10 Mitigation Potential and Costs

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Executive Summary

Renewable energy (RE) has the potential to play an important and increasing role in achieving ambitious climate mitigation targets. Many RE technologies are increasingly becoming market competitive, although some innovative RE technologies are not yet mature, economic alternatives to non-RE technologies. However, assessing the future role of RE requires not only consideration of the cost and performance of RE technologies, but also an integrative perspective that takes into account the interactions between various forces and the overall systems behaviours.

An increasing number of integrated scenario analyses are available in the published literature. They are able to provide relevant insights into the potential contribution of RE to future energy supplies and climate change mitigation. A review of 164 scenarios from 16 different large-scale integrated models was conducted through an open call. Although a collection of scenarios from the literature does not represent a truly random sample suitable for rigorous statistical analysis, a scenario overview can provide some critical and strategic insights about the role of RE in climate mitigation, in spite of the uncertainties involved.

Although it is not possible to precisely link long-term climate goals and global RE deployment levels, RE deployment significantly increases in the scenarios with ambitious greenhouse gas (GHG) concentration stabilization levels. Ambitious GHG concentration stabilization levels lead on average to higher RE deployment compared to the baseline. However, for any given long-term GHG concentration goal, the scenarios exhibit a wide range of RE deployment levels. In scenarios that stabilize the atmospheric carbon dioxide (CO_2) concentration at a level of less than 440 ppm, the median RE deployment levels are 139 EJ/yr in 2030 and 248 EJ/yr in 2050, with the highest levels reaching 252 EJ/yr in 2030 and up to 428 EJ/yr in 2050. 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 carbon capture and storage (CCS)); fundamental 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 towards long-term goals (e.g., overshoot versus stabilization). However, despite the observed variation, the scenarios indicate that, all else being equal, more ambitious mitigation generally leads to greater deployment of RE.

The majority of the 164 recent scenarios indicate a substantial increase in the deployment of RE by 2030, 2050 and beyond. In 2008, total RE production stood at roughly 64 EJ/yr (12.9% of total primary energy supply) with more than 30 EJ/yr of this being traditional biomass. More than 50% of the scenarios project levels of RE deployment in 2050 of more than 173 EJ/yr reaching up to over 400 EJ/yr in some cases. Given that traditional biomass demand decreases in most scenarios, an increase in the production level of RE (excluding traditional biomass) anywhere from roughly three-fold to more than ten-fold is projected. The global primary energy supply share of RE differs substantially among the scenarios. More than half of the scenarios show a contribution from RE in excess of a 17% share of primary energy supply in 2030, rising to more than 27% in 2050. The scenarios with the highest RE shares reach approximately 43% in 2030 and 77% in 2050. In other words, it is likely that RE will have a significantly larger role (in absolute and relative numbers) in the global energy system in the future than today.

Even without efforts to address climate change RE can be expected to expand. Most baseline scenarios with no assumed climate mitigation policy show RE deployments significantly above the 2008 level of 64 EJ/yr—up to 120 EJ/yr by 2030. By 2050 many baseline scenarios reach RE deployment levels of more than 100 EJ/yr, in some cases up to about 250 EJ/yr. These substantial deployment levels result from a range of assumptions, including, for example, the assumption that energy service demand will continue to grow substantially throughout the century and assumptions about the ability of RE to contribute to increased energy access and the limited long-term availability of fossil resources. Other assumptions (e.g., improved costs and performance of RE technologies) render RE technologies increasingly economically competitive in many applications even in the absence of climate policy.

RE deployment significantly increases in scenarios with low GHG stabilization concentrations. Low GHG stabilization scenarios lead on average to higher RE deployment compared to the baseline. However, for any given long-term GHG concentration goal, the scenarios exhibit a wide range of RE deployment levels (Figure 10.2). In scenarios that stabilize atmospheric CO_2 concentrations at a level of less than 440 ppm, the median RE deployment level in 2050 is 248 EJ/yr (139 EJ/yr in 2030), with the highest levels reaching 428 EJ/yr by 2050.

Many combinations of low-carbon energy supply options and energy efficiency improvements can contribute to given low GHG concentration levels, with RE becoming the dominant low- carbon energy supply option by 2050 in the majority of scenarios. Ambitious GHG concentration stabilization levels lead, on average, to higher RE deployment compared to the baseline, with above 400 EJ/yr by 2050 as the upper limit of RE deployment. Many scenarios were constructed as sensitivities with explicit limits on the deployment of nuclear energy and CCS, and RE played an increasingly important role in these scenarios. Yet even in scenarios with no explicit limits on these competing low-carbon options, RE often represents well over 50% of the global primary energy supply.

Scenarios generally indicate that growth in RE will be widespread around the world. Although the precise distribution of RE deployment across regions substantially varies across scenarios, they are largely consistent in indicating widespread growth in RE deployment around the globe. In addition, scenarios suggest that RE deployment levels will be higher over the long term in the group of non-Annex I countries than in the group of Annex I countries, 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.

Scenarios do not indicate an obvious single dominant RE technology at a global level. Besides the aspect that all RE obtains a more important role in the scenarios over time, a general trend is that bioenergy (predominantly modern biomass), wind energy and solar energy are commonly characterized by the largest contributions to the energy system among RE technologies by 2050.

Individual studies indicate that if RE deployment is limited, mitigation costs increase and low GHG stabilization concentrations may not be achieved. 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, but there is little agreement on the precise magnitude of the increase in costs. They also indicate that more ambitious GHG concentration goals may not be achievable when RE options are not available.

An in-depth analysis of four selected illustrative scenarios from the larger set of 164 scenarios allowed a more detailed look at the possible contribution of specific RE technologies in different regions and sectors. Even within this smaller set, the role of RE varies substantially, in part because the scenarios are aimed at different long-term climate goals, and because they are based on different assumptions about technology costs and also on distinct scenario methodologies.

In the four representative scenarios, the RE-based electricity generation develops most quickly, at least in the medium term, followed by RE for heating/cooling and transport. For RE-based electricity generation, the highest market shares are expected in the analyzed time span. In contrast, currently the heating sector in many regions of the world is one of the most dominant demand sectors. Its RE share is high, especially in non-Annex I countries, but it is mainly based on traditional bioenergy. The total share of RE-based electricity production for the four illustrative scenarios varies for the year 2050 (2030) from 24% (20%) up to 95% (61%) (cf. 19% RE-based electricity share in 2008). The corresponding range for the contribution of RE to the heating sector for these four scenarios lies for the year 2050 (2030) between 21% (20%) and 91% (49%). In most of the scenarios the heating and, particularly, the transport sector are less highlighted, showing that more importance should be given to thermal and transport RE applications in future studies.

Scenarios indicate that overall global technical potentials will not constrain the future contribution of RE. Although deployment of the different RE 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, for instance, despite significant technological and regional differences less than 2.5% of the global available technical RE potential is used. In this sense, scenario results confirm that technical potentials will not be the limiting factors for the expansion of RE on a global scale.

Increasing sectoral shares of RE can substantially contribute to GHG mitigation. The four in-depth analyzed illustrative scenarios span a range of global cumulative CO_2 savings, from about 220 to 560 Gt CO_2 between 2010 and 2050 compared to about 1,530 Gt CO_2 cumulative fossil and industrial CO_2 emissions in the IEA World Energy Outlook 2009 Reference Scenario during the same period. The precise attribution of mitigation potentials to RE not only depends on the role scenarios attribute to specific mitigation technologies, but also on complex systems behaviours and, in particular, on the energy sources that RE displaces. Therefore, attribution of precise mitigation potentials to RE should be viewed with appropriate caution.

Scenarios often do not directly associate mitigation potentials with different technological options. Instead, abatement cost curves are often used to discuss and to compare different mitigation strategies. Abatement cost curves and energy supply curves are an approach that is very often used for discussing mitigation strategies and prioritizing abatement options. One of the most important strengths of this method is that the results can be understood easily and that the outcomes of these methods give, at first glance, a clear orientation as they rank available options in order of cost-effectiveness. On the other hand, abatement cost curves have important limitations. In contrast to scenario analysis, they are not able to reflect the complex system behaviour and corresponding interdependencies. Thus they have to rely on simplified assumptions about the substituted non-RE supply and corresponding emission factors. In general, it is very difficult to compare data and findings from RE abatement cost and supply curves, as there have been very few studies using a comprehensive and consistent approach and detailing their methodologies, and most studies use different assumptions. Many of the regional and country studies provide less than 10% abatement of the baseline CO_2 emissions over the medium term at abatement costs under around USD_{2005} 100/t CO_2. The resulting low-cost abatement potentials are quite low compared to the reported mitigation potentials of many of the scenarios reviewed here.

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

In the field of RE, significant opportunities exist to further improve the energy efficiencies, and/or to decrease the costs of producing and installing the respective technologies. Together, these effects are expected to decrease the levelized cost of energy of many innovative RE-sourcing technologies in the future. Over time, energy generation costs of many RE technologies have shown significant declines. In general, historical cost decreases can be described by experience curves with global learning rates (the relationship between the reduction in cost and a doubling of production).

To realize the learning effects and to allow an increase in the competitiveness of RE technologies, upfront investments in deployment, as well as research and development, will be needed, which will result in new market opportunities for RE suppliers. The four illustrative scenarios analyzed in detail in this Special Report estimate global cumulative RE investments (in the power generation sector only) ranging from USD_{2005} 1,360 to 5,100 billion for the decade 2011 to 2020, and from USD_{2005} 1,490 to 7,180 billion for the decade 2021 to 2030. The lower values refer to the IEA World Energy Outlook 2009 Reference Scenario and the higher ones to a scenario that seeks to stabilize atmospheric CO_2 (only) concentration at 450 ppm. The annual averages of these investment needs are all smaller than 1% of the world's gross domestic product (GDP). The average annual investments in the reference scenario are slightly lower than the respective investments reported for 2009. Between 2011 and 2020, the higher end of the range of the annual averages of the RE electricity sector investments approximately correspond to a three-fold increase in the current global investments in this field. For the next decade (2021 to 2030), a five-fold increase is projected.

Increasing the installed capacity of RE power plants will reduce the amount of fossil and nuclear fuels that otherwise would be needed in order to meet a given electricity demand. In addition to investment, operation and maintenance (O&M) and (where applicable) feedstock costs related to RE power plants, any assessment of the overall economic burden that is associated with their application will therefore have to consider avoided fuel and substituted investment costs as well.

Assessments of the costs of future paths of RE deployment and mitigation have to consider the whole range of costs, including external costs and co-benefits. Literature on long-term scenarios does not normally take into consideration external costs (dominated typically by climate change and health impacts due to air pollution) of different energy technologies. Although the uncertainty is relatively high, in most cases RE sources have rather low external costs assessed on a lifecycle basis when compared to fossil fuel-based technologies. Particularly, the external costs of RE-based power generation technologies have most frequently been reported as being lower than those of fossil supply options.

In summary, scenarios strongly indicate that RE will become increasingly important over time, even without but particularly with GHG emissions constraints. However, the resulting contribution of RE in the various studies available in the literature is much lower than their corresponding technical potentials. Moreover, even if substantial growth rates are combined with future RE deployment paths, they are, in general, lower than what has been achieved by the RE industry during the past 10 years.

10.1 Introduction

The evolution of future GHG emissions is highly dependent on various future factors, including, among other things, economic growth, population growth, the associated demand for energy, energy resources and the future costs and performance of energy supply and end use technologies (IPCC, 2007; Chapter 1). Not only must all these different forces be considered when exploring the role of RE in climate mitigation, but also it is not possible to know today with any certainty how these different key forces might evolve decades into the future. Against that background, this chapter discusses the mitigation potentials and costs of RE technologies with a particular focus on a systems perspective and on an explicit consideration of the wide range of ways in which these various forces may evolve and shape the future.

Section 10.2 provides context for understanding the role of RE in climate mitigation through the review of 164 medium- to long-term scenarios from large-scale, integrated models. The review explores the range of global RE deployment levels emerging in recent scenarios and identifies some of the key forces that drive the variation among them. It does so at the scale of RE as a whole, but also in the context of individual RE technologies. The review highlights the importance of interactions and competition with other mitigation technologies as well as the evolution of energy demand more generally. Section 10.2 also considers the linkage between RE and mitigation costs in scenarios, and ends with a discussion, gleaned from Chapters 2 through 7, of the factors that might influence the ability to meet the deployment levels achieved in scenarios (e.g., technology and economic aspects).

