INTERGOVERNMENTAL PANEL ON climate change

# Summary for Policymakers

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# Summary for Policy Makers

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## 1. Introduction

The Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) presents an analysis of literature on and experiences with the scientific, technological, environmental, economic and social aspects of the contribution of six renewable energy (RE) sources to the mitigation of climate change. It is intended to provide input into the IPCC's fifth Assessment Report (AR5) and serve as a critical resource document for both the AR5 and for governments and others outside of the AR5 process. This Summary for Policy Makers provides an overview of the SRREN, summarizing the essential findings.

The SRREN consists of 11 chapters. Chapter 1 sets the context for RE and Climate Change; Chapters 2 – 7 provide information on six RE technologies while Chapters 8-11 deal with integrative issues (see Fig. SPM.1).

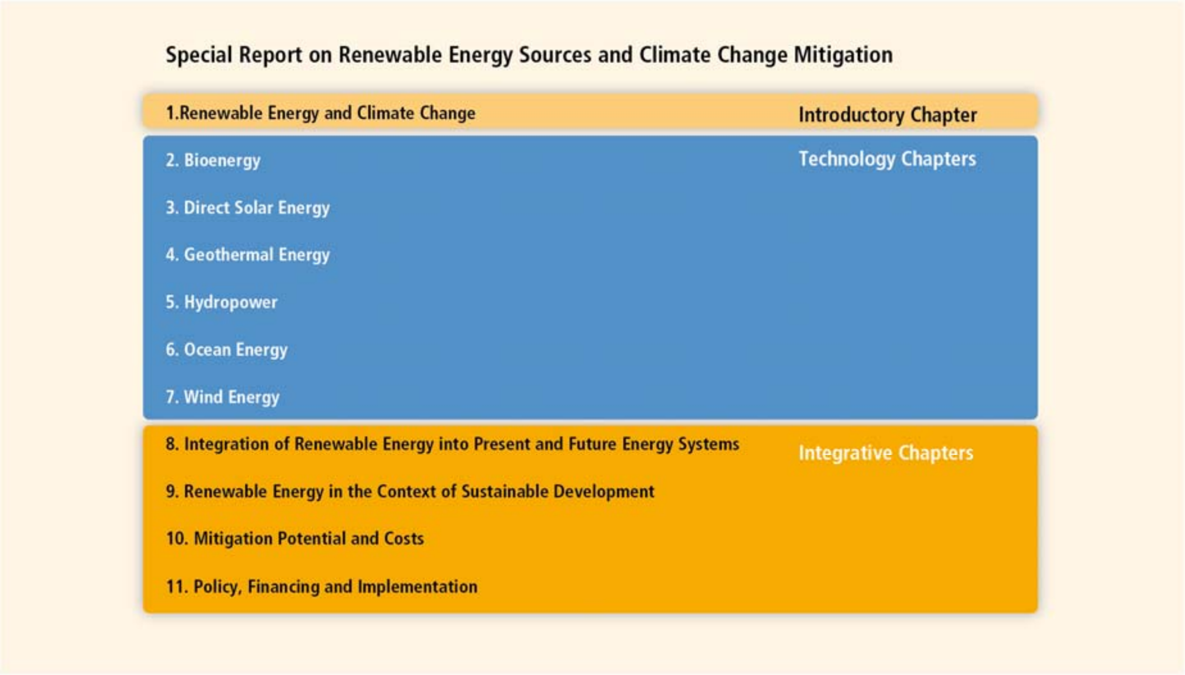

**Figure SPM.1.** Structure of the SRREN [Figure 1.1, 1.1.2]

References to chapters and sections are indicated with corresponding chapter and section numbers in square brackets. An explanation of terms, acronyms and chemical symbols used in this SPM can be found in the glossary to the main report (Annex I). Conventions and methodologies for determining costs, primary energy and other topics of analysis may be found in Annex II and Annex III.

## 2. Drivers and Solutions for a Low-Carbon Economy

***Access to energy services is fundamental for social and economic development as well as human welfare and health.*** All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, communication) and to serve productive processes. [1.1.1, 9.2.1, 9.3.2, 9.6, 11.3]

***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. [1.1, 9.3.2, 9.4.2, 9.6]

***GHG emissions associated with the provision of energy services is 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 GHG concentrations." Consumption of fossil fuels in the energy system accounts for some 60% of all GHG emissions. Concentrations have continued to grow since the AR4 to over 390 PPM or 39% above preindustrial levels. [1.1.1, 1.1.3]

***There are multiple means for lowering GHG emissions from the energy system while still providing energy services [1.1.3 and 10.1].*** Many options and combinations thereof are possible for reducing emissions. These include [1.1.6]:

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

***Renewable energy sources play a role in providing energy services in a sustainable manner and, in particular, in mitigating Climate Change.*** This special report 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 [1.1.2].

Figure SPM 2 demonstrates the role of RE supply in the energy flow from primary energy source through energy carriers to the delivery of energy services.

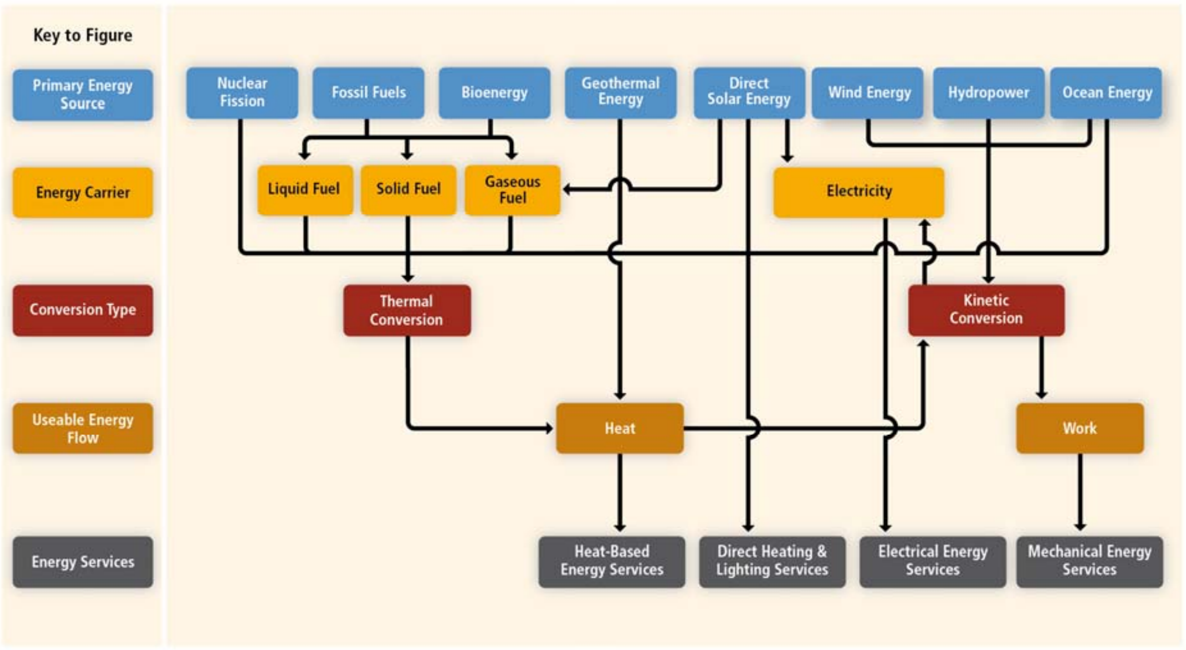

**Figure SPM.2.** Energy paths from Primary Energy Sources to Energy Services [Figure 1.16, 1.2.1].

## 3. Renewable Energy Technologies and Markets

***RE technologies are diverse and can serve the full range of energy service needs*** (Box SPM 1). 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 [1.2]. 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 [1.2, 8.2, 8.3, 9.3.2]. 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 [1.2]. The outputs of some RE technologies are variable or unpredictable over differing time scales (from minutes to years), whereas other RE technologies are less variable or can offer constant or controllable output [8.2, 8.3].

**Box SPM 1.** Overview of Renewable Energy Sources and Technologies

**Bioenergy** can be produced from a variety of biomass feedstocks, including forest, agricultural, and livestock residues, short-rotation forest plantations, dedicated energy crops, the organic component of municipal solid waste, and other organic waste streams. Through a variety of processes, these feedstocks can be used to produce electricity, heat, and gaseous and liquid fuels. Bioenergy technologies can be applied in centralized and decentralized settings, and have varying maturities, with some (e.g., small and large scale boilers, domestic pellet based heating systems, ethanol production from sugar and starch) at later stages of commercial development, others (e.g. gasification-based power plants, lignocellulose-based transport fuels) at early-stage commercial development, and still others (e.g. aquatic biomass) in the R&D phase. When used to generate electricity, bioenergy typically offers constant (base-load) or controllable output. Bioenergy projects can sometimes be influenced by local and regional fuel supply availability, but a recent trend is for solid biomass and liquid biofuels to be traded internationally. [1.2, 2.1, 2.3, 2.6, 8.2, 8.3]

**Direct solar energy** technologies harness the energy of solar irradiance to produce electricity using photovoltaics (PV) and concentrating solar power (CSP), to produce thermal energy (either through passive or active means), to meet direct lighting energy needs and, potentially, to produce solar fuels that might be used for transport and other purposes. The maturity of solar technologies ranges from early R&D (e.g., solar fuels) to fully mature (e.g., passive and active solar heating). Many of the technologies are modular in nature, allowing their use in both centralized and decentralized energy systems. Solar energy is variable and, to some degree, unpredictable, though the temporal profile of solar energy output sometimes correlates relatively well with energy demands. Thermal energy storage offers the option of controlled output for some technologies such as CSP and direct heating. [1.2, 3.1, 3.3, 3.5, 3.7, 8.2, 8.3]

**Geothermal energy** utilizes the accessible thermal energy stored in the Earth's interior. The heat is extracted from geothermal reservoirs using wells. Reservoirs that are naturally sufficiently hot and permeable are called hydrothermal reservoirs, whereas reservoirs that are sufficiently hot but need to be improved with hydraulic or chemical stimulation are called enhanced geothermal systems (EGS). Once at the surface, hot fluids from geothermal reservoirs can be used to generate electricity or can be used more-directly for applications that require thermal energy, including geothermal heat pumps. Hydrothermal power plants and thermal applications of geothermal energy rely primarily on mature technologies, whereas EGS projects are in the demonstration and pilot phases. When used to generate electricity, geothermal power plants typically offer constant (base-load) output. [1.2, 4.1, 4.3, 4.4, 8.2, 8.3]

**Hydropower** harnesses the potential energy of water moving from higher to lower elevations, primarily to generate electricity. Hydropower projects vary widely in type and size, creating a continuum from large-scale dam projects with reservoirs to small-scale run-of-river projects. This variety gives hydropower the ability to meet large centralized urban needs as well as decentralized rural needs. Hydropower technologies are mature. The controllable output provided by hydropower facilities that have reservoirs can be used to meet peak electricity demands and help to balance electricity systems that have large amounts of variable RE generation. Hydropower facilities often have multiple uses, meeting the needs of water management and navigation as well as energy supply. [1.2, 5.1, 5.3, 5.5, 5.10, 8.2]

**Ocean energy** derives from the potential, kinetic, thermal, and chemical energy of seawater, which can be transformed to meet electricity and thermal energy services. A wide range of technologies are possible, such as barrages for tidal range, submarine turbines for tidal and ocean currents, heat exchanges for ocean thermal energy conversion, and a variety of devices to harness the energy of waves and salinity gradients. With the exception of tidal barrages, most ocean technologies are at the demonstration and pilot project phases. Some of the technologies have variable output profiles with differing levels of predictability (e.g., wave, tidal range, current), while others may be capable of near-constant or even controllable operation (e.g., ocean thermal and salinity gradient). [1.2, 6.1, 6.2, 6.3, 6.4, 6.6, 8.2]

**Wind energy** harnesses the kinetic energy of moving air and can be used in many ways, but the primary application of relevance to climate change mitigation is to produce electricity from large wind turbines located on land (on-shore) or in sea- or fresh-water (off-shore). Wind energy relies on technologies that are already reasonably mature, but off-shore technologies have greater potential for continued technical advancement. Wind electricity is both variable and, to some degree, unpredictable, though experience and detailed studies have concluded that there are no insurmountable technical barriers to integrating wind energy into electric systems. [1.2, 7.1, 7.3, 7.5, 7.7, 8.2]

***On a global basis, it is estimated that RE accounted for 12.9% of the total 492 EJ of primary energy supply in 2008*** (Figure SPM.3). 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 bioenergy as well.1 Hydropower represented 2.3%, whereas other RE sources accounted for 0.4% [1.3]. 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, modern bioenergy, solar thermal, and geothermal together fuelled 27% of the total global demand for heat (the majority from traditional biomass). The contribution of RE to primary energy supply varies substantially by country and region [1.3, 8.1].

