Europe, and the rapid growth in wind and solar technologies for electric power generation (see Figure 1.12) demonstrate that modularity and more widely distributed smaller-scale units can also scale rapidly to meet large-scale energy demands. The technological and economic potential for each of these approaches and their costs have important implications for the scale and role of RE in addressing climate change (Pilavachi, 2002; MIT, 2003, 2007, 2009; Onovwiona and Ugursal, 2006). To achieve 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. Such a transition to low-carbon energy differs from previous ones (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 (Section 11.7 and Chapter 10).

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; policies 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 (Sections 11.6 and 11.7). 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 (Section 11.7).

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Appendix to Chapter 1

Table 1. A.1 | Global technical potential of RE sources (compared to global primary energy supply in 2008 of 492 EJ).[1]

		Technical Potential (EJ/yr)					Notes and Sources for Range of Estimates and Notes on Krewitt et al. (2009) estimates
		Krewitt et al. (2009)[2]			Range of Estimates Summarized in Chapters 2-7[3]		
		2020	2030	2050	Low	High	
Electric Power (EJ/yr)	**Solar PV[4]**	1,126	1,351	1,689	1,338	14,778	Chapter 3 – Hofman et al. (2002); Hoogwijk (2004); de Vries et al. (2007). The methodology used by Krewitt et al. (2009) differs between PV and CSP; details are described in Chapter 3.
	Solar CSP[4]	5,156	6,187	8,043	248	10,791	Chapter 3 – Hofman et al. (2002); Trieb (2005); Trieb et al. (2009). The methodology used by Krewitt et al. (2009) differs between PV and CSP; details are described in Chapter 3.
	Geothermal[5]	4,5	18	45	118	1,109	Hydrothermal and EGS: Chapter 4 – EPRI (1978); Rowley (1982); Stefansson (2005); Tester et al. (2005, 2006).
	Hydropower	48	49	50	50	52	Chapter 5 – Krewitt et al. (2009); International Journal of Hydro & Dams (2010).
	Ocean[6]	66	166	331	7	331	Chapter 6 – Sims et al. (2007); Krewitt et al. (2009); technical potential estimates may not include all ocean energy technologies; Sims et al. (2007) estimate is referred to as 'exploitable estimated available energy resource'.
	Wind On-Shore	362	369	379	70	450	Chapter 7 – low estimate from WEC (1994), high estimate from Archer and Jacobson (2005) and includes 'near-shore', more recent estimates tend towards higher end of range.
	Wind Off-Shore[7]	26	36	57	15	130	Chapter 7 – low estimate from Fellows (2000), high estimate from Leutz et al. (2001), only considering relatively shallow water and near-shore applications; greater technical potential exists if one considers deeper water applications (Lu et al., 2009; Capps and Zender, 2010).
Heat (EJ/yr)	**Solar**	113	117	123	N/A	N/A	Technical potential is mainly limited by the demand for heat. Krewitt et al. (2009) base estimates on available rooftop area and only solar water heating; technical potential considering non-rooftop applications and process heat would far exceed these estimates.
	Geothermal	104	312	1,040	10	312	Hydrothermal: Chapter 4 – Stefansson (2005). Although the estimates from Krewitt et al. (2009) are also based on Stefansson (2005), Krewitt et al. (2009) assume a higher capacity factor than Chapter 4.
Primary Energy (EJ/yr)	**Solar[8]**	N/A	N/A	N/A	1,575	49,837	Total solar energy technical potential: Chapter 3 – Rogner et al. (2000)
	Biomass Energy Crops[9]	43	61	96	small	120	Dedicated biomass production on surplus agriculture and pasture lands: Chapter 2 – Dornburg et al. (2010).
					small	140	Further intensification of agriculture: Chapter 2 – Dornburg et al. (2010).
					small	70	Dedicated biomass production on marginal/degraded lands: Chapter 2 – Dornburg et al. (2010).
					small	100	More intensive forest management: Chapter 2 – Dornburg et al. (2010).
	Biomass Residues[9]	59	68	88	40	100	Agriculture and forestry residues, other organic wastes, dung etc.: Chapter 2 – Dornburg et al. (2010).
	Biomass Total[9]	***102***	***129***	***184***	***50[10]***	***500[11]***	Rounded figures based on Chapter 2 expert review of technical potential assessments.