Section 10.3 complements the large-scale review with a more detailed review using 4 of the 164 scenarios as illustrative examples. The four scenarios span a range from a more baseline-oriented future development of RE to optimistic expectations about RE's future, and cover different GHG stabilization levels and underlying modelling methodologies. This section provides a next level of detail for exploring the role of RE in climate change mitigation. Section 10.3 provides the details of particular futures, giving more minute treatment to the regional and sectoral (e.g., power generation, heating, cooling, transport) character of RE deployment. Within this more detailed context, it considers such issues as required generation capacity, annual growth rates and estimates of the corresponding mitigation potentials of RE deployment. Additionally, and as another perspective on scenario results, Section 10.3 uses the methodology of supply cost curves to give a sense of how RE technologies are deployed in the four scenarios as a function of costs.

In this context, particularly for comparing RE with non-RE technologies or even biomass with other RE technologies, it is important to note that the direct equivalent method is used to calculate primary energy in this chapter and throughout this report. In comparison to other conventions, this approach tends to indicate lower primary energy shares for RE than other primary equivalent approaches (see Box 1.1 in Chapter 1 for further details).

Section 10.4 provides a more general discussion about cost curves. It starts with an assessment of the strengths and shortcomings of supply curves for RE and GHG mitigation, and then reviews the existing literature on regional RE supply curves, as well as abatement cost curves, as they pertain to mitigation using RE sources. The second part of the section includes a summary of technology-specific supply and cost curves, including consideration of uncertainty.

Section 10.5 addresses the costs of RE commercialization and deployment. It reviews current RE technology costs, as well as expectations about how these costs might evolve into the future. Learning by research (triggered by research and development (R&D) expenditures) and learning by doing (fostered by capacity expansion programs) might result in a considerable long-term decline in RE technology costs. The section, therefore, presents historic data on R&D funding as well as on observed learning rates. In order to allow an assessment of future market volumes and investment needs, investments in RE are discussed in particular with respect to what is required if ambitious climate protection goals are to be achieved, and compared with investment needs in RE following more or less a baseline pathway. To provide a consistent thread throughout the chapter, the discussion of investment needs is based on the four illustrative scenarios that are explored in Section 10.3.

Finally, Section 10.6 expands the consideration of cost beyond standard measures of technology and mitigation costs. It synthesizes and discusses social and environmental costs and benefits from increased deployment of RE in relation to climate change mitigation and sustainable development; costs that are often not considered in scenarios, but are important for an overall assessment of different future paths. It builds on the discussions in Chapter 9, but it is more focused on economic aspects.

Gaps in knowledge and uncertainties associated with RE technical potentials and costs are discussed at the end of each of the sections of the chapter.

The following guiding questions were used to structure the development of insights and themes:

- What roles are RE sources likely to play in the future and particularly in contributing to GHG-mitigation pathways?
- What factors influence the possible deployment of RE sources in meeting GHG mitigation pathways (e.g., energy demand, cost and performance, competing mitigation options, barriers, social factors, co-benefits, policies)?
- What is the resulting role of RE regarding specific RE technologies, demand sectors and regions?
- How do possible RE deployment paths from the literature mesh with the technical potentials at global and regional levels?

- What are the costs of RE commercialization and deployment and what are the resulting investment needs for RE deployment?

- To what extent are the non-market costs and benefits relevant for social and environmental factors?

- How uncertain are the possible answers to all these questions, and what are the robust findings despite all uncertainties involved?

10.2 Synthesis of mitigation scenarios for different renewable energy strategies

This section reviews 164 recent medium- to long-term scenarios from 16 global energy-economic and integrated assessment models. These scenarios are among the most sophisticated explorations of how the future might evolve to address climate change; as such, they provide a window into current understanding of the role of RE technologies in climate mitigation.

The discussion in this section is motivated primarily by three strategic questions. First, what RE deployment levels are consistent with different CO_2 concentration goals; or, put another way, what is the linkage between CO_2 concentration goals and RE deployments? Second, over what time frames and where will RE deployments occur and how might that differ by RE technology? Third, how do the costs of mitigation relate to RE deployments and the availability, cost and performance of RE?

(Note that Sections 10.2.1 and 10.2.2 rely heavily on, and largely follow, Krey and Clarke (2011), in terms of both analysis and discussion. Krey and Clarke's (2011) publication was produced in parallel with this report. It provides a more thorough and extensive review and discussion of the methodology and results of an analysis of 162 of the 164 scenarios reviewed in this section.)

10.2.1 State of scenario analysis

10.2.1.1 Types of scenario methods

The climate change mitigation scenario literature largely consists of two distinct approaches to scenario development: quantitative modelling and qualitative narratives (see Morita et al., 2001; Fisher et al., 2007 for a more extensive review). Several attempts have also been made to integrate narratives and quantitative modelling approaches (IPCC, 2000; Morita et al., 2001; Carpenter et al., 2005). The review in this section exclusively relies on scenarios developed through quantitative modelling. These scenarios provide estimates of RE deployments and other important parameters for understanding the role of RE in climate mitigation, and they do so based on models that follow a systems approach and thus explicitly and formally represent the interactions between RE technologies, other mitigation technologies and the various other factors that influence the characteristics of mitigation.

Although all of the scenarios in this review were developed using quantitative modelling, it is important to observe that there is enormous variation in the detail and structure of the models used to construct the scenarios. Many authors have, in the past, attempted to categorize models as either bottom-up or top-down. For several reasons (see Box 10.1), this review will not rely on the top-down/bottom-up taxonomy. Instead, the models are referred to generically as large-scale, integrated models. The important methodological characteristics of the scenarios reviewed in this section, and the models used to generate them, are: (1) they take an integrated view of the energy system so that they can

Box 10.1 | Moving beyond top-down versus bottom-up?

In previous IPCC reports (e.g., Herzog et al., 2005; Barker et al., 2007), quantitative scenario modelling approaches were broadly separated into two groups: top-down and bottom-up. Although this classification may have made sense in the past, recent developments make it decreasingly appropriate. Most importantly, (i) the transition between the two categories is continuous, and (ii) many models, although rooted in one of the two traditions (e.g., macro-economic or energy-engineering models), incorporate important aspects of the other approach and thus belong to the class of so-called hybrid models (Hourcade et al., 2006; van Vuuren et al., 2009).

In addition, the terms top-down and bottom-up can be misleading, because they are context dependent and used differently in different scientific communities. For example, in previous IPCC assessments, all integrated modelling approaches were classified as top-down models regardless of whether they included significant technology information (van Vuuren et al., 2009). In the energy-economic modelling community, macro-economic approaches are traditionally classified as top-down models and energy-engineering models as bottom-up. However, in engineering sciences, even the more detailed energy-engineering models that represent individual technologies such as power plants, but essentially treat them as 'black boxes', are characterized as top-down models because they do not assume a component-based view, which would be considered bottom-up. For these reasons, the modelling tools used to generate scenarios in this review are simply referred to as large-scale, integrated models.

capture the interactions, at least at an aggregate scale, between competing energy technologies; (2) they have a basis in economics in the sense that decision making is largely based on economic criteria; (3) they are long-term and global in scale, but with some regional detail; (4) they include the policy levers necessary to meet emissions outcomes; and (5) they have sufficient technology detail to explore RE deployment levels at both regional and global scales. Many also have integrated views beyond the energy system, for example, fully coupled models of agriculture and land use.

10.2.1.2 Strengths and weaknesses of quantitative scenarios

Scenarios are a tool for understanding, but not predicting, the future. They provide a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships (IPCC, 2007). In the context of this report, scenarios are thus a means to explore the potential contribution of RE to future energy supplies and to identify the drivers of renewable deployment.

The benefit of scenarios generated using large-scale, integrated models, such as those reviewed in this section, is that they capture many of the key interactions with other technologies (including competing mitigation technologies such as fossil energy with CCS, nuclear energy and demand reduction options), other parts of the energy system, other relevant human systems (e.g., agriculture, the economy as a whole) and important physical processes associated with climate change (e.g., the carbon cycle), that serve as the environment in which RE technologies will be deployed. This integration provides an important degree of internal consistency. In addition, they explore these interactions over at least several decades to a full century into the future and at a global scale. This degree of spatial and temporal coverage is crucial for establishing the strategic context for RE.

The design, assumptions and focus of the scenarios covered in this assessment vary greatly: some are based on a more detailed representation of individual renewable and other energy technologies and aspects of systems integration of RE, while others focus on the implications of RE deployment for the economy as a whole. This variation in methods, assumptions and focus provides a window into the deep uncertainties associated with future dynamics of the energy system and the role of RE sources in climate change mitigation.

As discussed in Krey and Clarke (2011), two important caveats must be kept in mind when interpreting the scenarios in this section. First, maintaining a global, long-term, integrated perspective involves tradeoffs in terms of detail. For example, the models do not represent all the forces that govern decision making at the national or even the company or individual scale, in particular in the short term. Further, these are not power system models or engineering models, and they therefore employ stylized representations of many details that influence the performance and deployment of RE, for example, the challenges of incorporating variable electricity generation into the electric grid. The level of sophistication in representing these details varies substantially across models. An outcome of these simplifications is that integrated global and regional scenarios are most useful for the medium- to long-term outlook, say 2020 onwards. For shorter time horizons, tools such as market outlooks or short-term national analyses that explicitly address all existing policies and regulations are more suitable sources of information.

Second, the scenarios do not represent a random sample of possible scenarios that could be used for formal uncertainty analysis. They were developed for different purposes and are not a set of 'best guesses'. Many of the scenarios represent sensitivities, particularly along the dimensions of future technology availability and the timing of international action on climate change, and are therefore related to one another. Some modelling groups provided substantially more scenarios than others. In scenario ensemble analyses based on collecting scenarios from different studies, such as the review here, there is a constant tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into our collective lack of knowledge about the future.

10.2.2 The role of renewable energy sources in scenarios

10.2.2.1 Overview of the scenarios reviewed in this section

The 164 scenarios reviewed in this section were collected through an open call to modellers for RE data from recently published scenarios. All scenarios that were submitted were included in the review. The bulk of the scenarios in this assessment (see Table 10.1) come from three coordinated, multi-model studies: the Energy Modeling Forum (EMF) 22 international scenarios (Clarke et al., 2009), the Adaptation and Mitigation Strategies (ADAM) project (Knopf et al., 2009; Edenhofer et al., 2010) and the Report on Energy and Climate Policy in Europe (RECIPE) comparison (Edenhofer et al., 2009; Luderer et al., 2009). These three exercises harmonize some scenario dimensions, such as baseline assumptions or climate policies, across the participating models. The remaining scenarios come from individual publications. Although the 164 scenarios are clearly not exhaustive of recent literature, nor do they represent a truly random sample, the set is large and extensive enough to provide robust insights into current understanding of the role of RE in climate change mitigation.

The full set of scenarios covers a large range of CO_2 concentrations (350 to 1,050 ppm atmospheric CO_2 concentration by 2100, see Table 10.2), representing both mitigation and no-policy, or baseline, scenarios. The full set of scenarios also covers the time horizon 2050 to 2100, and all of the scenarios are global in scope.

There are several characteristics of the scenarios included in this review that make them particularly valuable for this discussion. First, they come from the most recent work of the integrated modelling community;

all of the scenarios in this study were published during or after 2006. The scenarios therefore reflect the most recent understanding of key underlying parameters and the most up-to-date representations of the dynamics of the underlying human and Earth systems. The scenarios are also valuable in that they include a relatively large number of scenarios that represent less optimistic views on international action to deal with climate change (second-best policy) or address consequences of limited technology portfolios (constrained technology). The assumptions regarding second-best policy vary considerably across the scenarios, but are mostly taken from the EMF 22 study (Clarke et al., 2009) and the RECIPE project (Edenhofer et al., 2009; Luderer et al., 2009) and capture delayed action by developing countries. Technology availability is not defined homogenously across all scenarios in the analyzed set, but the limited technology portfolio studies that are highlighted here are those with limitations on the deployment of fossil energy with CCS, nuclear energy and RE. Finally, data regarding RE deployment were collected at a level of detail beyond that found in most published papers or existing scenario databases, for example, those compiled for IPCC reports (Morita et al., 2001; Hanaoka et al., 2006; Nakicenovic et al., 2006). Whereas RE deployment information was often collected in the past in terms simply of bioenergy and non-biomass renewable sources, the data reviewed here explicitly include information on the deployment of wind energy, solar energy, bioenergy, geothermal energy, hydroelectric power and ocean energy.