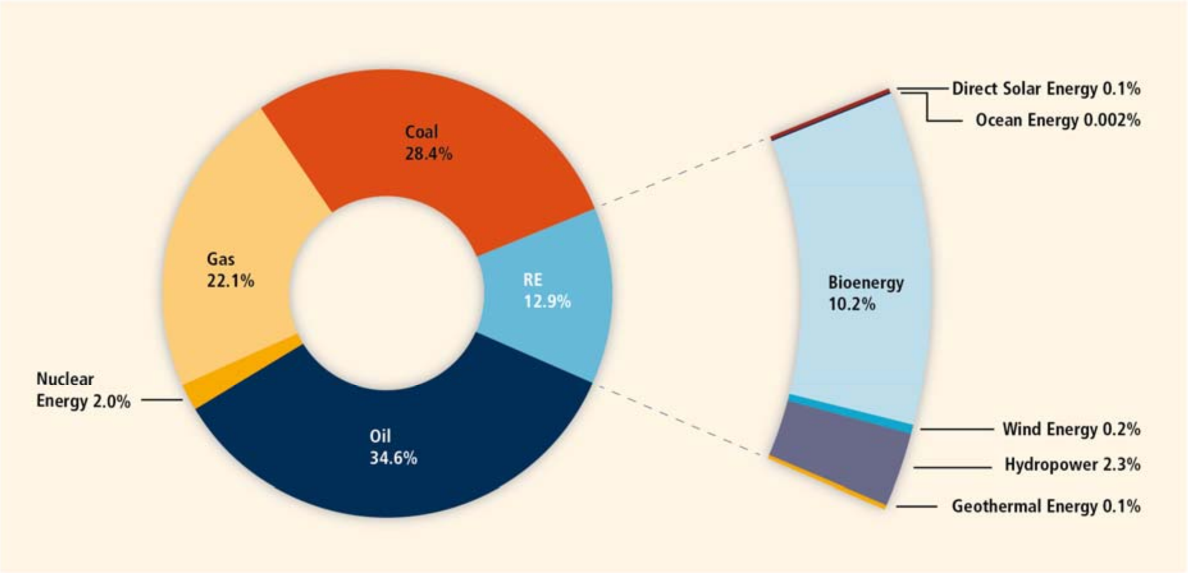

**Figure SPM.3.** Total Global Primary Energy Supply in 2008 [Figure 1.10, 1.1.5]

Notes: Roughly 60% of the primary biomass supply is used in traditional cooking and heating applications in developing countries. Underlying data for figure from the International Energy Agency, converted to the "direct equivalent" method of accounting for primary energy supply [1.1.9, Annex II].

***Deployment of RE has been increasing rapidly in recent years.*** 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 (Figure SPM 4) [1.1.5, 9.3, 10.5, 11.2, 11.3]. 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 GW added), geothermal power (4%, 0.4 GW added), and solar hot water/heating (21%, 31 $GW_{th}$ added). The production of ethanol increased by 10% in 2009 (7 billion litres added) and biodiesel by 9% (2 billion litres added) [1.1.5, 2.4, 3.4, 4.4, 5.4, 7.4].

Of the approximate 300 GW of new electricity generating capacity added globally over the two year period from 2008-2009, 140 GW came from RE additions. Collectively, developing countries host more than 50% of global RE power generation capacity, with China adding more capacity than any other country in 2009. [1.1.5] The U.S. 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 bioenergy (270 $GW_{th}$), solar (180 $GW_{th}$), and geothermal (60 $GW_{th}$). The use of RE (excluding traditional biomass) in meeting rural

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

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. [1.1.5, 2.4, 3.4, 4.4, 5.4]

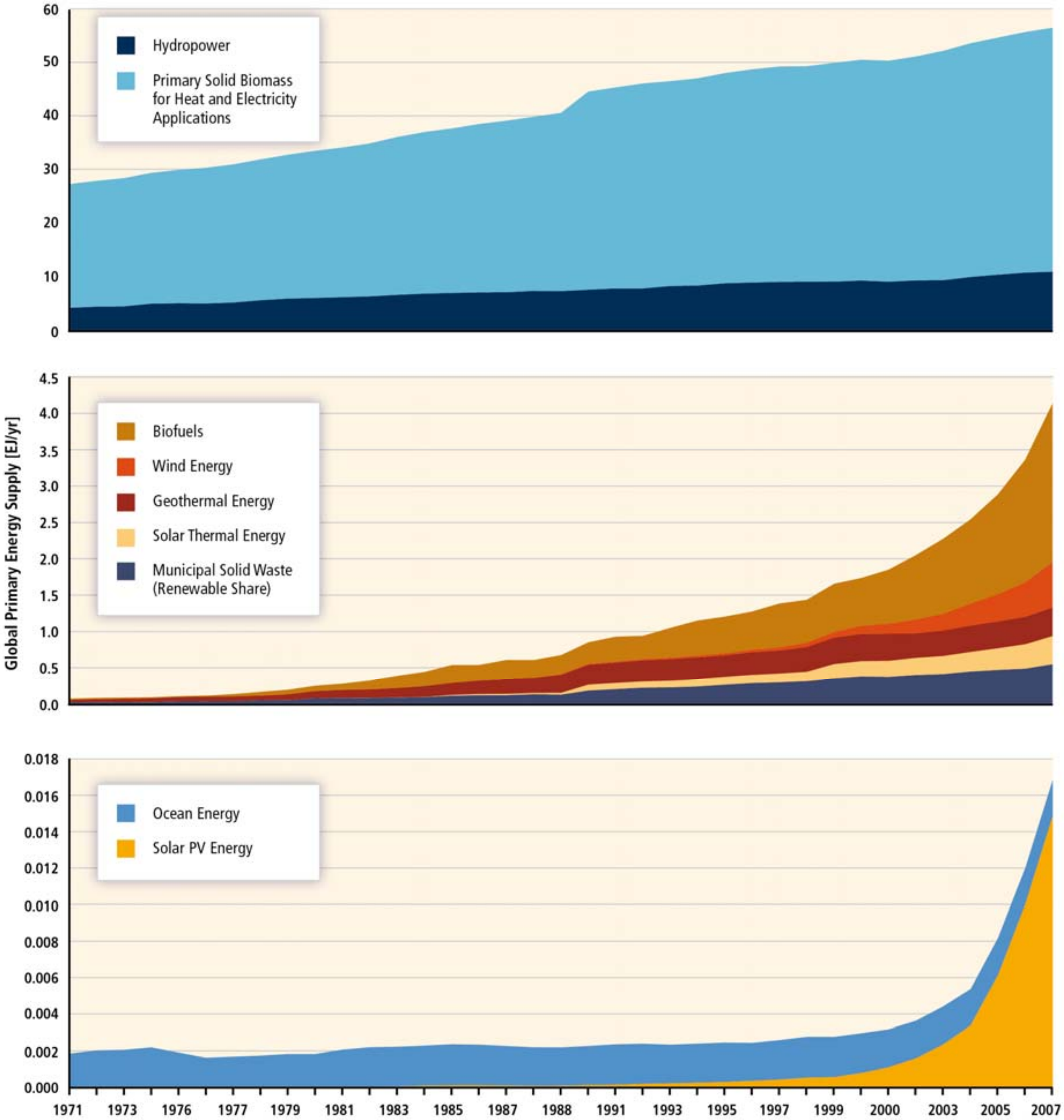

**Figure SPM.4.** Historical Development of Global Primary Energy Supply from Renewable Energy from 1971 – 2007. [Figure 1.12, 1.1.5]

Notes: Underlying data from the International Energy Agency, converted to direct equivalent, except that the energy content of biofuels is reported in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses [2.3, 2.4])

***The global technical potential[2] of RE sources will not limit continued market growth.*** A wide range of estimates are provided in the literature but studies have consistently found that the total

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[2] Definitions for technical potential often vary by study; see Annex I for the general definition of "technical potential" used in this report.

global technical potential for RE is substantially higher than both current and projected future global energy demand (Figure SPM.5) [1.2.2, Chapter 1 Annex]. The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all forms of RE. Even in regions with relatively low levels of technical potential for any individual RE source there are typically significant opportunities for increased deployment compared to current levels. [1.2.2, 2.2, 2.8, 3.2, 4.2, 5.2, 6.2, 6.4, 7.2, 10.3] The absolute size of the global technical potential for RE as a whole is unlikely to constrain RE deployment [1.2, 10.3]. Global and regional technical potentials may limit the future use of some RE technologies at higher levels of deployment, however, as might sustainability concerns [9.3], system integration and infrastructure constraints [8.2], and economic factors [10.3].

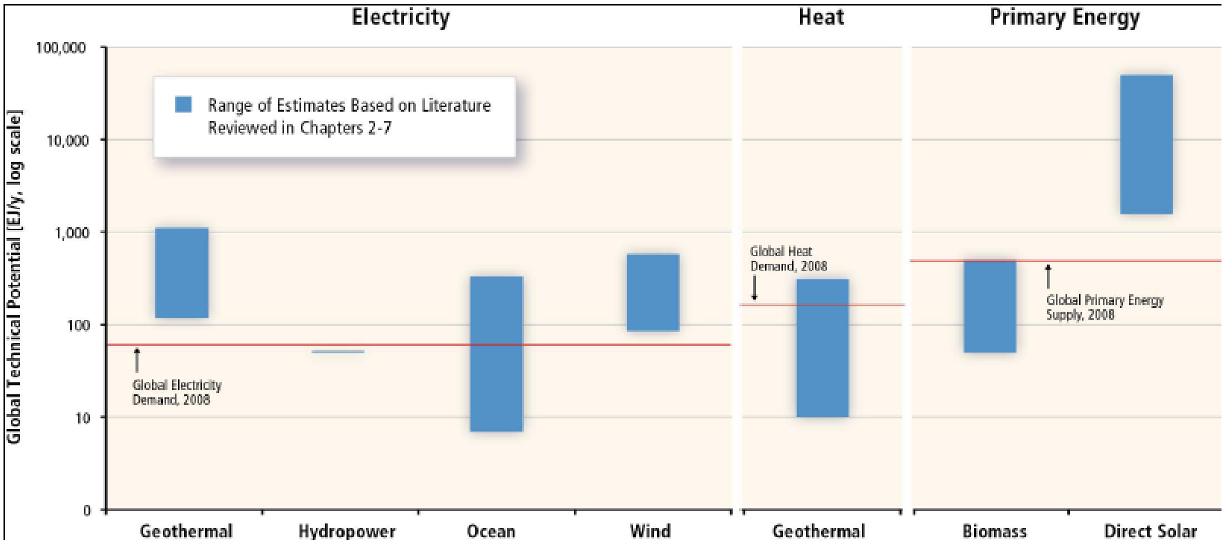

**Figure SPM.5.** Range of Global Technical Potentials of Renewable Energy Sources Used for Electricity and Heat with Biomass and Solar Shown as Primary Energy Due to Their Multiple Uses [Figure 1.17, 1.2.3]

Notes: Technical potentials reported here represent total worldwide potentials for annual renewable energy supply and do not deduct any potential that is already being utilized. The range of estimates for technical potential are based on a review of the literature covered in Chapters 2-7. 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. For the data behind Figure SPM 5 and additional notes that apply, see Chapter 1 Annex, Table Ch01A.1 (as well as the underlying chapters).