Notes:

1 Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized for energy production. In 2008, total primary energy supply from RE sources on a direct equivalent basis equalled: bioenergy (50.33 EJ); hydropower (11.55 EJ); wind (0.79 EJ); solar (0.50 EJ); geothermal (0.41 EJ); and ocean (0.002 EJ). According to the definition of technical potential in the Glossary (see Annex I), many of the studies summarized here take into some account broader economic and socio-political considerations. For example, for some technologies, land suitability or other sustainability factors are included, which result in lower technical potential estimates.

2 Technical potential estimates for 2020, 2030 and 2050 are based on a review of studies in Krewitt et al. (2009). Due to differences in methodologies and accounting methods between studies, comparison of these estimates across technologies and regions, as well as to primary energy demand, should be exercised with caution. Data presented in Chapters 2 through 7 may disagree with these figures due to differing methodologies. Krewitt et al. (2009), as well as many of the other studies reported in the table, assume that technical potential increases over time due, in part, to technological advancements.

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3 Range of estimates derives from studies presented in Chapters 2 through 7 (occasionally including some of the studies reported in the Krewitt et al. (2009) review). As a result, ranges do not always encompass the figures presented in Krewitt et al. (2009). Ranges are based on various methods and apply to different future years; consequently, as with Krewitt et al. (2009), the resulting ranges are not strictly comparable across technologies.

4 Estimates for PV and CSP in Krewitt et al. (2009) are based on different data and methodologies, which tend to significantly understate the technical potential for PV relative to CSP. In part as a result, a range for total solar energy technical potential is provided in the primary energy category based on Rogner et al. (2000). Note that this technical potential for total solar primary energy is not the sum of the three listed technologies (PV, CSP and solar heat) due to different studies used. Also note that the technical potentials for PV, CSP and solar heat listed in the table are not strictly additive due to possible competition for land among specific solar technologies.

5 Estimates for geothermal electricity in Krewitt et al. (2009) appear to largely consider only hydrothermal resources. The range of estimates presented in Chapter 4 derives from EPRI (1978), Rowley (1982), Stefansson (2005), and Tester et al. (2005, 2006) and includes both hydrothermal and EGS potential.

6 The absolute range of technical potential for ocean energy is highly uncertain, because few technical potential estimates have been conducted due to the fact that the technologies are still largely in the R&D phase and have not been commercially deployed at scale.

7 Estimates for offshore wind energy in Krewitt et al. (2009) and the range of estimates provided in the literature as presented in the table are both based on relatively shallow water and near-shore applications. Greater technical potential for offshore wind energy is found when considering deeper-water applications that might rely on floating wind turbine designs.

8 The technical potential for total solar primary energy is not the sum of the three listed technologies (PV, CSP and solar heat) due to different studies used; also note that possible competition for land among specific solar technologies makes it inappropriate to add the technical potential estimates for PV, CSP and solar heat to derive a total solar technical potential. The estimates of the total solar energy technical potential provided in the table do not differentiate between the different solar conversion technologies, but just take into account average conversion efficiency, available land area and meteorological conditions. At certain geographical locations all listed solar technologies could be used and users will decide what service they need from which technology.

9 Primary energy from biomass (in direct equivalent terms) could be used to meet electricity, thermal or transportation needs, all with a conversion loss from primary energy ranging from roughly 20 to 80%. As a result, comparisons of the technical potential for biomass in primary energy terms to the technical potentials of other RE sources in delivering secondary energy supply (i.e., electric power and heat) should be made with care.

10 The conditions under the low technical potential estimate could emerge when agricultural productivity increases stall worldwide combined with high food demand and no surplus land for energy crops being available. It is also assumed that marginal and degraded lands are not utilized and a large fraction of biomass residue flows is assumed to be used as feedstock in other sectors rather than for bioenergy. However, low-grade residues, dung and municipal waste will in such a situation likely still remain available for bioenergy.

11 The higher end of the biomass potential is conditional and assumes proper land management and substantial increases in agricultural yields and intensified forestry management. Achieving such a potential will be sustainable only if monitoring and good governance of land use is effective, and sustainability frameworks are in place.