10.2.2.2 Overview of the role of renewable energy in the scenarios

A fundamental question relating to the role of RE in climate mitigation is how closely correlated are RE deployment levels and long-term climate concentration or related climate goals. As background to understanding the relationship of RE deployments to climate goals, it is important to first observe that, consistent with past scenario literature (Fisher et al., 2007), there is a strong correlation between fossil and industrial CO_2 emissions pathways and long-term CO_2 concentration goals across the

Table 10.1 | Energy-economic and integrated assessment models considered in this analysis. The total number of scenarios per model varies significantly. Scenarios are further classified by the inclusion of delayed participation in mitigation (second-best policy) and constraints on and/or variations in the deployment of fossil energy with CCS, nuclear energy and RE (constrained technology). Adapted from Krey and Clarke (2011), modified to include IEA (2009) and Teske et al. (2010).

Model	Number of scenarios	Baseline scenarios	Policy Scenarios				Comparison project	Citation
			First best	Constrained technology[1]	Second-best policy	Constrained technology & second-best policy		
AIM/CGE	3	1	1	0	1	0	—	Masui et al. (2010)
DNE21	7	1	3	3	0	0	—	Akimoto et al. (2008)
GRAPE	2	1	1	0	0	0	—	Kurosawa (2006)
GTEM	7	1	4	0	2	0	EMF 22	Gurney et al. (2009)
IEA-ETP	3	1	2	0	0	0	—	IEA (2008b)
IEA-WEM	1	1	0	0	0	0	—	IEA (2009); extension to 2050, Teske et al. (2010)
IMACLIM	8	1	2	4	1	0	RECIPE	Luderer et al. (2009)
IMAGE	17	3	5	6	0	3	EMF 22 / ADAM	van Vuuren et al. (2007, 2010); van Vliet et al. (2009)
MERGE-ETL	19	4	3	12	0	0	ADAM	Magne et al. (2010)
MESAP/PlaNet	2	0	0	2	0	0	—	Krewitt et al. (2009); Teske et al. (2010)
MESSAGE	15	2	4	7	2	0	EMF 22	Riahi et al. (2007); Krey and Riahi (2009)
MiniCAM	15	1	5	4	3	2	EMF 22	Calvin et al. (2009)
POLES	15	4	3	8	0	0	ADAM	Kitous et al. (2010)
ReMIND	28	4	6	14	4	0	ADAM / RECIPE	Luderer et al. (2009); Leimbach et al. (2010)
TIAM	10	1	5	0	4	0	EMF 22	Loulou et al. (2009)
WITCH	12	1	4	4	3	0	EMF 22 / RECIPE	Bosetti et al. (2009); Luderer et al. (2009)
TOTAL	**164**	**27**	**48**	**64**	**20**	**5**		

Note: 1. While in the vast majority of constrained technology scenarios, the deployment of individual technologies or technology clusters has actually been constrained, in a few cases included under this category, the potential for bioenergy was expanded compared to the model's default assumption.

Table 10.2 | Categorization of the 164 scenarios reviewed in this section based on CO_2 concentration levels in 2100, the inclusion of delayed participation in mitigation (second-best policy), and constraints on and/or variations in the deployment of fossil energy with CCS, nuclear energy and RE. The CO_2 concentration categories are defined consistently with those in the IPCC Fourth Assessment Report (AR4), WGIII (Fisher et al., 2007). Note that Categories V and above are not included here and Category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100 and because the lowest baseline scenarios reach concentration levels of slightly more than 600 ppm by 2100.[1] Data adapted from Krey and Clarke (2011) modified to include two additional scenarios.

	CO_2 concentration by 2100 (ppm)	Number of scenarios	Policy Scenarios			
			First-best	Constrained technology	Second-best policy	Constrained technology & second-best policy
Baselines	>600	27	—	—	—	—
Category IV	485–600	32	11	13	6	2
Category III	440–485	63	20	29	11	3
Category II	400–440	14	7	6	1	0
Category I	<400	28	10	16	2	0

Note: 1. This definition of CO_2 concentration stabilization categories is consistent with that used in the AR4. Section 3.3.5 in Fisher et al. (2007) explains that most scenarios assessed in the AR4 stabilize concentrations between 2100 and 2150 while the definition used here is based on CO_2 concentrations in 2100. Stabilization after 2100 is typically relevant for scenarios with high CO_2 concentration targets, that is, Categories V and higher, which have not been assessed here and for very low stabilization scenarios in Category I that show a temporary overshoot in concentrations before reaching the final target. The latter does not influence the assignment to categories, since Category I is not bounded from below. In addition, it should be noted that CO_2 concentrations are affected by assumptions about the carbon cycle that may result in differences across models.

scenarios (Figure 10.1, as depicted by close grouping of the coloured categories). An important reason for this correlation is similarity across scenarios in assumptions regarding the key physical processes underlying the global carbon cycle. Any variation in emissions pathways reflects remaining differences in assumptions about the carbon cycle as well as assumptions regarding factors that determine the allocation of emissions over time in mitigation scenarios. This includes the rate of technological improvements, underlying drivers of emissions in general such as economic growth, and methodological approaches for allocating emissions over time, including discount rates and the choice of overshoot and not-to-exceed pathways.

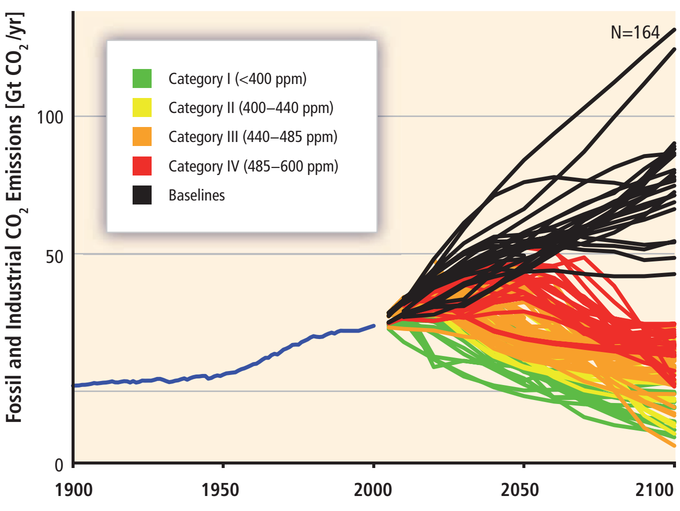


Figure 10.1 | Historic global fossil and industrial CO_2 emissions and projections from 164 long-term scenarios. Colour coding is based on categories of atmospheric CO_2 concentration in 2100 as defined in the IPCC AR4, WGIII (Fisher et al., 2007), with historic emission data from Nakicenovic et al. (2006). Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

The relationship between RE deployment and CO_2 concentration goals is far less robust (Figure 10.2). On the one hand, RE deployment is generally increasing with the stringency of the CO_2 concentration goal, particularly several decades into the future and beyond. In other words, all other things being equal, more stringent CO_2 concentration goals will generally lead to larger RE deployment. At the same time, there is enormous variation among RE deployment levels for any CO_2 concentration goal. This variation is a reflection of uncertainty regarding the precise role that RE might play in climate mitigation, illustrating a lack of consensus among scenario developers as to what degree of RE deployment would be associated with any particular climate goal.

At the same time, it is also important to note that despite the variation, the absolute magnitudes of RE deployment are dramatically higher than those of today in the vast majority of the scenarios. In 2008, global renewable primary energy supply in direct equivalent stood at 63.6 EJ/yr (IEA, 2010d),[1] with more than 30 EJ/yr of this being traditional biomass. In contrast, by 2030 many scenarios indicate a doubling of RE deployment or more compared to today, and this is accompanied in most scenarios by a reduction in traditional biomass, implying substantial growth in modern sources. By 2050, RE deployment levels in most scenarios are higher than 100 EJ/yr (median at 173 EJ/yr), reach 200 EJ/yr in many of the scenarios and more than 400 EJ/yr in some cases. Given that traditional biomass use decreases in most scenarios, the scenarios represent an increase in RE production (excluding traditional biomass) of anywhere from roughly three- to more than ten-fold. Similarly, the global primary energy supply share of RE differs substantially among

1 Note that there is a small difference from the value of 65.6 EJ published by the IEA (and shown in Figure 8.2) due to the different primary energy accounting methods used. See Box 1.1 in Chapter 1, Section 1.2.1 and Appendix A.II.4 for additional background on this topic.

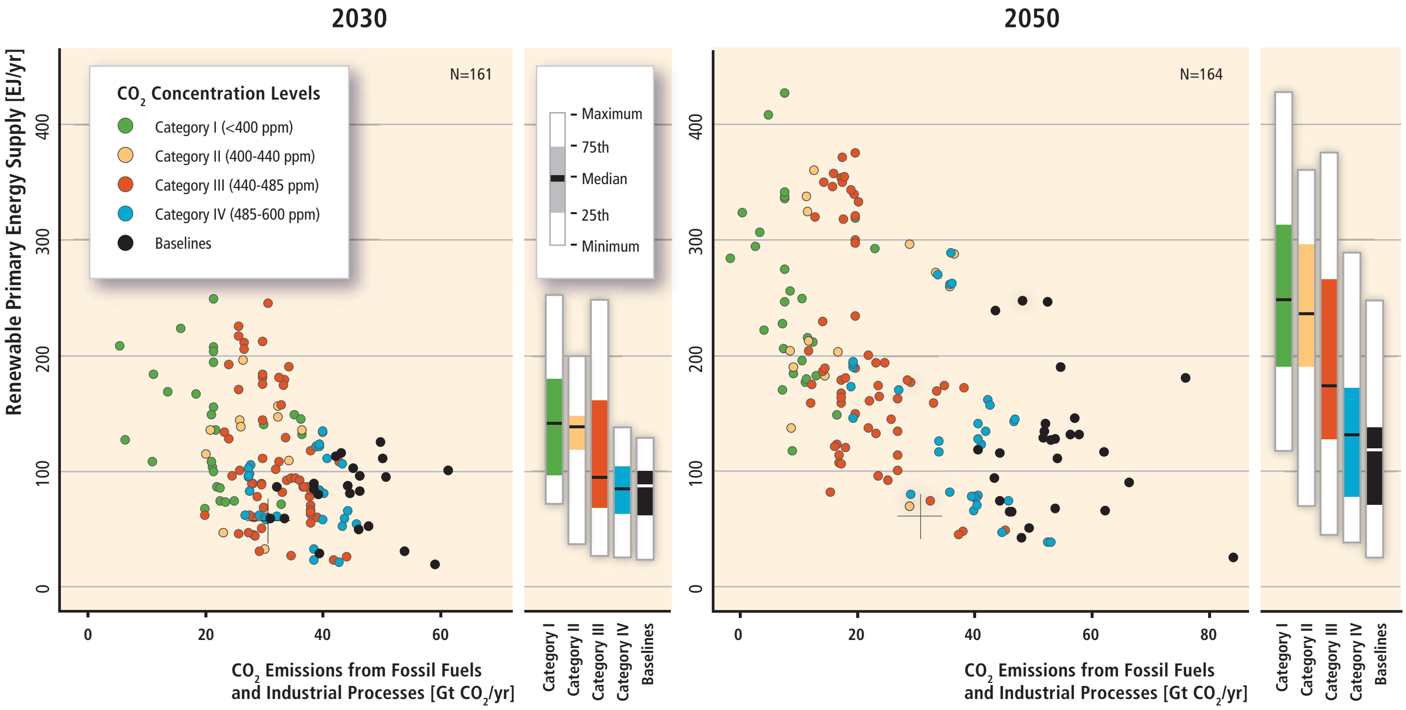


Figure 10.2 | Global RE primary energy supply (direct equivalent) from 164 long-term scenarios versus fossil and industrial CO_2 emissions in 2030 and 2050. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (Fisher et al., 2007). The panels to the right of the scatterplots show the deployment levels of RE in each of the atmospheric CO_2 concentration categories. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. The crossed-lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are -0.40 (2030) and -0.55 (2050). For data reporting reasons only, 161 scenarios are included in the 2030 results shown here, as opposed to the full set of 164 scenarios. RE deployment levels below those of today are a result both of model output as well as differences in the reporting of traditional biomass. Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

the scenarios. More than half of the scenarios show a contribution of RE in excess of a 17% share of primary energy supply in 2030, rising to more than 27% in 2050. The scenarios with the highest RE shares reach approximately 43% in 2030 and 77% in 2050. RE deployment levels in 2100 are substantially larger than these, reflecting continued growth throughout the century.