***Climate change will have impacts on the size and geographic distribution of the technical potential for RE sources.*** Because RE sources are, in many cases, dependent on the climate, global climate change will affect the RE resource base. Research into these possible effects is nascent. The technical potential for bioenergy is influenced by climate change through impacts on biomass production (via altered soil conditions, precipitation, crop productivity and other factors), but details remain poorly understood. The overall impact of a global mean temperature change of below 2°C on the technical potential of bioenergy is likely to be relatively small on a global basis, but considerable regional differences can be expected [2.2, 2.6]. For solar energy, though climate change is expected to influence the distribution and variability of cloud cover, the impact of these changes on overall technical potential will be small [3.2]. For hydropower, climate change is expected to increase overall average precipitation, but regional patterns will vary. The impact of changes in the volume and timing of precipitation, evaporation, and snowmelt on river flows and hydropower technical potential on a global basis is likely to be relatively small, but significant regional changes in river flow volumes and seasonal timing are possible [5.2]. Climate change may alter the regional distribution of the wind energy resource [7.2]. Climate change is not anticipated to have significant impacts on the size or geographic distribution of geothermal or ocean energy resources [4.2, 6.2].

***The levelized cost of energy for many RE technologies is currently higher than market energy prices, though in other cases RE is already economically competitive.*** Ranges of recent levelized costs of energy for selected commercially available RE technologies are wide, depending on technology characteristics, regional variations in cost and performance, and differing discount rates (Figure SPM.6) [1.3.2, 2.3, 2.7, 3.8, 4.7, 5.8, 6.7, 7.8, 10.5, Annex III].[3] Some RE technologies are broadly competitive with current market energy prices. Many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favourable resource conditions or that lack the infrastructure for other low-cost energy supplies. In most regions of the world, policy measures are still required to ensure rapid deployment of many RE sources. [2.3, 2.7, 3.8, 4.7, 5.8, 6.7, 7.8, 10.5, 11.2]

If environmental and other impacts, including GHG emissions, were monetized and included in energy prices, a broader array of RE technologies would appear economically attractive [10.6]. The levelized cost of energy for a technology is not the sole determinant of its value or economic competitiveness because relative environmental and social impacts must be considered, as well as the contribution that the technology provides 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) [8.2, 9.3, 10.6].

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[3] The levelized cost of energy of even technically identical devices can vary across the globe, and depend on the services rendered by the device (e.g., peaking vs. base-load in the case of hydropower), on the quality of the resource, on local investment costs, on the cost of financing, and on the cost of operation and maintenance.

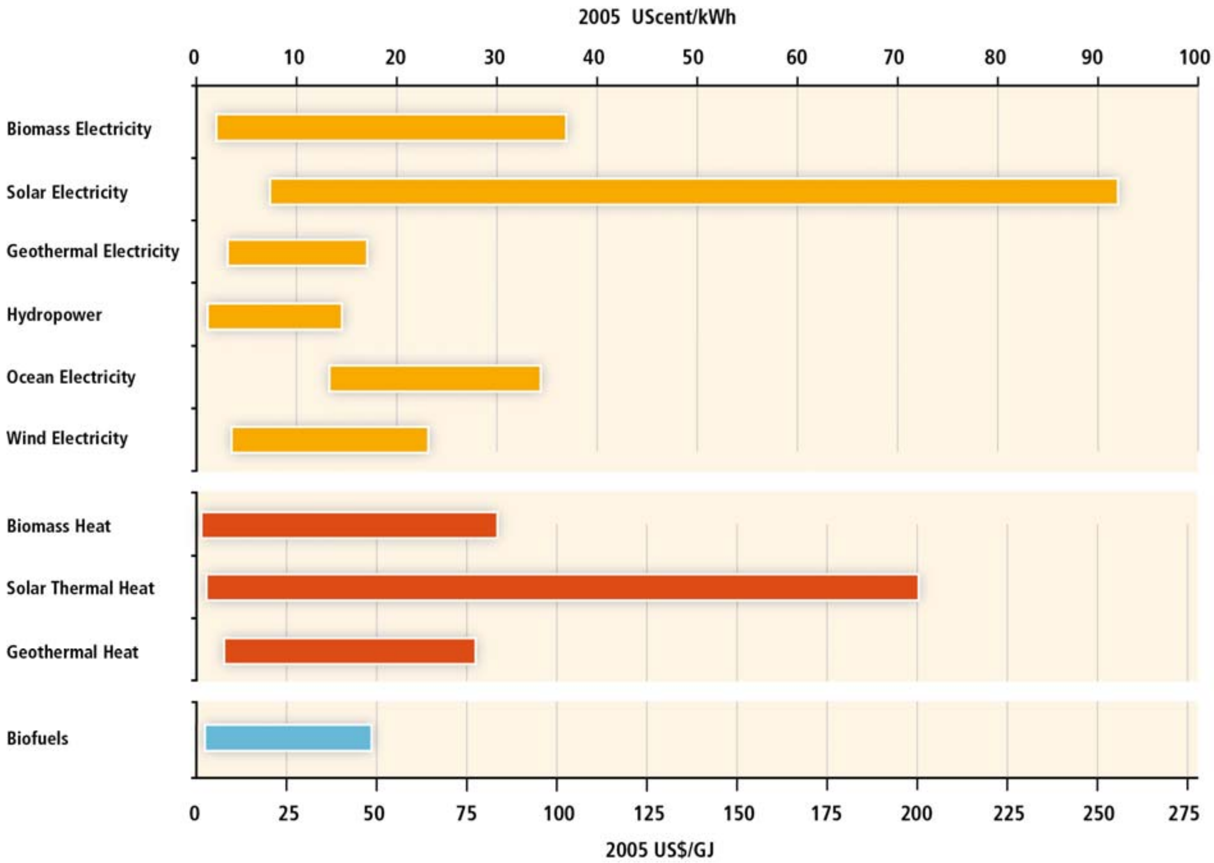
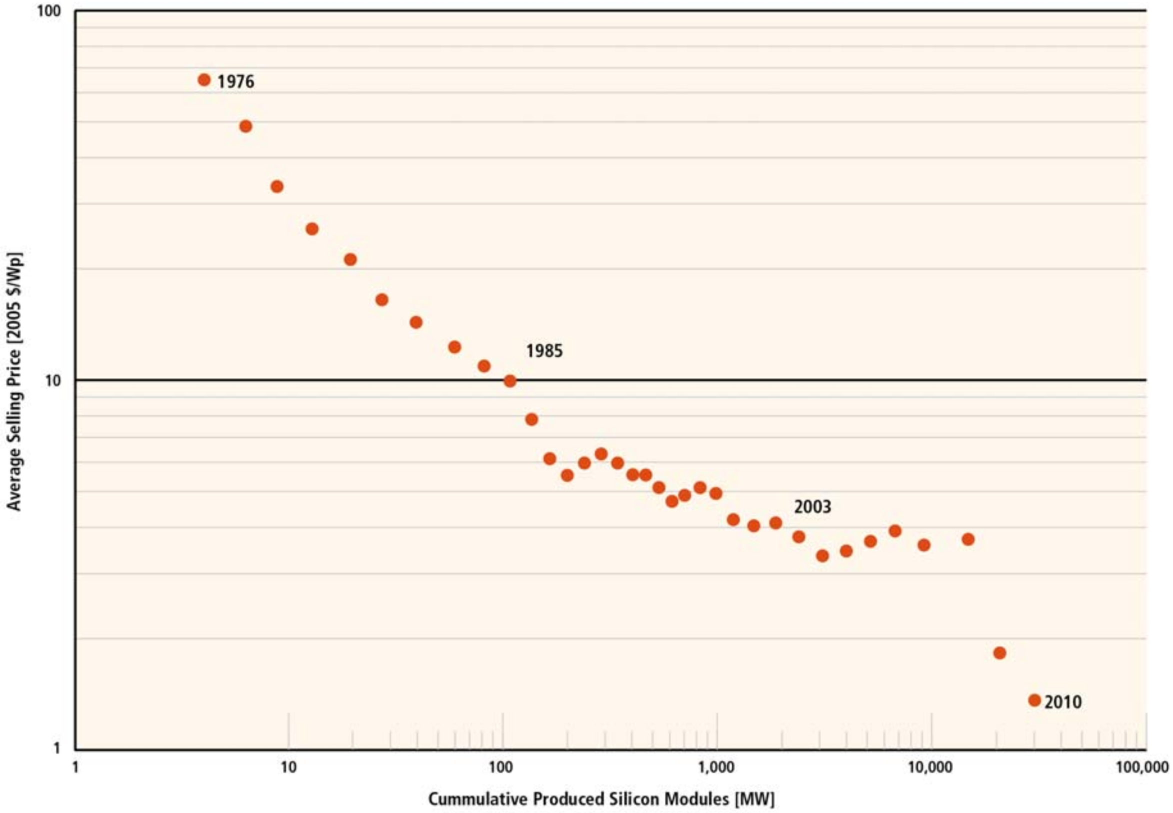


**Figure SPM.6.** Range in recent levelized cost of energy for selected commercially available RE technologies. [Figure TS1.9]

Notes: The broad range in the levelized cost of energy for most technologies was based on input data summarized in Annex III with calculations based on the methodology outlined in Annex II. Technology subcategories and discount rates were aggregated for this figure: for related figures with less or no such aggregation, see [1.3.2, 10.5].

***The cost of most RE technologies has declined and significant additional technical advancements are expected.*** Significant advancements in RE technologies and associated cost reductions have been demonstrated over the last decades, though the contribution of different drivers (e.g., R&D, deployment-oriented learning, and increased market competition) is not always understood in detail (Figure SPM.7) [2.7, 3.8, 7.8, 10.5]. Further cost reductions are expected, resulting in greater potential for climate change mitigation and reducing the need for policy measures to ensure rapid deployment. Important areas of potential technological advancement include (but are not limited to): next-generation biofuels and biorefineries [2.6]; advanced PV and CSP technologies and manufacturing processes [3.7]; enhanced geothermal systems [4.6]; multiple emerging ocean technologies [6.6]; and foundation and turbine designs for off-shore wind energy [7.7]. Further cost reductions for hydropower are likely to be less significant than some of the other RE technologies, but R&D opportunities exist to make hydropower projects technically feasible in a wider range of natural conditions and improve the technical performance of new and existing projects [5.3, 5.7, 5.8].