Indeed, RE deployment is quite large in many of the baseline scenarios; that is, scenarios without any explicit climate policy. By 2030, RE deployment levels of up to about 120 EJ/yr are projected, with many baseline scenarios reaching more than 100 EJ/yr in 2050 and in some cases up to 250 EJ/yr. These large RE baseline deployments result directly from the assumption that energy consumption will continue to grow substantially throughout the century and assumptions that render RE technologies economically competitive in many applications absent climate policy.

10.2.2.3 Setting the scale of renewable energy deployment: Energy system growth and long-term climate goals

Section 10.2.2.2 demonstrated the large variation in RE deployment levels across scenarios for a given CO_2 concentration goal. This section explores the variation primarily through the lens of energy system growth. Section 10.2.2.4 then explores the competition with other low-carbon energy supply sources.

A first step in unpacking the variation in RE deployment levels is to note that there is only a weak correlation between primary energy consumption and long-term climate goals across the 164 scenarios (Figure 10.2). For example, in scenarios that stabilize atmospheric CO_2 concentrations at a level of less than 440 ppm (Categories I and II), the median RE deployment levels are 139 EJ/yr in 2030 and 248 EJ/yr in 2050, with the highest levels reaching 252 EJ/yr in 2030 and up to 428 EJ/yr in 2050. These levels are considerably higher than the corresponding RE deployment levels in baseline scenarios, while it has to be acknowledged that the range of RE deployment in each of the CO_2 stabilization categories is wide. Although, all other things being equal, CO_2 mitigation puts downward pressure on total global energy consumption,[2] the magnitude of this effect is highly varied across scenarios, and often small enough so that there is far less correlation in the scenarios between total primary energy consumption and long-term climate goals (Figure 10.3) than there is for CO_2 emissions and long-term climate goals (Figure 10.1). In other words, the effect of mitigation on primary energy consumption is variable across models and scenarios. In addition, variation in primary energy consumption under mitigation is heavily influenced by variation in assumptions about the fundamental drivers of energy consumption, such as economic growth and associated demand for energy services, that drive baseline primary energy consumption. The variation results from

2 Note that this is not always true. Scenarios exist in which primary energy increases because of large-scale electrification in response to climate policy (see, e.g., Loulou et al., 2009).

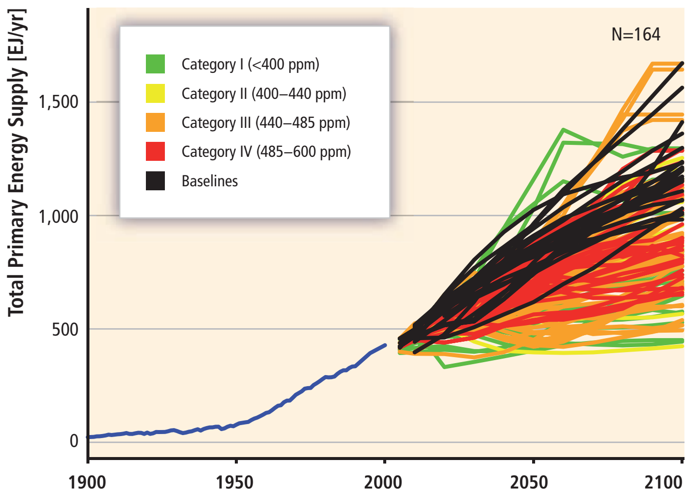


Figure 10.3 | Historic global total primary energy supply (direct equivalent) and projections from 164 long-term scenarios. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (Fisher et al., 2007), with historic data from Grubler (2008). Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

the lack of consensus about these fundamental drivers; these are forces that simply cannot be understood with any degree of certainty today.

In contrast to the variation in total primary energy, the production of freely-emitting fossil energy (fossil sources without CCS) is tightly constrained by CO_2 emissions at any point in time (Figure 10.4). Meeting long-term climate goals requires a reduction in the CO_2 emissions from energy and other anthropogenic sources. Important Earth systems, most notably the global carbon cycle, put bounds on the levels of CO_2 emissions that are associated with meeting any particular long-term goal; this, in turn, bounds the amount of energy that can be produced from freely-emitting fossil energy sources. Factors leading to remaining variation in freely-emitting fossil energy associated with a given level of CO_2 emissions include the ability to switch between fossil sources with different carbon contents (e.g., natural gas has a lower carbon content than coal per unit of energy) and the potential to achieve negative emissions by utilizing bioenergy with CCS (see Section 2.6.3.3) or forest sink enhancements. The relationship between CO_2 emissions and long-term goals is influenced by differences in the time path of emissions reductions over time as a result of differing underlying model structures, assumptions about technology and emissions drivers, and representations of physical systems such as the carbon cycle.

RE is only one of three major low-carbon supply options. The other two options are nuclear energy and fossil energy with CCS. The demand for low-carbon energy (the total of all three) is, in the context of the discussion here, simply the difference between total primary energy demand and the production of freely-emitting fossil energy (see Figure 10.5). That is to say, whatever energy cannot be supplied from freely-emitting fossil energy because of climate constraints must be supplied either by low-carbon energy or by measures that reduce energy consumption. Given, as discussed above, that the demand response from mitigation is swamped by variability in demand more generally across a scenario set such as the one explored here, the result is that although there is a strong correlation between the CO_2 concentration goal and low-carbon energy (see also Clarke et al., 2009; O'Neill et al., 2010), there is still

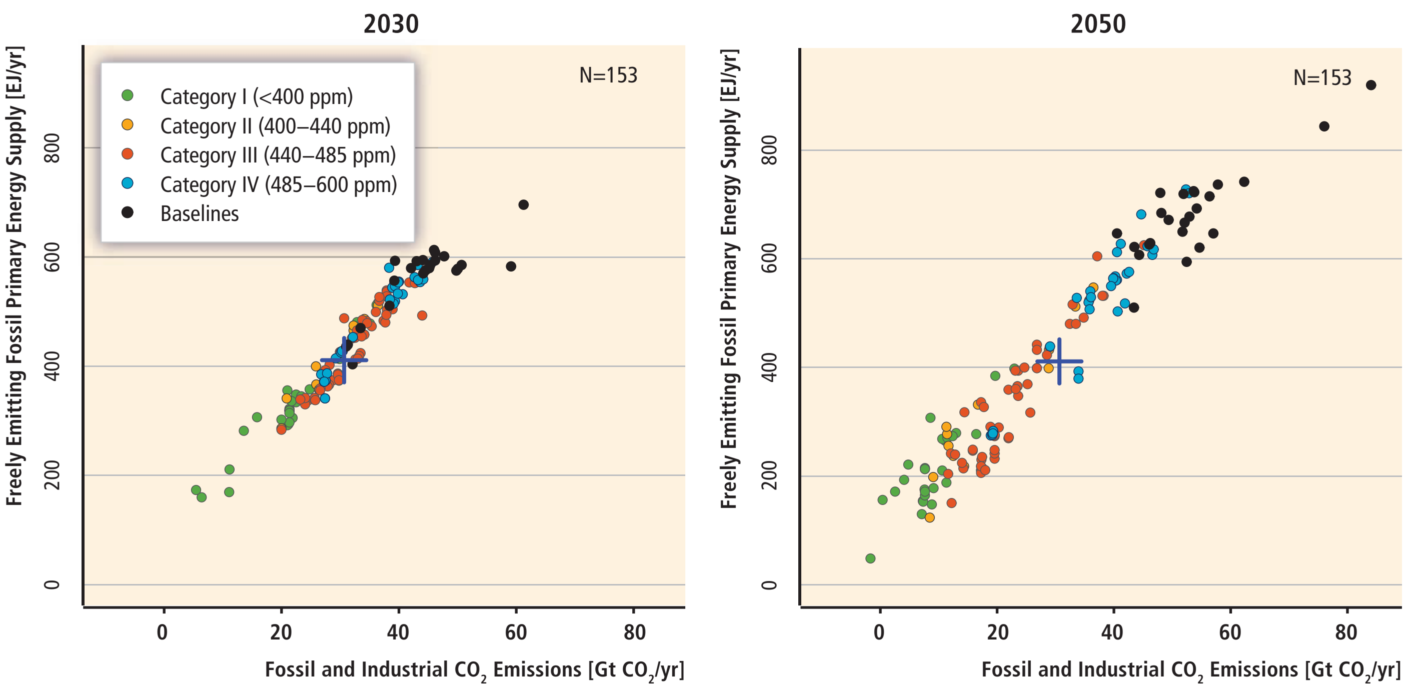


Figure 10.4 | Global freely-emitting fossil primary energy supply (direct equivalent) from 164 long-term scenarios by 2030 and 2050 as a function of fossil and industrial CO_2 emissions. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (Fisher et al., 2007). The blue crossed lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are 0.96 (2030) and 0.97 (2050). For data reporting reasons only 153 scenarios are included in the 2030 and 2050 results shown here, as opposed to the full set of 164 scenarios. Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

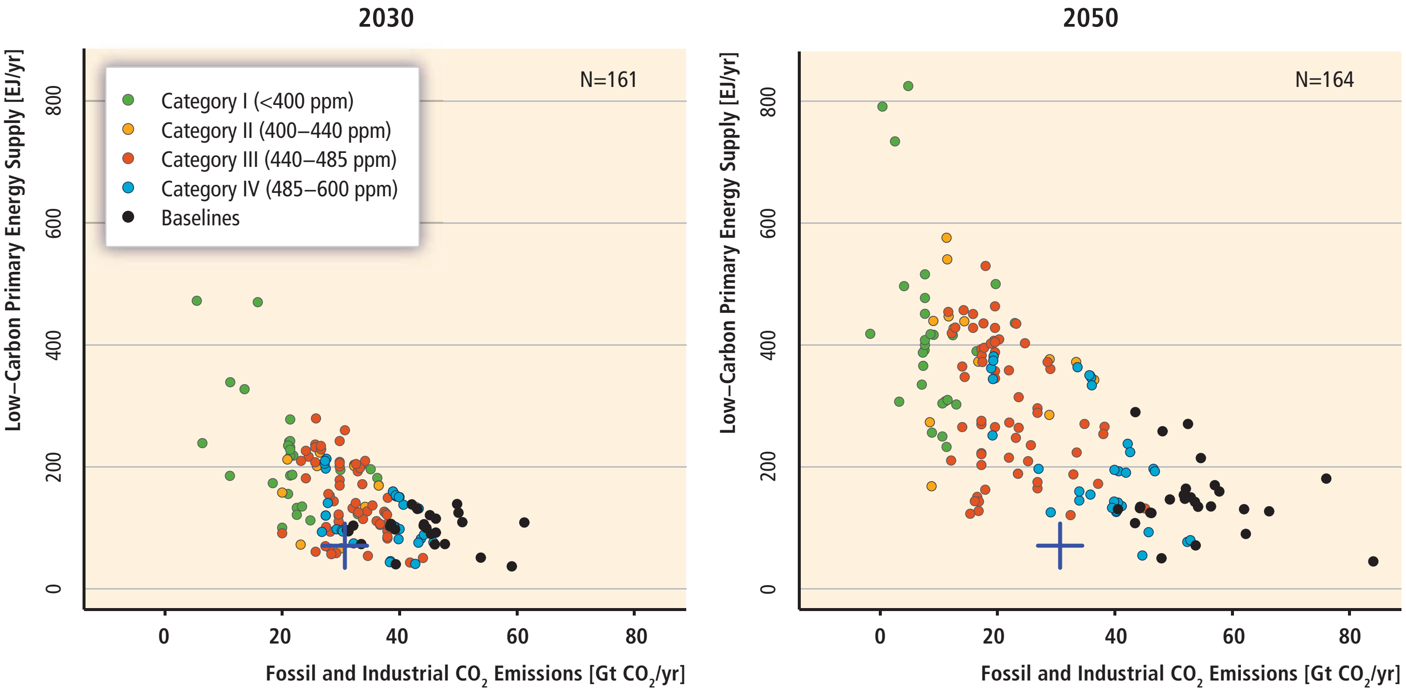


Figure 10.5 | Global low-carbon primary energy supply (direct equivalent) in 164 long-term scenarios by 2030 and 2050 as a function of fossil and industrial CO_2 emissions. Low-carbon energy refers to energy from RE, fossil energy with CCS, and nuclear energy. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (Fisher et al., 2007). The blue crossed lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are -0.60 (2030) and -0.68 (2050). For data reporting reasons, only 161 scenarios are included in the 2030 results shown here, as opposed to the full set of 164 scenarios. Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

substantial variability in low-carbon energy for any given CO_2 concentration goal. The competition between RE, nuclear energy and fossil energy with CCS then adds another layer of variability in the relationship between RE deployment and CO_2 concentration goal (Figure 10.2).