(a)


100
10
1
Average Selling Price [2005 $/Wp]
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2003
2010
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10
100
1,000
10,000
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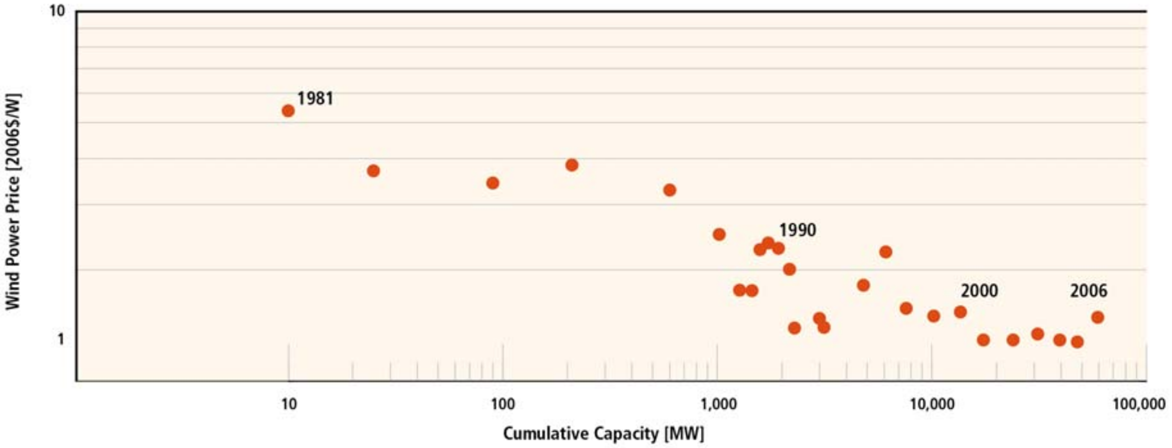
Cummulative Produced Silicon Modules [MW]

(b)


10
1
Wind Power Price [2006$/W]
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2006
10
100
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Cumulative Capacity [MW]

(c)

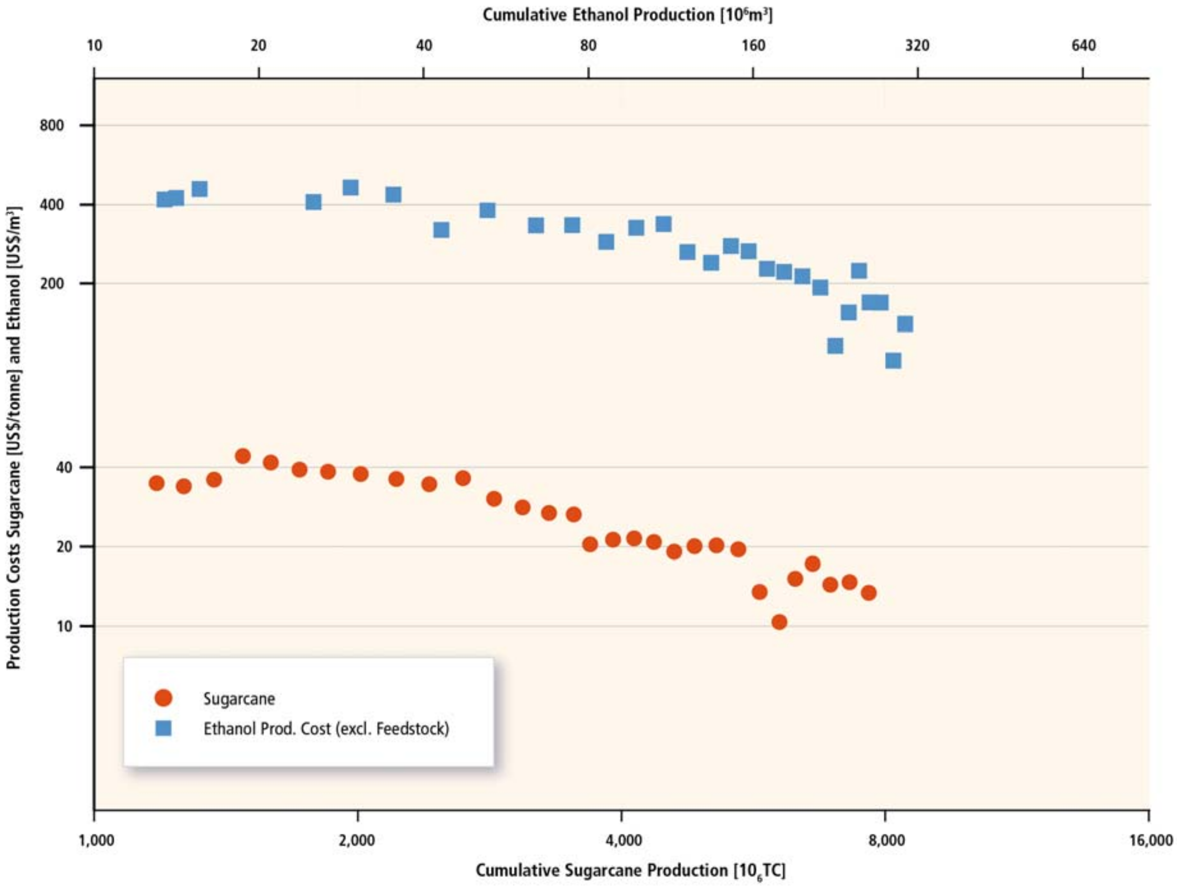


**Figure SPM.7.** Selected experience curves for (a) silicon photovoltaic modules, (b) wind power plants, and (c) sugarcane-based ethanol [Figure 3.17, 3.8.3, Figure 10.31, 10.5.2, Figure 2.21, 2.7.2]

Notes: Due in part to an imbalance between supply and demand, RE prices have sometimes experienced periods of rising prices.

***In addition to cost, a variety of technology-specific challenges need to be addressed to enable RE to achieve its potential to significantly reduce GHG emissions.*** A key precondition for the increased use of bioenergy is the application of well functioning sustainability frameworks and policies that can balance competing demands for the land that may be used for biomass feedstocks [2.2, 2.5, 2.8]. For solar energy, regulatory and institutional barriers often impede the deployment of solar systems [3.9]. For geothermal, an important challenge will be to prove that enhanced geothermal systems (EGS) can be deployed economically, sustainably, and widely [4.5, 4.6, 4.7, 4.8]. New hydropower projects are sometimes controversial, and increased deployment may require improved sustainability assessment tools and regional and multi-party collaborations to address energy and water needs [5.6, 5.9, 5.10]. The deployment of ocean energy will benefit from testing centres for demonstration projects, and from dedicated policies that encourage early deployment [6.4]. For wind energy, technical and institutional solutions to transmission constraints and operational integration concerns are especially important, as are public acceptance issues relating primarily to landscape impacts [7.5, 7.6, 7.9].

## 4. Integration into Present and Future Energy Systems

***Several RE technologies are already being successfully integrated into present energy supply systems.*** Various RE technologies can be utilized directly in all end-use sectors (such as first generation biofuels, building-integrated solar water heaters and wind power) [8.3] and indirectly into energy supply systems (such as injection of biomethane into natural gas grids) [8.2] (Figure SPM.8).

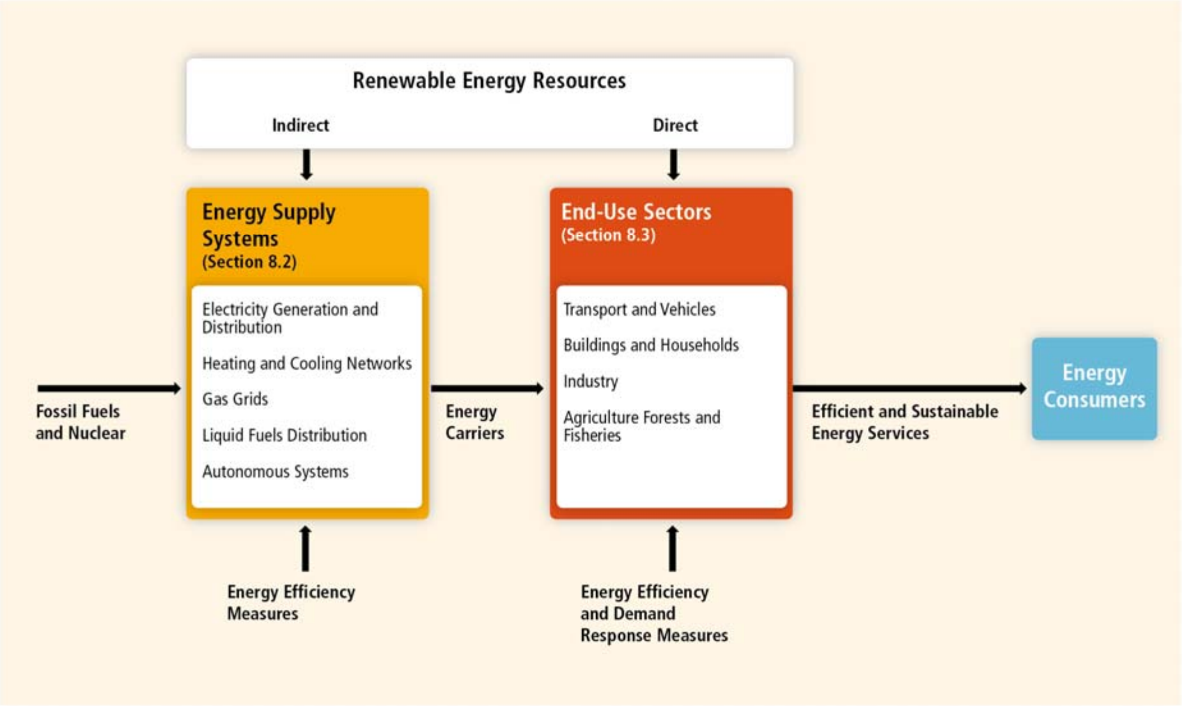


**Figure SPM.8.** RE resources can be utilised to provide sustainable energy services either directly on-site by the end-use sectors or indirectly through integration into energy supply systems then delivered to end-use sectors by energy carriers with varying shares of RE [Figure 8.1, 8.1].

***In the short term, integrating RE into most existing energy supply systems and end-use sectors at an accelerated rate, leading to high shares of RE is feasible, though will result in new technological and institutional challenges***. All countries have access to RE resources. Some, such as solar and to a more limited extent ocean energy, are widely distributed, whereas others, such as large hydro, can be more centralized but have integration options constrained by geographic location. Some RE resources are variable with limited predictability. Others have lower energy densities and different technical specifications from liquid and gaseous petroleum fuels. Such characteristics can constrain ease of integration and invoke additional system costs particularly when reaching higher shares of RE [8.2].

***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. Additional integration costs reported in the literature cover a wide range [8.2, 8.3].

- RE can be integrated into all types of *electricity* systems from large interconnected continental scale grids [8.2.1] down to small autonomous buildings [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, can be more difficult to integrate than dispatchable hydro, bioenergy and geothermal. Partly because of the geographical distribution and fixed remote locations of many RE resources, as the penetration level of RE increases, additional electricity network transmission and/or distribution infrastructure generally has to be constructed to supply the load.

  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 hydro), and modified institutional arrangements including regulatory and market mechanisms [8.2.1].

- *District heating and cooling systems* offer flexibility with regard to the primary energy source and can therefore use low temperature thermal RE inputs (such as solar and geothermal heat), biomass with few competing uses (such as refuse-derived fuels), or, for a source of cold, natural waterways [8.2.2]. Thermal storage capability can overcome variability challenges.

- In *gas distribution grids*, injecting biomethane, or in the future, RE-derived hydrogen, can be achieved for a range of applications but successful integration requires that appropriate gas quality standards are met [8.2.3].