10.2.2.4 Competition between renewable energy sources and other forms of low-carbon energy

This section addresses the competition between RE and the two other low-carbon supply options: nuclear energy and fossil energy with CCS. Many of the 164 scenarios are characterized by explicit limits on the deployment of one or both of these two options. The constrained CCS scenarios simply excluded the option to install CCS either on new or existing power plants or other energy conversion facilities with fossil or bioenergy as an input (e.g., refining). The constrained nuclear energy scenarios take on three forms. Two approaches maintain nuclear deployments at or below today's levels, allowing existing power plants to retire over time and not allowing any new installations, or maintain the total deployment of nuclear at current levels, which might reflect either lifetime extensions or just enough new installations to counteract retirements. A third option applied in a number of scenarios is to maintain nuclear deployment over time in mitigation scenarios at baseline levels. The difficulty in interpreting this third category of scenarios is that nuclear energy expands to substantially different degrees across baseline scenarios, limiting comparability (see caption of Figure 10.6 for details).

All other things being equal, when competing options are not available or are otherwise constrained, RE deployments are higher (Figure 10.6). Two effects simultaneously contribute to the increase in the renewable primary energy share. First, with fewer competing options, RE will constitute a larger share of low-carbon energy. Second, higher mitigation costs resulting from the lack of options put downward pressure on total energy consumption, because end-use options become increasing economically attractive. The relative influence of these two forces varies across models.

At the same time, it is important to reemphasize that technology competition is only one factor influencing RE deployment levels; it cannot by itself explain the variation in RE deployments associated with different mitigation levels. The discussion to this point should make clear that for any mitigation level, the fundamental drivers of energy demand—economic growth, population growth, energy intensity of economic growth and energy end-use improvements—along with the technology characteristics of RE technologies themselves are equally critical drivers of RE deployments. Nonetheless, if environmental, social or national security barriers largely inhibit *both* fossil energy with CCS and nuclear energy, then it is appropriate to assume that RE will be required to provide the bulk of low-carbon energy (Figure 10.7). Independent of the availability of these non-renewable low-carbon energy supply options, the majority of scenarios relies to a greater extent on RE sources than on nuclear energy and fossil energy with CCS to provide low-carbon energy by 2050 (see upper left triangle of Figure 10.7). If only one of these options is limited, then the RE deployment

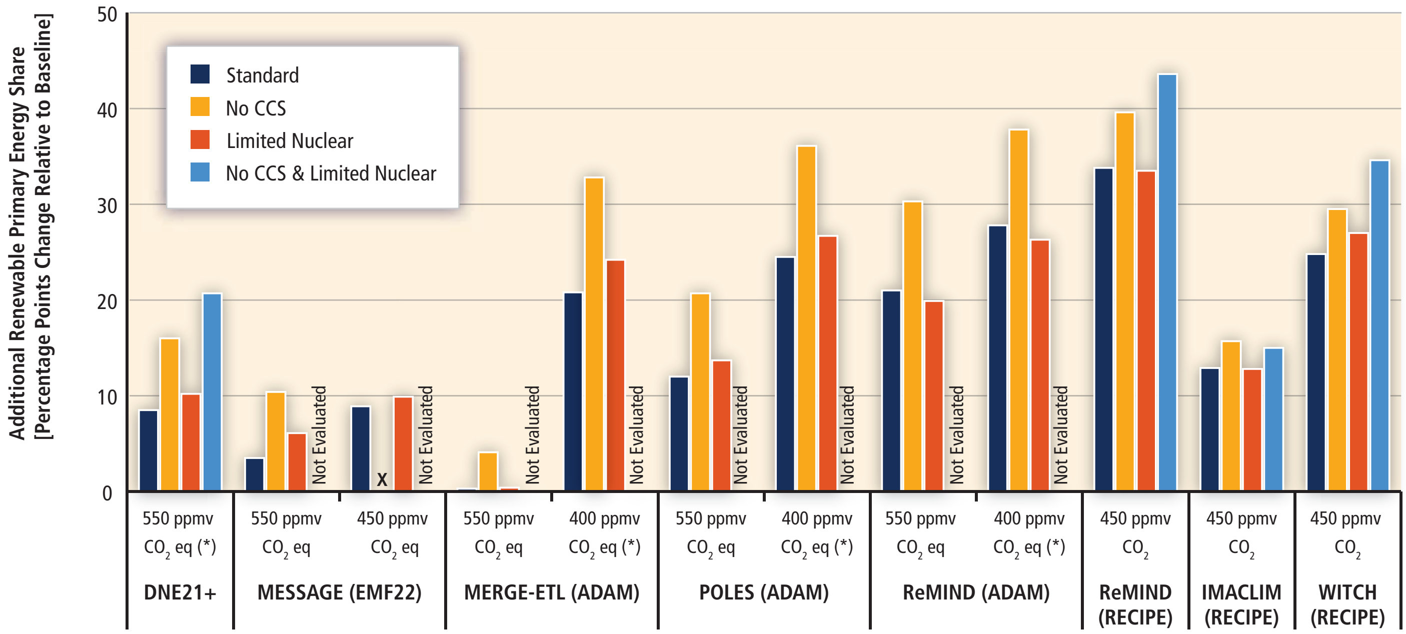


Figure 10.6 | Increase in global renewable primary energy share (direct equivalent) in 2050 in selected constrained technology scenarios compared to the respective baseline scenarios. The 'X' indicates that the respective concentration level for the scenario was not achieved. The definition of 'Limited Nuclear' and 'No CCS' cases varies across models. The DNE21+, MERGE-ETL and POLES scenarios represent nuclear phase-outs at different speeds; the MESSAGE scenarios limit the deployment to 2010; and the ReMIND, IMACLIM and WITCH scenarios limit nuclear energy to the contribution in the respective baseline scenarios, which can still imply a significant expansion compared to current deployment levels. The REMIND (ADAM) 400 ppm no CCS scenario refers to a scenario in which cumulative CO_2 storage is constrained to 120 Gt CO_2, The MERGE-ETL 400 ppm no CCS case allows cumulative CO_2 storage of about 720 Gt CO_2. The POLES 400 ppm CO_2eq no CCS scenario was infeasible and therefore the respective concentration level of the scenario shown here was relaxed by approximately 50 ppm CO_2. The DNE21+ scenario is approximated at 550 ppm CO_2eq based on emissions pathways through 2050. Figure adapted from Krey and Clarke (2011).

proportions of low-carbon energy are generally higher than they would otherwise be, but the degree of this effect is dependent on the ability of the other of these options to take up the slack in lieu of RE. In many modelling paradigms, fossil energy with CCS and nuclear energy are assumed to be close substitutes for the production of base-load electricity production. When one is not available, the majority of the generation it would have provided is provided instead by the other rather than by RE sources, because solar, wave and wind energy are variable. At the same time, it is important to note that reservoir hydropower, bioenergy and geothermal energy can be dispatchable base load (Section 8.2.1).

A fundamental question raised by limited technology scenarios is whether one or more energy supply options are 'necessary' this century to meet low stabilization goals; that is, could the goal still be met if these technologies were not available. One way to explore this issue is to identify scenarios that were attempted with limited technology, but that could not be produced by the associated models. These attempts give a sense of the difficulty of meeting stabilization goals with limited technology options, although, in most cases, they cannot truly be considered as indications of physical feasibility (Clarke et al., 2009). These attempted scenarios tell a mixed story. In some cases, models could not achieve stabilization without nuclear and CCS; however, in others, models were able to produce these scenarios (Figure 10.6). Several studies found that limits on RE deployments kept models from achieving stabilization goals (see, e.g., Figure 10.11). Other studies have indicated that it is the combination of RE, in the form of bioenergy, with CCS that makes low stabilization goals substantially easier through negative emissions (Azar et al., 2006; van Vuuren et al., 2007; Clarke et al., 2009; Edenhofer et al., 2010; Tavoni and Tol, 2010).

10.2.2.5 Renewable energy deployment by technology, over time and by region

There is great variation in the deployment characteristics of individual technologies (Figures 10.8 and 10.9). Several dimensions of this variation bear mention. First, the absolute scales of deployments vary considerably among technologies. Bioenergy, wind and solar energy generally show higher incremental deployment levels than hydropower and geothermal energy, although the variation is large enough that there are clearly scenarios with minimal penetration of wind and solar relative to hydropower and geothermal energy. Ocean energy is currently only represented in very few scenarios and will therefore not be discussed here (see also Section 10.2.4). Further, deployment magnitudes are characterized by greater variation for some technologies relative to others. For example, variation in hydroelectric deployment is far less than in geothermal deployment. The high deployment scenarios for geothermal energy probably assume competitive electricity from enhanced geothermal systems and/or wide application of geothermal heat pumps (see Sections 4.2 and 4.8). It is important to use some caution in interpreting the bioenergy numbers in Figures 10.8 and 10.9 relative to those associated with the other renewable energy technologies. This analysis is being conducted using the direct equivalent

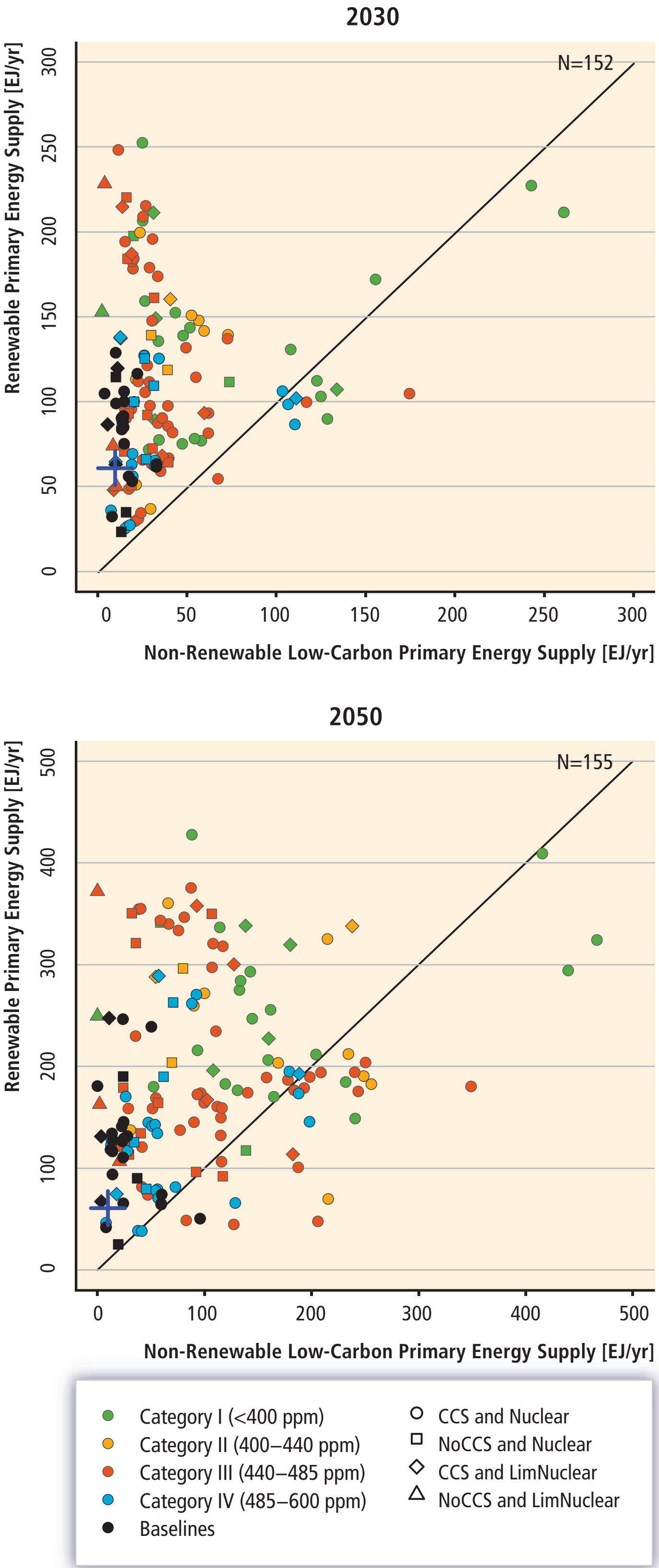


Figure 10.7 | Global RE primary energy supply (direct equivalent) plotted against non-renewable low-carbon energy primary energy supply (direct equivalent) in 2030 and 2050. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (Fisher et al., 2007). The shapes identify constraints on the availability of the competing low-carbon energy supply options, fossil with CCS and nuclear. Note that limited nuclear scenarios include nuclear phase-outs, constraints on the production of new nuclear energy and scenarios in which nuclear production is constrained to baseline levels. The blue crossed lines show the relationship in 2007. For data reporting reasons, only 152 and 155 scenarios are included in the 2030 and 2050 results shown here, as opposed to the full set of 164 scenarios. Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

accounting method. Bioenergy is accounted for prior to conversion to fuels such as ethanol or electricity when it is used in those applications. In contrast, the other technologies generally produce electricity, and they are accounted for as electricity produced in these cases. If they were to be converted to primary energy by using the substitution method, then they might be roughly three times larger, based on average fossil electricity efficiencies.

Second, the time scale of deployment varies across different RE technologies (Figures 10.8 and 10.9), in large part representing differences in deployment levels today and (often) associated assumptions about relative technological maturity. For example, hydroelectric power experiences only modest growth across scenarios (a 1.7-fold increase in the median case and a 3-fold increase in the highest scenario by 2050 compared to today); wind energy grows more rapidly, beginning from lower deployment levels today; and solar energy grows most rapidly, beginning from only minimal deployment today, as well as in 2020 in most scenarios. Indeed, much of the growth in solar energy occurs after 2030, indicating a general consistency among scenarios that solar energy at a large scale is a longer-term option than several other options. Global bioenergy production includes both traditional uses of biomass (more than 30 EJ/yr or roughly two-thirds of all bioenergy consumption in 2008, see Chapter 2) as well as more advanced methods, including cellulosic approaches. Traditional biomass use is typically assumed to decline as economic development progresses, implying that the growth in bioenergy is largely in modern applications. It is also useful to note that some technologies appear to be more clearly influenced by the climate policy than others. For example, solar energy deployment levels are noticeably higher in the most ambitious climate scenarios than in the other scenarios. All of the technologies experience this effect but to varying degrees.

Finally, scenarios generally indicate that RE deployment is larger in non-Annex I countries over time than in the Annex I countries (Figure 10.8 and Krey and Clarke, 2011). Virtually all scenarios include the assumption that economic and energy demand growth will be larger in the non-Annex I countries than in the Annex I countries (Clarke et al., 2007, 2009). The result is that the non-Annex I countries account for an increasingly large proportion of CO_2 emissions in baseline, or no-policy, cases and must therefore make larger emissions reductions over time. All other things being equal, larger reductions imply larger deployment of low-carbon supply options, including RE. Hence, it is not surprising that scenarios generally indicate larger RE deployment levels in non-Annex I regions.

At the same time, it is important to note that the actual deployment levels, particularly in the nearer term, will depend not only on the long-term

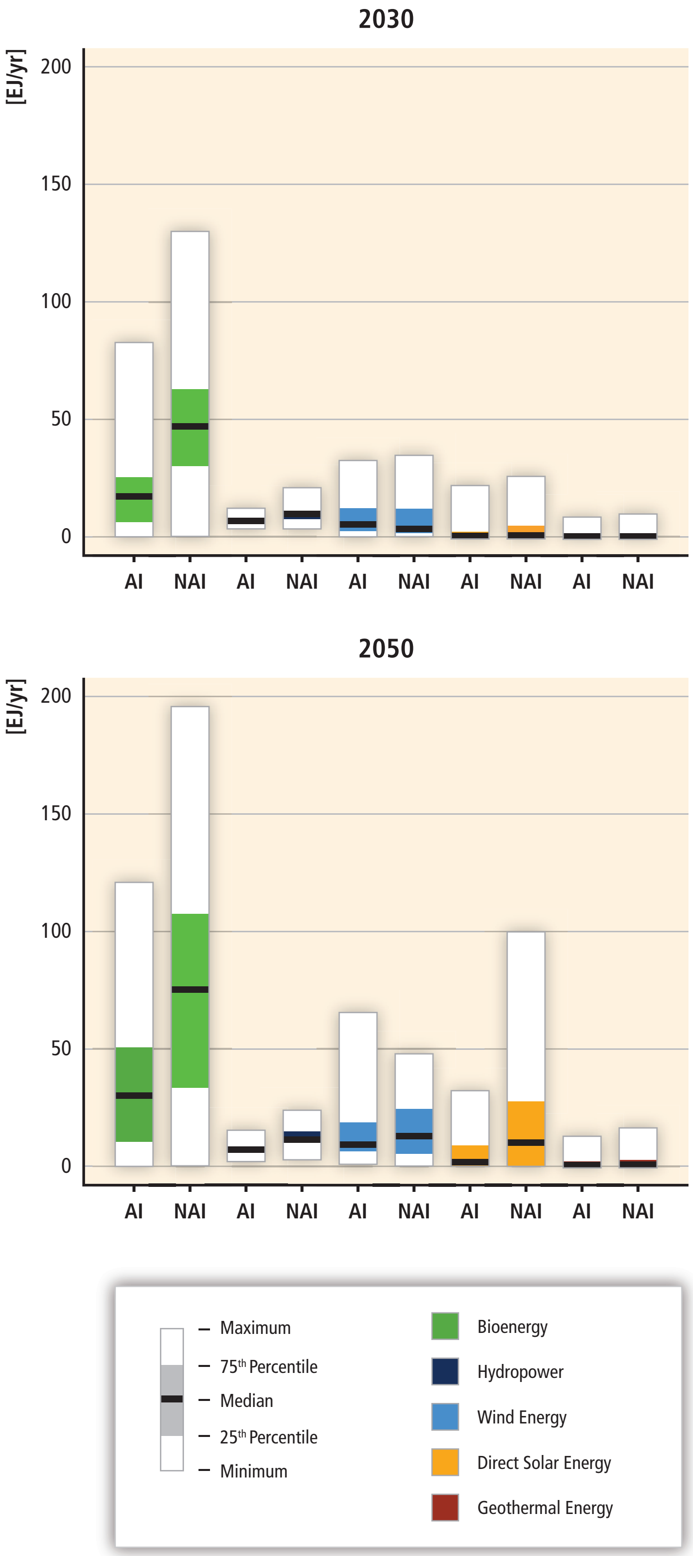


Figure 10.8 | Global RE primary energy supply (direct equivalent) by source in Annex I (AI) and Non-Annex I (NAI) countries in 164 long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. Depending on the source, the number of scenarios underlying these figures varies between 122 and 164. Note that ocean energy is represented in very few scenarios, insufficient to generate a similar graph. Although instructive for interpreting the information, it is important to note that the 164 scenarios are not explicitly a random sample meant for formal statistical analysis. (One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as ethanol or electricity. The other technologies produce primarily (but not entirely) electricity and they are accounted for based on the electricity produced. If primary equivalents were used, based on the substitution method, rather than direct equivalents, then energy production from non-biomass renewable sources would be of the order of three times larger than shown here.) Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

goal, but also on the degree to which countries take action towards the long-term goal. For example, in scenarios in which some countries delay participation in global emissions reductions, RE deployment is necessarily lower than it is in scenarios with full global participation (Clarke et al., 2009; Krey and Clarke, 2011). Nonetheless, because stabilization of CO_2 concentrations means bringing CO_2 emissions to near zero, all countries must eventually bring their emissions to this point, and those with larger energy consumption will require more low-carbon energy than others, regardless of which countries may have initiated action on climate the soonest. It is also important to note that countries may take different approaches to mitigation, some focusing on price-based policies where others use regulatory policies that could include mandates for RE, and this could influence the spatial character of RE deployments. The scenarios described here mostly rely exclusively on price-based mitigation and therefore do not capture this sort of variation.

10.2.2.6 Renewable energy and the costs of mitigation

RE's role in climate mitigation might be observed not only through the lens of RE deployment levels, but also by an exploration of the manner in which RE availability and deployment influences the economic consequences, or costs, of mitigation. One way that researchers have attempted to link particular technologies to mitigation costs is to build mitigation cost curves; that is, relationships that indicate how much mitigation might be achieved by particular technologies at a given carbon price. In the context of RE, these curves attempt to answer the question: how much CO_2 abatement and at what cost can be provided by RE technologies? Such mitigation cost curves are not provided here for reasons discussed more thoroughly in Section 10.4. It is noted here only that assigning mitigation to particular technologies is not a primary output of integrated models. Integrated models provide information on prices, emissions and deployments, but in general they do not assign emissions to the presence or absence of specific technologies. Such assignments are the result of post-processing, offline accounting calculations that rely on analyst judgment about key assumptions. Applying these post-processing assumptions to the scenarios would constitute new analysis rather than synthesis, and it would blur the signal from the scenarios themselves. A sense of the variation of CO_2 emission mitigation due to the use of different methods is given in Section 10.3 on the basis of 4 selected scenarios from the whole set of 164 analyzed in this section. In addition, these analyses do not account for the benefits of climate mitigation (e.g., less severe climate change impacts in the long term, reduced need for adaptation), secure energy supply and air pollution