- *Liquid fuel systems* can integrate biofuels either for cooking applications (such as ethanol gels) or for transport, either neat (100%) but more usually blended with petroleum-based fuels to meet vehicle engine fuel specifications [8.2.4, 8.3.1].

***There are multiple pathways for increasing the shares of RE across all end-use sectors, but the ease of integration varies depending on region, characteristics specific to the sector and technology.***

- For *transport*, liquid and gaseous biofuels are already fairly well integrated into the fuel supply systems of a few countries. Future integration options include on-site or centralized production of RE electricity [8.2.5, 8.2.1] or RE hydrogen [8.2.3] depending on infrastructure and vehicle technology developments [8.3.1].

- In the *building* sector, RE technologies can be integrated into both new and existing structures with the potential to reduce fossil fuel demand and enable buildings, especially energy efficient designs, to become net suppliers of electricity and heat [8.3.2]. In developing countries, owners of even modest dwellings can benefit in many ways from the integration of modern RE supply systems, including energy access, reduced air pollution and energy security [8.3.2, 9.3.2].

- Food and forest production and process *industries* often use biomass for direct energy needs on-site. They can also be net exporters of surplus fuels, heat, and electricity to adjacent supply systems [8.3.3, 8.3.4]. Increasing the indirect integration of RE for use by industries is an option in several sub-sectors, for example through electro-thermal technologies or, in the longer term, using RE hydrogen [8.3.3].

***In order to accommodate higher RE shares in the longer term, energy systems will need to evolve and be adapted [8.2, 8.3].*** Most scenarios that stabilize GHG concentrations around 450 ppm $CO_{2\text{-eq}}$ show rapidly increasing shares of RE being integrated into all sectors within a portfolio of low carbon technologies. The majority show the RE share of low carbon primary energy exceeding 50% by 2050 [10.2.2.4, Fig 10.2.7]. This transition is illustrated by many scenarios [10.2], the single example shown in Figure SPM 9 being based on the IEA World Energy Outlook 2010 "450 Policy Scenario" out to 2035.

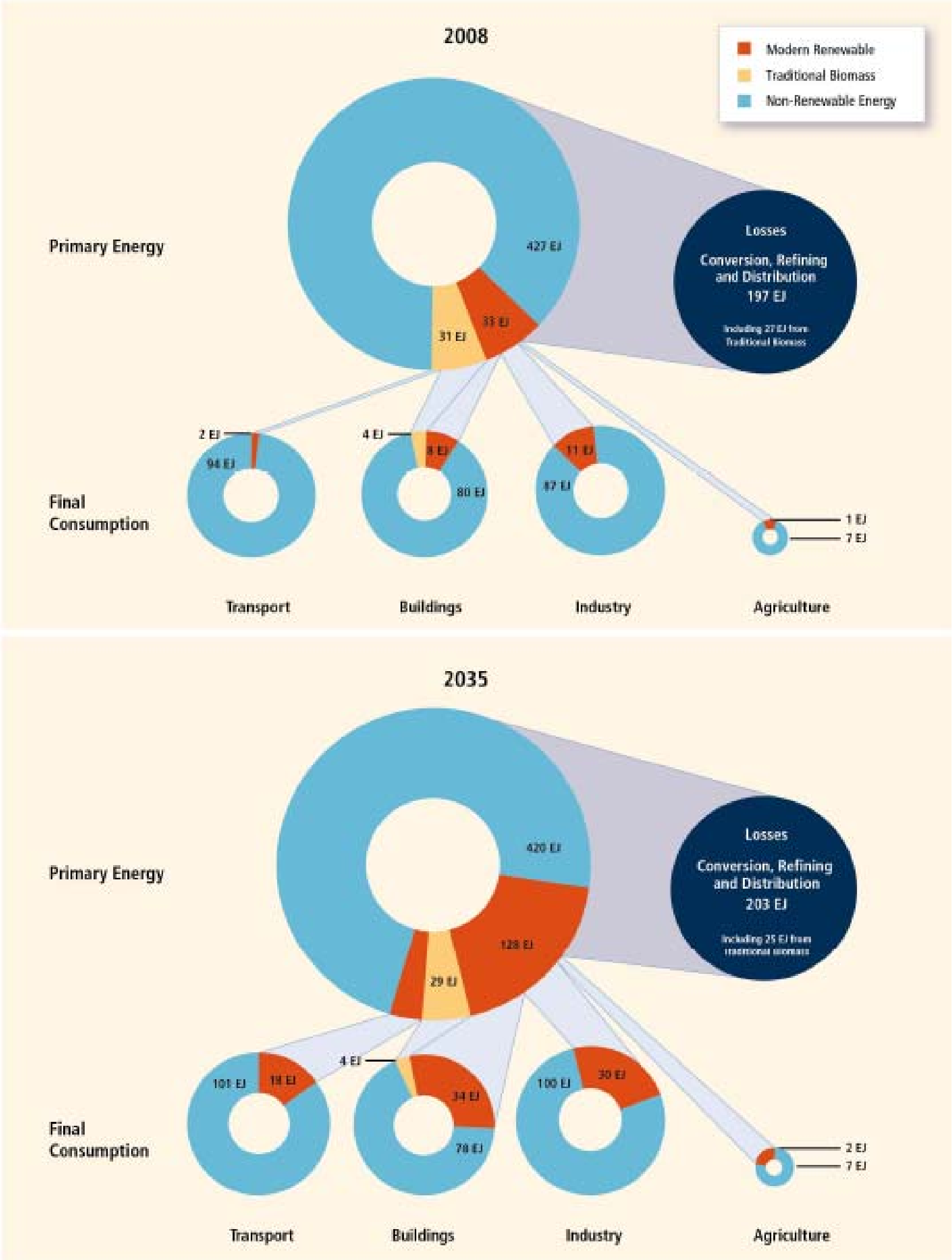


**Figure SPM.9.** RE shares of primary and final consumption energy in the transport, buildings (including traditional biomass), industry and agriculture sectors in 2008 and an indication of the projected RE shares needed by 2035 in order to move towards a 450 ppm $CO_{2\text{-eq}}$ stabilisation target [Figure 8.2, 8.1].

Notes: Area of circles approximately to scale. “Non-renewable” energy (yellow) includes coal, oil, natural gas (with and without CCS by 2035) and nuclear power. This scenario example is based upon data taken from the IEA World Energy Outlook 2010 and converted to direct equivalents [A.II.4]. Energy efficiency improvements above the baseline are included in the 2035 projection. RE in the buildings sector includes traditional solid biomass fuels [2.2]. By 2035 some traditional biomass has been replaced by modern bioenergy.

As infrastructure and energy systems develop, there are few, if any, fundamental technical limits to integrating a portfolio of RE technologies that meet a majority share of total energy demand in locations where suitable RE resources exist, though costs and social barriers will influence actual implementation [8.2, 8.2.1]. To achieve such increased shares of RE in total primary energy supply and in all end-use sectors by 2035 and beyond [Tables 10.3.2-4] will require overcoming the challenges of system integration for all RE technologies.

Long-term integration efforts would include investment in enabling infrastructure and R&D, modification of institutional and governance frameworks, innovative thinking, attention to social aspects, markets and planning, and capacity building in anticipation of RE growth [8.2, 8.3]. Integration of less mature technologies, including advanced biofuels, solar fuels, solar coolers, fuel cells and electric vehicles will require continuing investments in research, development and demonstration (RD&D), capacity building and other supporting measures over the longer term [11.5, 11.6].

The expansion of RE is expected to shape future energy supply and end-use systems, in particular for electricity which is expected to attain higher shares of RE until 2050 than either the heat or transport fuel sectors [10.3]. This could be driven by parallel developments in electric vehicles [8.3.1], increased heating and cooling using electricity (including heat pumps) [8.2.2, 8.3.2, 8.3.3], flexible demand response services (including the use of smart meters) [8.2.1], and other technologies.

## 5. Sustainable Development

***Historically, economic development has been strongly correlated with increasing energy use and growth of GHG emissions. RE can help decouple development and rising emissions, contributing to sustainable development (SD).*** Providing access to modern energy services remains crucial for the achievement of each of the Millennium Development Goals. [9.3.1, 9.3.2] Though the exact contribution of RE to SD has to be evaluated in a country specific context, RE offers the opportunity to contribute to a number of important SD goals: 1) social and economic development, 2) energy access, 3) energy security, 4) climate change mitigation, and reduction of negative environmental and health impacts. The prioritisation of these goals may vary. [9.2]

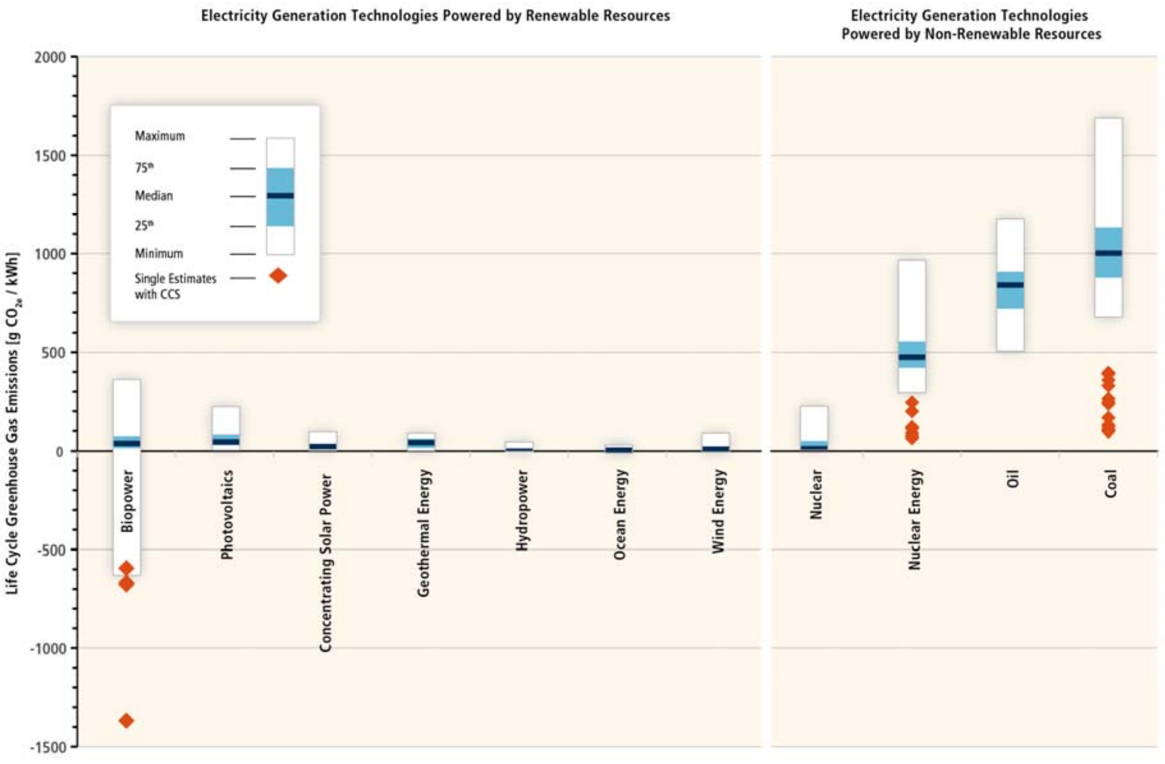
- ***The contribution of RE to social and economic development may differ between developed and developing countries.*** In poor rural areas lacking grid access, RE can lead to substantial cost savings already today. [9.3.2.] To the extent that developing countries can avoid expensive energy imports by deploying economically more efficient RE technologies, they can redirect foreign exchange flows towards imports of other goods that cannot be produced locally [9.3.3]. The creation of employment opportunities and actively promoting structural change in the economy are seen, especially in industrialized countries, as goals that support the promotion of RE. [9.3.1]

- ***RE used in an appropriate SD framework can help accelerate access to energy.*** Even basic levels of access to modern energy services can provide substantial benefits to a community or household (e.g. lighting and communication, healthcare and education). In developing countries, decentralized grids based on RE have expanded and improved energy access; they are generally more competitive in rural areas with significant distances to the national grid. In addition, non-electrical RE technologies offer opportunities for direct modernization of energy services, for example using solar energy for water heating and crop drying, biogas for cooking and lighting, and wind or PV for water pumping. [9.3.2] If developing countries are able to secure dedicated financing for enhanced energy access and apply tailored policies, the number of people with access to modern energy services can expand more rapidly [9.3.2, 9.4.2].