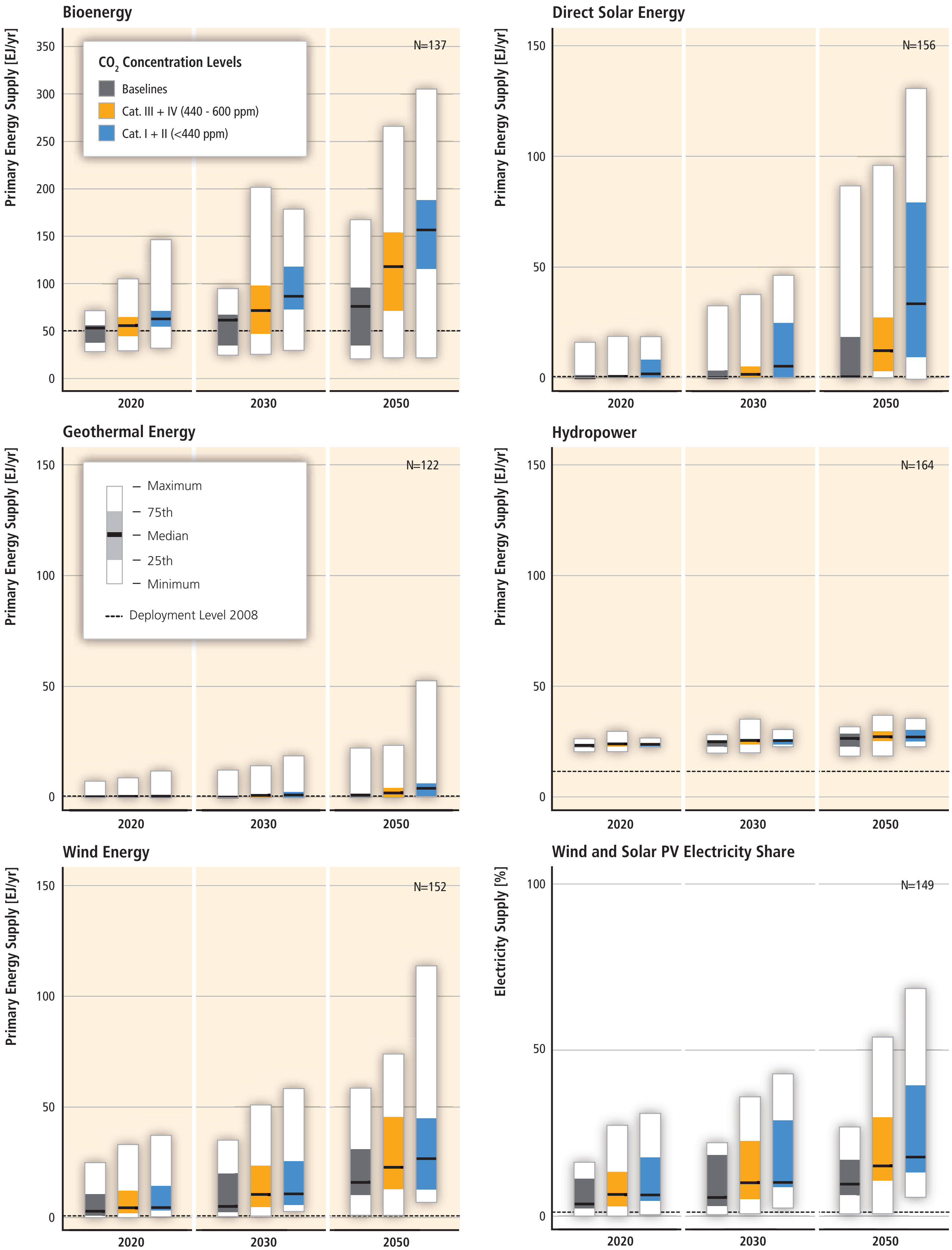

Bioenergy
CO2 Concentration Levels
Baselines
Cat. III + IV (440 - 600 ppm)
Cat. I + II (<440 ppm)
N=137
Primary Energy Supply [EJ/yr]
350
300
250
200
150
100
50
0
2020
2030
2050
Direct Solar Energy
N=156
Primary Energy Supply [EJ/yr]
150
100
50
0
2020
2030
2050
Geothermal Energy
Maximum
75th
Median
25th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

Figure 10.9 | (Preceding page) Global primary energy supply (direct equivalent) of biomass, wind, solar, hydro, and geothermal energy and share of variable RE (wind and solar photovoltaic) in global electricity generation in 164 long-term scenarios in 2020, 2030 and 2050, and grouped by different categories of atmospheric CO_2 concentration level in 2100 (Fisher et al., 2007). Following the direct equivalent methodology, biomass primary energy supply is accounted for prior to conversion whereas the other RE options are accounted for based on secondary energy produced. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. Although instructive for interpreting the information, it is important to note that the 164 scenarios are not explicitly a random sample meant for formal statistical analysis. For data reporting reasons, the number of scenarios included in each of the panels shown here varies considerably. The number of scenarios (N) underlying the individual panels, as opposed to the full set of 164 scenarios, is indicated in the right upper corner of each panel. Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

(e.g., reduced health expenditures) due to the deployment of RE technologies (see e.g., Nemet et al., 2010). A more detailed discussion of co-benefits can be found in Section 10.6.

Another possible view into the relationship between RE and mitigation costs is afforded by considering the relationship between RE deployment levels and carbon prices across scenarios. This approach attempts to answer the question: how much RE will be deployed at a given carbon price? The 164 scenarios demonstrate no meaningful correlation between RE deployment and carbon prices (see Figure 10.10). All the forces that blur the relationship between RE deployment levels and long-term concentration goals, as discussed in Sections 10.2.2.2, 10.2.2.3 and 10.2.2.4, influence the relationship between RE deployment and carbon prices. In addition, integrated energy models are characterized by a wide range of carbon prices based both on parameter assumptions and model structure (Clarke et al., 2007, 2009). The result is little ability to link RE deployment levels to carbon prices when looking across a wide range of models.

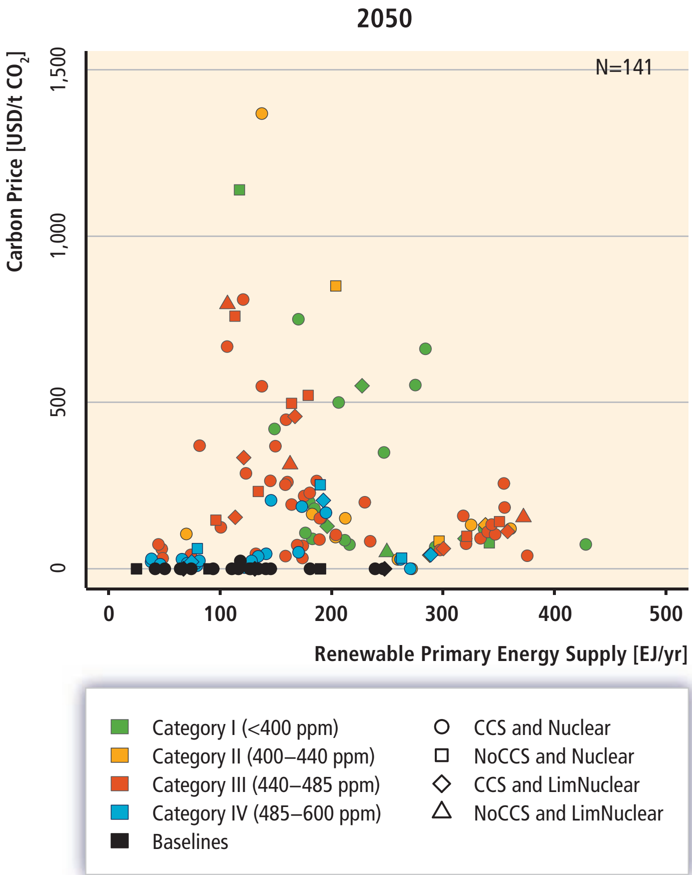


Figure 10.10 | Carbon prices (in USD_{2005}) as a function of global RE primary energy supply (direct equivalent) in 2050. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (Fisher et al., 2007). Different symbols in the graph denote the availability of CCS and nuclear energy. Note that limited nuclear scenarios include nuclear phase-outs, constraints on the production of new nuclear and scenarios in which nuclear production is constrained to baseline levels. For data reporting reasons, only 141 scenarios are included in the 2050 results shown here, as opposed to the full set of 164 scenarios. Figure and data adapted from Krey and Clarke (2011), modified to include two additional scenarios.

CO_2 prices are only a limited metric for cost because they represent the marginal costs of abatement and not the total cost. A range of other cost measures have been used in the literature to capture the economic consequences of mitigation. These include changes in gross domestic product (GDP) or consumption, or total mitigation costs, that is, the additional cost to deploy and operate an energy system with lower GHG emissions, which can provide a broader sense of the cost implications of RE. In general, mitigation tends to reduce GDP (Fisher et al., 2007).[3] However, these measures do not necessarily lead to a stronger correlation with RE deployment than carbon prices. For example, the overall variation of GDP in the baseline scenarios reviewed in this section (a factor of 1.8 in 2050 between the lowest and the highest GDP) is much larger than the changes in GDP as the result of climate mitigation (up to a few percent of baseline GDP by 2050), which can be derived by comparing the GDP in mitigation scenarios to their respective baseline for those models that include feedbacks to GDP. The dominance of, and variation in, baseline GDP would further obscure any relationship between total GDP and RE deployment.

A different reflection of the relationship between the economic consequences of mitigation and RE deployments can be ascertained by exploring how mitigation costs would change under differing assumptions about the availability or cost and performance of RE as well as competing mitigation options. A number of researchers have explored this issue (see, e.g., Clarke et al., 2008; Luderer et al., 2009; Edenhofer et al., 2010; Tavoni and Tol, 2010). Consistent with intuition, these studies demonstrate that the presence of RE technologies or improvements in the cost and performance of RE technologies reduces mitigation costs. This is not surprising: more or better options should not increase costs. More important is the relative magnitude of the change in mitigation costs resulting from increases in the availability, cost or performance of RE technologies relative to the change in mitigation costs resulting from

3 Note that a minority of researchers have argued that climate mitigation could lead to increased economic output (e.g., Barker et al., 2006). The basic argument is that under specific assumptions, induced technological change due to a carbon price increase leads to additional investments that trigger higher economic growth.

increases in the availability of fossil energy with CCS and/or nuclear energy. For example, in both the ADAM (Edenhofer et al., 2010) and RECIPE projects (Luderer et al., 2009), each involving three models, the cost increase that results from the absence of the option to expand RE deployment is not of a distinctly different order of magnitude than the cost increase from the absence of the option to implement fossil energy with CCS or expand production of nuclear energy beyond today's levels or beyond baseline levels (see Figures 10.11 and 10.12). Indeed, in several scenarios, constraining RE results in larger cost increases than constraining nuclear power or fossil energy with CCS. The value of RE availability, cost and performance may also vary with the degree of ambition. For example, the availability of bioenergy with CCS has been identified as a particularly valuable technology combination for meeting tight stabilization constraints (Azar et al., 2006; van Vuuren et al., 2007; Clarke et al., 2009; Edenhofer et al., 2010; Tavoni and Tol, 2010). To summarize, while there is an agreement in the literature that mitigation costs will increase if the deployment of RE technologies is constrained and that more ambitious stabilization levels may not be reachable, there is little agreement on the precise magnitude of the cost increase.

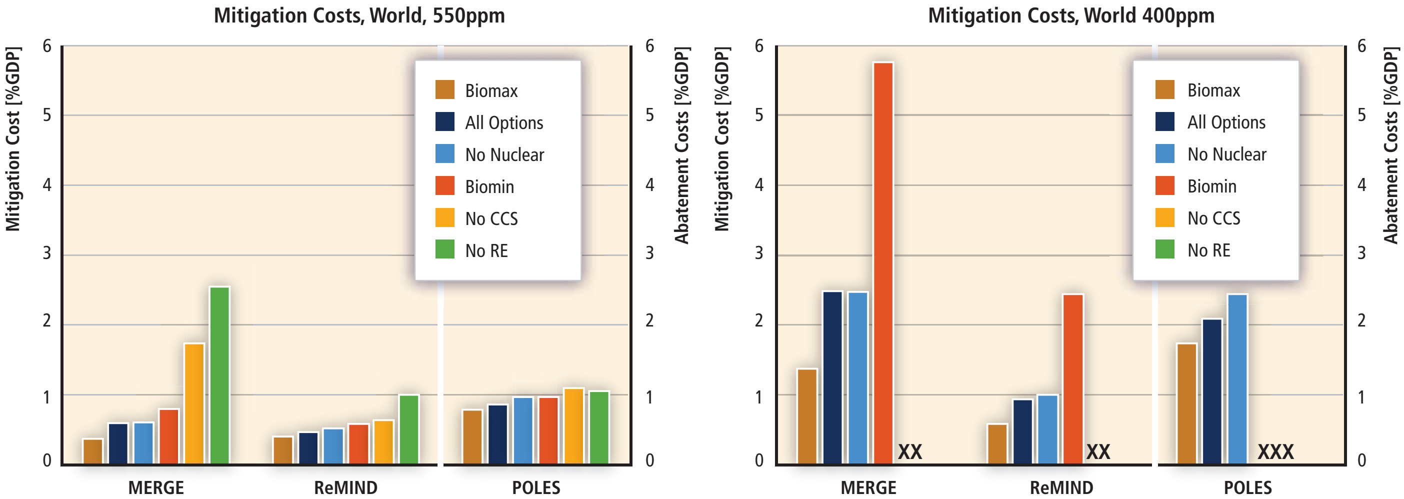


Figure 10.11 | Global mitigation costs from the ADAM project under varying assumptions regarding technology availability for long-term stabilization levels of 550 and 400 ppm CO_2eq (Edenhofer et al., 2010). Mitigation costs are given as aggregated GDP losses (MERGE, REMIND) or increase of abatement costs (POLES) up to 2100 relative to baseline in % of GDP. 'All Options' refers to the standard technology portfolio assumptions in the different models, while 'Biomax' and 'Biomin' assume double and half the standard technical potential of biomass of 200 EJ, respectively. 'No CCS' excludes CCS from the mitigation portfolio and 'No Nuclear' and 'No RE' constrain the deployment levels of nuclear and RE to the baseline level, which still potentially means a considerable expansion compared to today. The '**x**' in the right panel indicates non-attainability of the 400 ppm CO_2eq level in the case of limited technology options.