- ***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.*** As long as RE markets (e.g. bioenergy) are not characterized by concentrated supply, this may help reduce economic vulnerability by reducing price volatility. [9.3.3, 9.4.3] The variable output profiles of some RE technologies often necessitate technical and institutional measures appropriate to local conditions to assure a constant and reliable energy supply. [8.2, 9.3.3] The degree to which RE can substitute for liquid fossil fuels used in transport will depend on technology, market, and institutional developments. Without technological breakthroughs, oil and related energy security concerns will likely continue to play a dominant role in the global energy system of the future. [9.4.3.1]

- ***RE technologies can provide important environmental benefits compared to fossil fuels, including reduced GHG emissions. Maximizing these benefits often depends on the specific technology, management, and site characteristics associated with each RE project.***

    - ***Life cycle assessments for electricity generation indicate that GHG emissions from RE technologies are, in general, considerably lower than those associated with fossil fuel options, and under most conditions, less than fossil fuels employing CCS (Figure SPM 10).*** GHG balances of bioenergy production, however, have more uncertainties (see Box SPM 2); excluding land-use impacts, most bioenergy systems reduce GHG emissions compared to fossil fuels. While some first-generation biofuels result in relatively modest GHG mitigation potential, most second-generation options could provide greater climate benefits. [9.3.4.1, 2.2, 2.5]



| | Biopower | Photovoltaics | Concentrating Solar Power | Geothermal Energy | Hydropower | Ocean Energy | Wind Energy | Nuclear | Nuclear Energy | Oil | Coal |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Count of Estimates | 222(+4) | 124 | 42 | 8 | 28 | 10 | 126 | 125 | 83(+7) | 24 | 169(+12) |
| Count of References | 52(+0) | 26 | 13 | 6 | 11 | 5 | 49 | 32 | 36(+4) | 10 | 50(+10) |

**Figure SPM.10.** Estimates of life cycle GHG emissions (g CO2e / kWh) for broad categories of electricity generation technologies, plus some technologies integrated with carbon capture and storage (CCS). Land use related changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) are excluded. References and methods for review are reported in the Annex A II. Number of estimates is greater than references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to those technologies evaluated with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions weighted by generation. [Figure 9.8, 9.3.4.1]

- ***RE technologies can offer benefits with respect to air pollution and health.*** 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. [9.3.4.3, 9.3.4.4, 9.4.2] Improving traditional biomass use can reduce negative SD impacts, including local and indoor air pollution, GHG emissions, deforestation and forest degradation. [2.5.4, 9.4.2]
- ***Impacts on water and biodiversity depend on local conditions.*** Under certain circumstances, some RE technologies may exacerbate water scarcity or negatively impact biodiversity. In areas where water scarcity is already a concern, non-thermal RE technologies (e.g. wind and PV) can provide energy services without additional stress on water resources [9.3.4.2]. Many impacts can be mitigated by siting considerations and integrated planning. [9.3.4.2, 9.3.4.5, 9.3.4.6, 2.5, 3.6, 4.5, 5.6, 6.5]

- ***Risks of severe accidents leading to contamination or high fatalities are likely lower for most renewable technologies than for existing fossil fuel and nuclear energy supply chains*** [9.3.4.7].

**Box SPM 2. Land Use Change, Bioenergy and Rural Development**

The sustainability of bioenergy, in particular in terms of life cycle GHG emissions, is strongly influenced by land and biomass resource management practices. Changes to land use or management, brought about *directly* or *indirectly* by biomass production for use as fuels, power or heat, can lead to changes in terrestrial carbon stocks. Depending on the converted land's prior condition, this can either cause significant upfront emissions, requiring a time lag of decades to centuries before net savings are achieved, or improve the net uptake of carbon into soils and aboveground biomass. The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause land use change (LUC) if these biomass sources were not utilised for alternative purposes. [2.5]

Assessments of the net GHG effects of bioenergy are made difficult by challenges in observation, measurement, and attribution of *indirect* LUC (iLUC), which depends on the environmental, economic, social and policy context and is neither directly observable nor easily attributable to a single cause. (i)LUC effects are likely significant if high expansion rates and large future markets are assumed. Proper governance of land-use, zoning, and choice of biomass production systems are key considerations for policy makers interested in promoting sustainable bioenergy use. [9.3.4, 9.4.4, 2.4.5, 2.5.1]

Other effects of bioenergy deployment on social and environmental concerns – ranging from health and poverty to biodiversity, $N_2O$ emissions, and water use and quality – may also be positive or negative depending upon local conditions, the specific feedstock and technology paths chosen, and how actual projects are designed and implemented. The development of bioenergy options is strongly linked to rural development and overall improvement of agricultural management, which can also offset increased land requirements for bioenergy production. Sustainability frameworks aim to ensure that social and environmental conflicts, e.g. regarding food security and water resources, are avoided and that the benefits from bioenergy production, such as the contribution to climate change mitigation, outweigh the challenges [2.2, 2.5, 2.8].

**The integration of RE policies and measures in SD strategies at various levels can help overcome barriers and create opportunities for RE deployment that more fully meet SD goals.** In the context of SD, barriers continue to impede RE deployment. Besides market related and economic barriers, those barriers intrinsically linked to societal and personal values and norms will fundamentally affect the perception and acceptance of RE technologies and related deployment impacts by individuals, groups and societies. Dedicated communication efforts are therefore a crucial component of any transformation strategy and local SD initiatives can play an important role in this context. [9.5.1, 9.5.2] At international and national levels, strategies could include: 1) removal of mechanisms that are perceived to work against SD; 2) mechanisms for SD that internalize environmental and social externalities; and 3) strategies supporting low-carbon, green and sustainable development including leapfrogging. [9.5.2]

## 6. Mitigation Potentials and Costs

***An increasing number of integrated scenario analyses that are able to provide relevant insights into the potential contribution of RE to future energy supplies and climate change mitigation has become available.*** *[10.1]* The results of the scenario analyses is used to explore the range of RE depending on, for example, on future technical advancements and cost reductions of RE technologies and other mitigation options, and the effort to reduce GHG emissions. For this purpose a review of 164 scenarios from large-scale integrated models was conducted through an open call.[4] For more specific analysis, a subset of four illustrative scenarios from the set of 164 was used.

***The scenario review confirms that RE has a large potential to mitigate GHG emissions.*** [10.2, 10.3]. Allocation of mitigation to RE technologies in scenarios generally confirms an important role for RE in the future energy system and therefore a substantial role in reducing GHG emissions. The four in-depth analysed illustrative scenarios span a range of global cumulative CO2 savings between 2010 and 2050 from about 220 Gt CO2 to 560 Gt CO2 compared to about 1530 Gt CO2 cumulative fossil and industrial CO2 emissions in the WEO 2009 Reference scenario during the same period. However, the precise attribution of mitigation potentials to RE not only depends on the role scenarios foresee for these specific mitigation technologies, but also on complex system behaviours and, in particular, on the energy sources that RE displaces. Therefore, attribution of precise mitigation potentials to RE should be viewed with caution. It should, however, be noted that in the majority of reviewed scenarios, RE makes a higher contribution to low-carbon energy supply by 2050 than the competing low-carbon supply options (nuclear and fossil CCS).

***The majority of 164 recent scenarios indicate a substantial increase in the deployment of RE by 2030, 2050 and beyond.*** [10.2, 10.3]. In 2008 total RE production stood at roughly 64 EJ/yr (12.9% of total primary energy supply) with about 40 EJ/yr of this being traditional biomass. In contrast, projected levels of RE deployment in 2050 are greater than 100 EJ/yr in most scenarios and reach 200 EJ/yr to 400 EJ/yr in many scenarios (Figure SPM.9). Given that traditional bioenergy production decreases in most scenarios, an increase of production level of RE (excluding traditional bioenergy) anywhere from roughly three-fold to twenty-fold is necessary (Figure SPM.11). In other words, it is likely that RE will have a significantly larger role in the global energy system in the future than today. The global primary energy supply share of RE differs substantially among the scenarios reviewed here. The most ambitious penetration of RE in the scenarios is 77% of global primary energy supply in 2050.

***The scenarios indicate that even without efforts to address climate change RE can be expected to expand*** *[10.2]*. Even in baseline scenarios with no assumed climate mitigation target, scenarios show large RE deployments of more than 100 EJ/yr, in some cases even up to about 250 EJ/yr (Figure SPM.9). These substantial baseline deployment levels result from a range of assumptions, including, for example, the assumption that energy consumption will continue to grow substantially throughout the century, assumptions about the ability of RE to contribute to increased energy access and assumptions about the long-term availability of fossil resources. Additionally other assumptions (e.g. improved costs and performance of RE technologies) that render RE technologies increasingly economically competitive in many applications even absent climate policy are relevant and determine the scenario results.

***RE deployment significantly increases in the scenarios with ambitious GHG concentration targets, although it is not possible to precisely link long-term climate goals and global RE deployment levels*** [10.2]. Ambitious GHG concentration targets lead on average to higher RE deployment compared to baseline. However, for any given long-term GHG concentration goal, the scenarios exhibit a wide range of RE deployment levels (Figure SPM.9 and SPM.12). This range is a result of differences in assumptions about factors such as: developments in RE technologies and their associated resource bases and costs; comparative attractiveness of competing mitigation options (i.e. end-use energy efficiency, nuclear energy and fossil energy with CCS); fundamental

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[4] Although the reviewed 164 scenarios do not represent a fully random sample suitable for rigorous statistical analysis and do not represent always the full RE portfolio (e.g. so far ocean energy only considered in a few scenarios), the set of scenarios does provide a meaningful window into uncertainty [10.2.2].

drivers of energy services demand (including population, economic growth); the ability to integrate variable RE sources into power grids; fossil fuel resources; specific policy approaches to mitigation; and emissions pathways toward long-term goals (e.g., overshoot versus stabilization). However, despite the observed variations, the scenarios indicate that, all else being equal, more ambitious mitigation generally leads to greater deployment of RE.

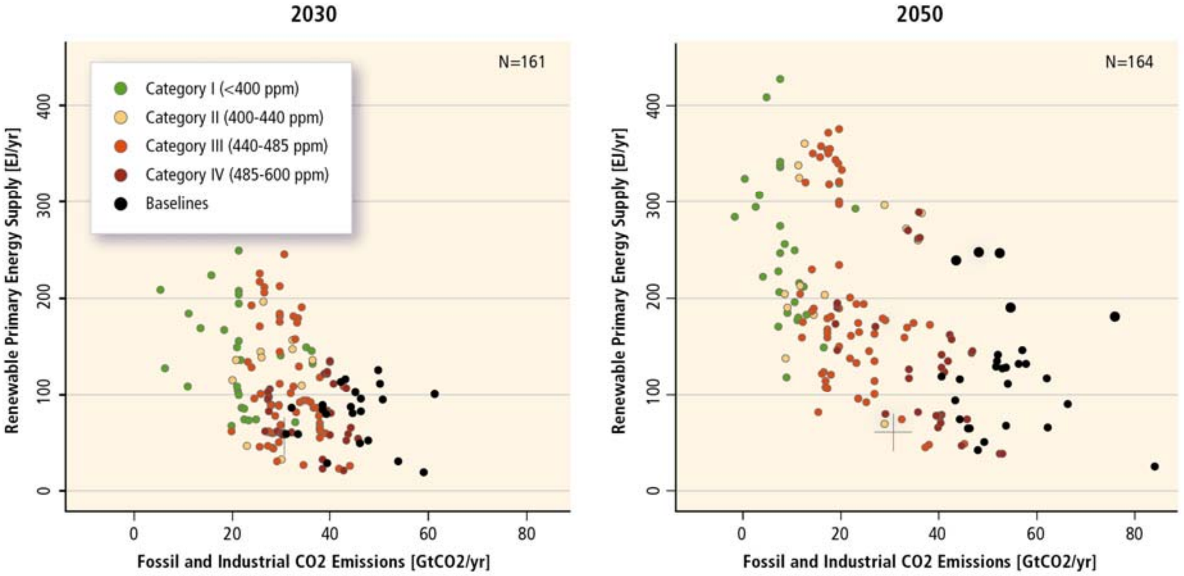


**Figure SPM.11.** Global RE primary energy supply (direct equivalent) from 164 long-term scenarios as a function of fossil and industrial $CO_2$ emissions in 2030 and 2050. Colour coding is based on categories of atmospheric $CO_2$ concentration level in 2100.The blue crossed-lines show the relationship in 2007. [Figure 10.2, 10.2.2.2]

Notes: Note that for data reporting reasons only 161 scenarios are included in 2030 results shown here, as opposed to the full set of 164 scenarios. RE deployment levels below those of today are a result both of model output as well as differences in the reporting of traditional bioenergy.

***Scenarios generally indicate both that growth in RE will be widespread around the world*** *[10.2, 10.3]* Although the precise distribution of RE deployment across regions varies substantially across scenarios, scenarios are largely consistent in indicating widespread growth in RE deployment around the globe. In addition, RE deployment is higher over the long-term in Non-Annex I countries than in Annex I countries in most scenarios, in part a reflection of the fact that non-Annex I countries are expected to represent an increasing share of total global energy demand over the coming decades (Figure SPM.10 and SPM.11).

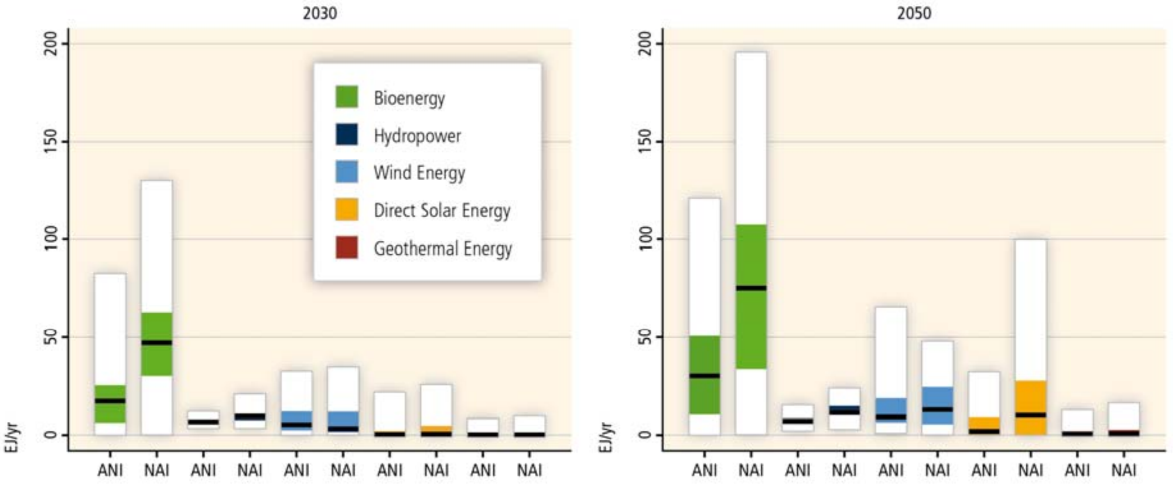
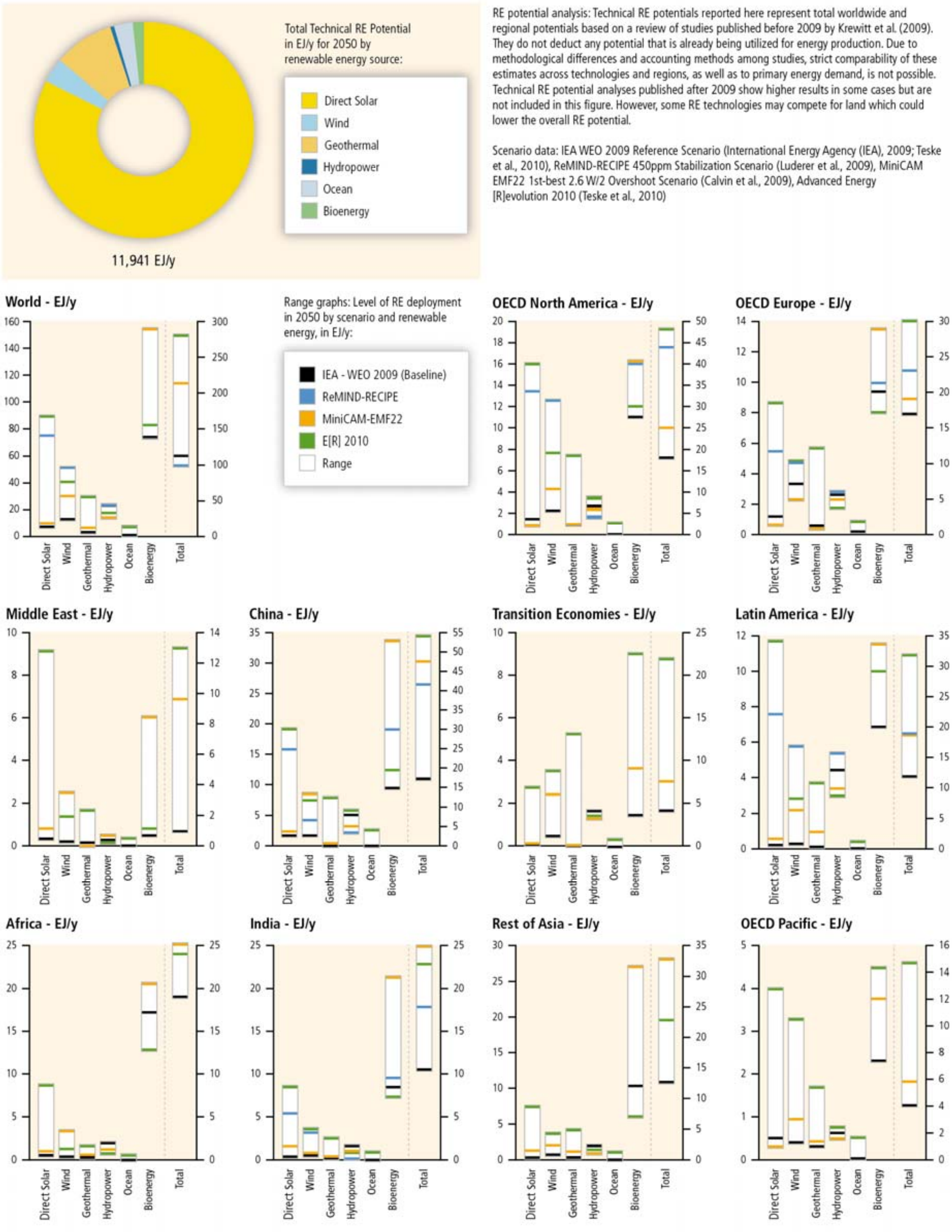


**Figure SPM.12.** Global RE primary energy supply (direct equivalent accounting method) by source in Annex I (ANI) and Non-Annex I (NAI) countries in 164 long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. [Figure 10.8, 10.2.2.5]

Notes: One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as biofuels, electricity and heat. The other technologies produce primarily (but not entirely) electricity and heat, and they are accounted for based on this secondary energy produced. If primary equivalents based on the substitution method were used rather than direct equivalent accounting, then energy production from non-biomass RE would be on the order of two to three times larger than shown here.

***Scenarios do not indicate an obvious single dominant RE technology at a global level; in addition, the global overall technical potentials do not constrain the future contribution of RE*** [10.2, 10.3]. Although there is high uncertainty in deployments across scenarios, a general trend is that bioenergy (predominantly modern bioenergy), wind energy, and solar energy are commonly characterized by the largest contributions of RE technologies to the energy system by 2050 (Figure SPM.10, 11 and SPM.12). In addition, although deployment of the different technologies significantly increases over time, the resulting contribution of RE in the scenarios for most technologies is much lower than their corresponding technical potentials. In the four illustrative scenarios less than 2.5% of the global available technical RE potential is used (Figure SPM.11). In this sense, scenario results confirm that technical potentials will not to be the limiting factors for the expansion of RE on a global scale.



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

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

**Figure SPM.13.** Regional breakdown of RE deployment in 2050 for an illustrative set of four scenarios and comparison of the potential deployment to the corresponding technical potential for different technologies. The selected four illustrative scenarios are a part of the comprehensive survey of 164 scenarios. They represent a span from a reference scenario (WEO 2009) without specific mitigation target to three scenarios representing different $CO_2$ concentration categories, one of them (REMind) Category III (440-485 ppm) and two of them (MiniCAM and Energy

[R]evolution) Category I (<400ppm). From the latter MiniCAM includes nuclear energy and CCS as mitigation options and allows overshoot to get to the concentration level, while Energy [R]evolution follows an optimistic application path for RE [10.3]. Transition economies are countries which changed from a former centrally planned economy to a free market system. [Excerpt from Figure 10.19, 10.3.2.2]

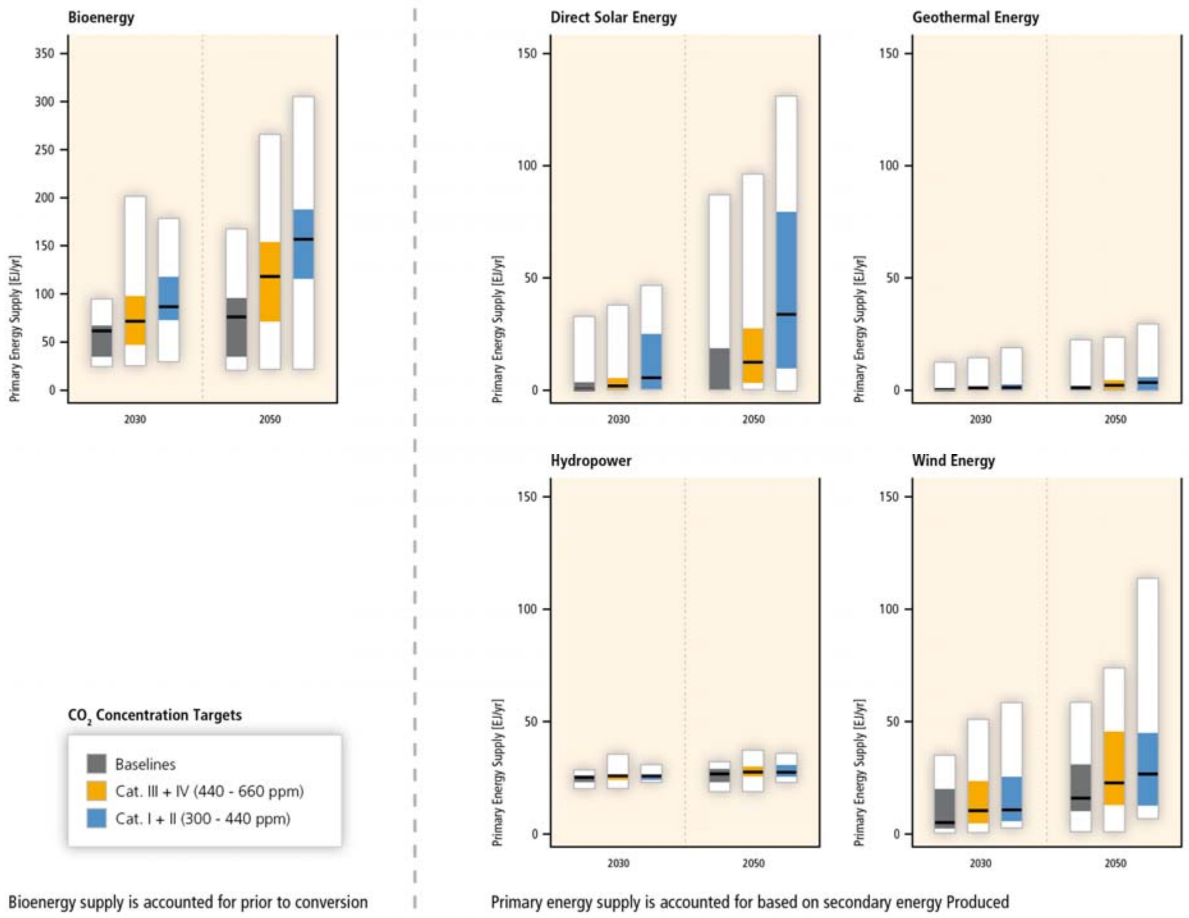


**Figure SPM.14.** Global primary energy supply (direct equivalent) of biomass, wind, solar, hydro, and geothermal energy in 164 long-term scenarios in 2030 and 2050, and grouped by different categories of atmospheric CO2 concentration level in 2100 (Fisher et al., 2007). The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. [Excerpt of Figure 10.9, 10.2.2.5]

Notes: One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as biofuels, electricity and heat, thus conversion factors are considered. The other technologies produce primarily (but not entirely) electricity and heat, and they are accounted for based on this secondary energy produced. If primary equivalents based on the substitution method were used rather than direct equivalent accounting, then energy production from non-biomass RE would be on the order of two to three times larger than shown here. Ocean Energy is not presented here as scenarios so far seldom consider this RE technology.

***Individual studies indicate that the absence of RE as a mitigation option will increase mitigation costs*** *[10.2].* A number of studies have pursued scenario sensitivities that assume constraints on the deployment of individual mitigation options, including RE as well as nuclear and fossil energy with

CCS. These studies indicate that mitigation costs are higher when options, including RE, are not available. They also indicate that more ambitious GHG concentration goals may not be achievable when RE options are not available.

***Assessing the corresponding costs of future paths would benefit from considering the whole range of costs including external costs*** [10.6]. Literature on scenarios normally does not take into consideration the external costs (dominated typically by climate change and health impacts due to air pollution) of different energy technologies. Although the uncertainty is relatively high, the external costs of RE technologies have usually been reported at a lower cost level compared to fossil supply options.

## 7. Policy, Implementation and Financing

***An increasing number and variety of RE policies—motivated by a variety of factors—have driven substantial growth of RE technologies in recent years*** (see Figures SPM.15 and SPM.4) [1.4, 11.1, 11.4, 11.5]. Energy access is the primary driver in developing countries whereas energy security and environmental concerns have been most important in developed countries [9.3, 11.3]. The focus of policies is broadening from a concentration almost entirely on RE electricity to include RE heating and transportation [11.2, 11.5].

***RE policies have promoted an increase in RE shares by helping to overcome various barriers that impede technology development and deployment of RE*** [1.4, 11.1, 11.4, 11.5]. Barriers to RE include information and awareness barriers related to lack of RE data, lack of human engineering or knowledge capacity, and public or institutional awareness; land use barriers; institutional barriers related to existing infrastructure, regulation of the energy system and intellectual property concerns; and market failures and economic barriers that are typified by market structure and cost-based issues [1.4].

There are two market failures particularly pertinent to RE: 1) research and development, innovation, diffusion and deployment of low-carbon technologies such as RE create benefits to society beyond those captured by the innovator, leading to under-investment in such efforts. 2) Prices set on externalities of fossil fuels are either insufficient to enable deployment of low-carbon technologies or inadequate to internalize all costs, including those associated with $CO_2$ emissions. [11.1.1]

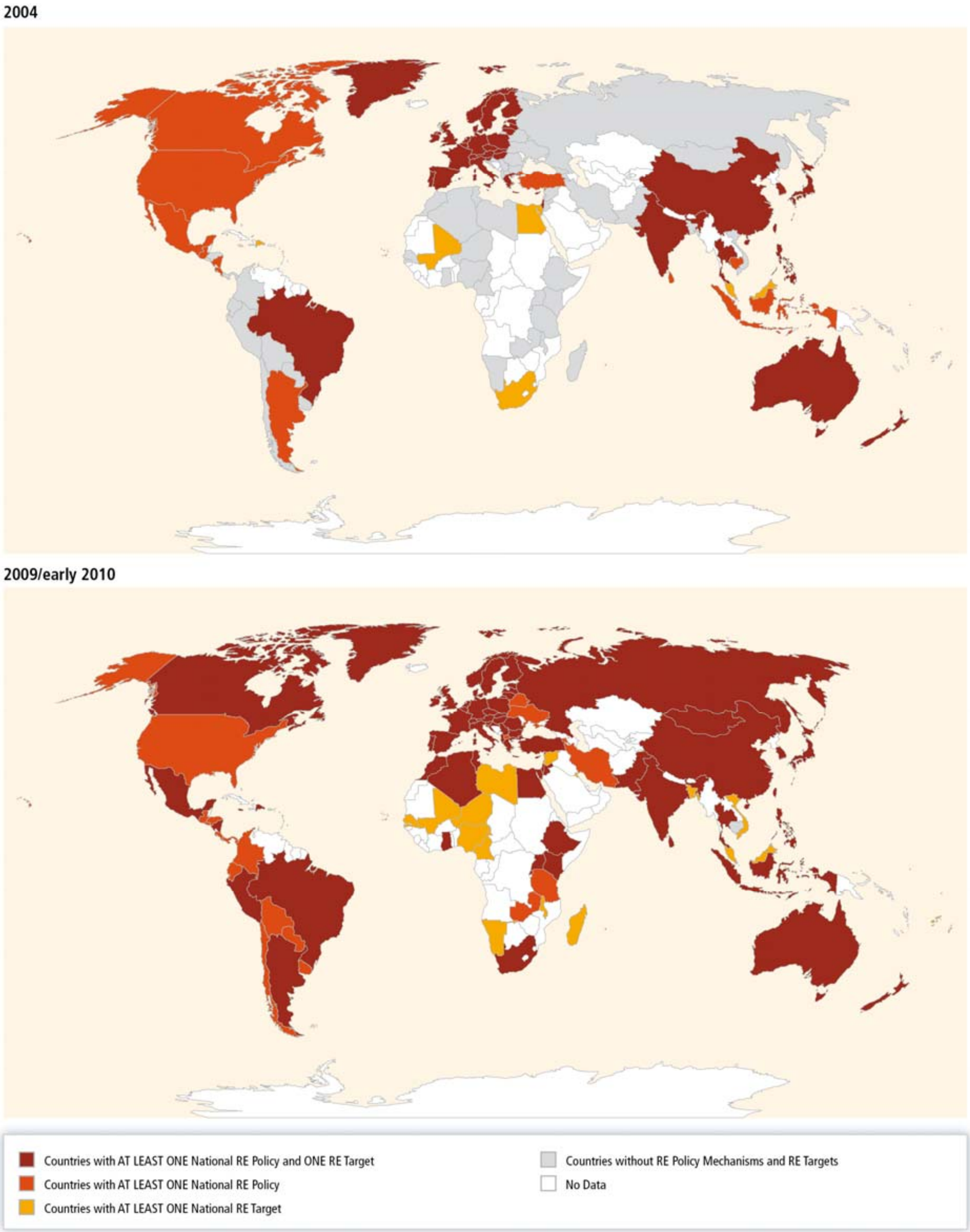


**Figure SPM.15.** Countries with RE targets and/or two or more RE policies, mid-2004 and 2009/early 2010. [Figure 11.1, 11.2]

***A shift to a low-carbon economy based largely on RE will require additional policies to attract significant increases in investment in technologies and infrastructure.*** The four illustrative scenarios that were analyzed in detail estimate global investments ranging from 1360 to 5100 billion $USD_{2005}$ for the decade 2011 to 2020, and from 1490 to 7180 billion $USD_{2005}$ for the decade 2021 to 2030. These investments will need to come from a wide spectrum of financiers. Due to avoided fuel costs and decreased investment needs for non-RE technologies, the additional costs of a future system with increasing shares of RE—compared to business-as-usual—are considerably lower than the aforementioned investment needs. Moreover, further deployment of RE technologies will result in new market opportunities for RE suppliers. [10.5]

***Policy mechanisms enacted specifically to promote RE are varied and can apply to all energy sectors.*** They include fiscal incentives such as grants and tax credits; public finance policies such as as low-interest loans; and regulations such as quantity-driven policies like quotas and price-driven policies including feed-in tariffs for electricity; mandates for RE heating installations, and biofuels blending requirements. Policies can be enacted by local, state/provincial, national, regional and international authorities. [11.5]

***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.

***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 are also important.*** 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 can 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 policy(ies) that are used [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 [11.2, 11.4, 11.5].

***RE technologies can play a greater role in climate change mitigation 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. [11.6]

***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***. Impacts can be positive or negative, depending on policy choice, design, and the level of implementation (local, state or sub-national, national, regional or global). Negative effects would include the risk of carbon leakage and rebound effects, which need to be taken into account when designing policies. Conversely, RE can help reduce costs of mitigation, and putting a price on carbon can increase the competitiveness of RE. Several models suggest that an optimal portfolio of policies, including combined RE and carbon-pricing policies, can reduce $CO_2$ emissions at a lower social cost than any single policy can alone. [11.1, 11.5.7]

***If decision makers intend to increase the share of RE and, at the same time, to meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical.*** To achieve international climate mitigation targets that incorporate high shares of RE, a structural shift in today's energy systems-will be required over the next few decades. A structural shift might begin with a prominent role for energy efficiency in combination with RE, followed by the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning. [11.6, 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.

## 8. Advancing Knowledge about Renewable Energy

The body of scientific knowledge on RE and on the possible contribution of RE towards meeting climate change 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 change 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:

- Future cost and timing of RE deployment for GHG mitigation
- Realizable technical potential for RE on a regional and local level
- Technical and institutional challenges and costs of integrating diverse RE technologies into energy markets
- Comparative social and environmental impacts of RE and other energy technologies
- Opportunities for meeting the needs of developing countries with modern RE services
- Policy, institutional, and financial mechanisms to enable deployment of RE under wide variety of contexts

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