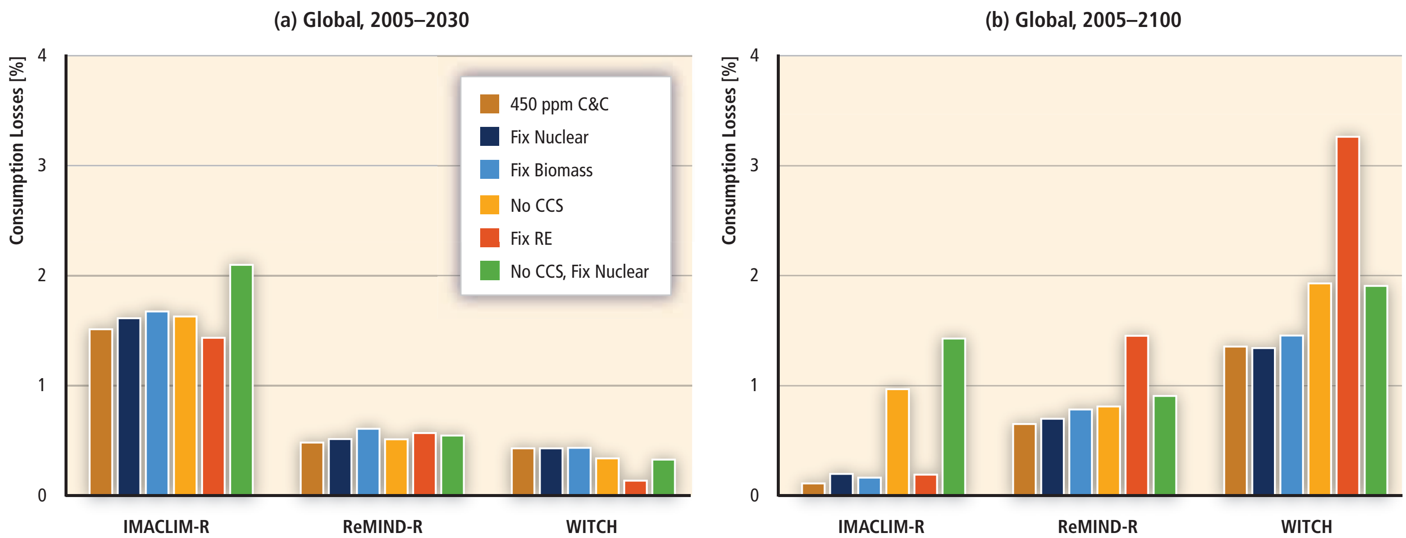


Figure 10.12 | Mitigation costs from the RECIPE project under varying assumptions regarding technology availability for a long-term stabilization level of 450 ppm CO_2 (Luderer et al., 2009). Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to baseline levels (all other technologies) for the periods (a) 2005 to 2030 and (b) 2005 to 2100. Option values are calculated as differences in consumption losses for a scenario in which the use of certain technologies is limited with respect to the baseline scenario. Note that for WITCH, the generic backstop technology was assumed to be unavailable in the 'Fix RE' scenario.

10.2.3 The deployment of renewable energy sources in scenarios from the technology perspective

The scenarios in this section were produced using global, integrated models. These models have several advantages, but they also have the weakness that they pay only limited attention to many critical factors that ultimately will influence the deployment of RE. As a means to better understand the role of these forces, the scenarios from this section are briefly explored in the 'long-term deployment in the context of carbon mitigation' sections of Chapters 2 through 7. The aim of these individual technology explorations is to identify potential barriers that an expansion of RE may face and enabling factors to achieve the higher RE deployments levels as found in the scenario literature. This section briefly summarizes the key elements of those sections.

Resource Potential: In general, even the highest deployment levels were not considered to be constrained by the available technical potentials at the global level for all of the RE categories. However, because RE resources are regionally heterogeneous, some of the higher deployment levels may begin to constrain the economically most attractive sites, for example, for hydro and wind energy. For most RE sources, availability is geographically constrained, for example, for certain forms of ocean, geothermal, biomass and solar energy, as well as hydropower and wind energy. In the case of bioenergy, the supply levels in the scenarios with low GHG stabilization levels of up to about 300 EJ/yr by 2050 almost exactly coincide with the upper range of possible deployment levels as discussed in Chapter 2 (see Section 2.8.4 and Figure 2.8.3).

Regional Deployment: Economic development and technology maturity are primary determinants of regional deployment levels. Regional policy frameworks for RE need to be economically attractive and predictable. For mature technologies such as large hydropower, a large fraction of available technical potential in Organisation for Economic Cooperation and Development (OECD) countries has been exhausted and the largest future expansion is expected in the non-OECD countries of Asia and Latin America. For wind energy, which has seen high expansion rates, mostly in Europe and North America over the past decade as well as in China and India more recently, a greater geographical distribution of deployment than currently observed is likely to be needed to achieve the higher deployments indicated by the scenario literature. The other, less mature technologies are likely to initially focus on expansion in affluent regions (Europe, North America, Australia and parts of Asia) where financing conditions and infrastructure integration are favourable.

Supply Chain Issues: In general, no insurmountable medium- to long-term constraints of materials, labour and manufacturing capacity were identified that would prevent higher deployment levels in the scenarios. For example, the wind industry has witnessed rapid expansion over the past that led to globalization of the production chain, but further scaling up of the industry will be needed to reach the capacity addition rates seen in the more stringent scenarios. It is also important to recognize that markets and supply chains for some technologies are global (e.g., wind, solar photovoltaic (PV)) while others (e.g., passive solar and low-temperature solar thermal) to date are largely local. As markets expand, they are likely to become more global in scope. Past rates of growth suggest that, assuming that policy and market signals are clear, no absolute long-term constraints exist.

Technology and Economics: Because the maturity of the renewable technologies is highly variable, so is the need for cost and technological advances. On the one end of the spectrum, hydropower is competitive with thermal power plants, while on the other end of the spectrum, commercial-scale demonstration plants for most ocean energy technologies do not yet exist. For offshore wind energy, more remote offshore locations will require further technology advances; further, cost reductions will impact deployment outcomes. Similarly, concentrating solar power (CSP), solar PV, geothermal heat pumps, and enhanced geothermal systems (EGS) will require technological improvements, but in particular further reductions in electricity generation costs. Technical progress is similarly required for advanced biofuels and bio-refineries with potential for commercialization around 2020 given R&D investment and near-market support.

Systems Integration and Infrastructure: Systems integration is challenging for the variable electricity generation technologies wind, solar PV and wave energy (Section 8.2.1). Technical (e.g., balancing generation capacity, inter-connection and storage) and institutional (e.g., market design and operations, market access and tariff structure) solutions will need to be implemented to address operational integration concerns. Additionally, substantial new transmission infrastructure may be required under even modest expansion scenarios to connect remote resources, for example, off- but also onshore wind power, central station CSP and PV, hydrothermal geothermal power and hydropower. A greater reliance on offshore wind power is likely for regions such as Europe, which will require the development of offshore transmission infrastructure; certain forms of ocean energy face similar integration challenges and synergies may therefore exist in the deployment of these technologies. To gain greater penetration into the energy supply systems, other RE-based energy carriers such as heat, biogas, liquid bio-fuels, solid biomass and hydrogen all need appropriate integration into existing system infrastructure as outlined in Section 8.2.

10.2.4 Knowledge gaps

The primary knowledge gap with respect to the assessment of RE in large-scale, integrated models is the representation of RE technologies themselves within these models. The coverage of different RE sources in the scenario literature varies significantly. Mature technologies such hydropower were included by all models reviewed in this assessment, while less mature technologies or those not deployed today at large scale—for example, ocean energy, offshore wind, concentrating solar power and geothermal energy—were addressed by smaller sets of scenarios. One reason is that there is less demand to specifically address less mature technologies or those that are a priori assumed to have lower contributions. A second reason is that there is a lack of high-quality global resource data (preferably gridded) for some renewable resources (e.g., geothermal energy, the various ocean energy forms), which is a precondition for constructing resource supply curves that are inputs to energy-economic and integrated assessment models. More broadly, beyond representations of the technologies themselves, many issues related the implementation of RE technologies require further research and inclusion in large-scale integrated models. Important areas in this regard include the integration of RE into the electricity grid and the relationship between bioenergy production, crop production and deforestation.

However, it is important to note that improved representations of RE technologies and associated systems will not entirely eliminate the uncertainty regarding the role of RE in climate mitigation. As was discussed throughout this section, a range of other uncertainties, unrelated to RE technologies, such as economic and population growth, the availability, cost and performance of competing technologies, and the nature of mitigation approaches and ambitions will influence the role of RE in climate mitigation. Uncertainty derived simply from the design of different modelling platforms can also influence results. Therefore, an important research priority for the future is to improve the understanding of why model results vary with respect to RE and to attribute these differences in model outcomes to differences in assumptions and methodologies.

10.3 Assessment of representative mitigation scenarios for different renewable energy strategies

Section 10.2, coming from a more statistical perspective, gave a comprehensive overview of the possible role RE technologies could play in different mitigation pathways. In contrast, this section goes beyond the more aggregated data level and focuses on regional and sectoral perspectives. For this in-depth analysis, four scenarios from the previous section's full set of the scenario assessments have been chosen to represent different illustrative energy and emission pathways (see Table 10.3). The scenarios differ in assumptions, mitigation goals and in the types of underlying models used. For a description of the scenarios and models, see Box 10.2. Primary data for this analysis go beyond what has been published to date, and were provided at special request by the scenario authors and institutions.[4]

4 The International Energy Agency (IEA) and the German Aerospace Center for IEA-WEO2009 Baseline; the Potsdam Institute for Climate Impact Research for ReMIND-RECIPE; the Pacific Northwest National Laboratory for MiniCAM-EMF22; and the German Aerospace Center for ER-2010.

10.3.1 Sectoral breakdown of renewable energy sources

The amount of RE deployed in the scenarios depends on a large number of variables, assumptions and input data (see also Section 10.2.1, especially Section 10.2.1.1). Often most influential are the cost and performance assumptions for the different RE technologies. They help determine the comparative attractiveness of competing low-carbon supply options (i.e., nuclear energy and fossil energy with CCS), but also of end-use energy efficiency measures. Underestimation of costs leads to overestimation of RE deployment and vice versa. The share of RE calculated is furthermore determined by the general availability of competing options. Constraints on alternative mitigation options mean that more RE deployment will occur for a given level of GHG mitigation. Assumptions about infrastructure restrictions and system integration options are further important determinants. In this context, a significant factor relates to assumptions about how the power grid would adapt to significant amounts of variable renewable resources. In contrast, the overall technical potential for RE—that is, the total amount of energy that can be produced taking into account the primary resources, the socio-geographical constraints and the technical losses in the conversion process (see definition in Annex I)—is not considered to be a limiting factor at the global level as the technical potential supersedes the current and projected future demand by orders of magnitude (see Section 1.2.2). Thus, to fully exploit the entire technical RE potential is neither needed nor necessary.

In practice, deployment of RE resources should respect sustainability criteria in order to achieve an environmentally friendly future energy supply (see Chapters 1 and 9). Public acceptance is crucial to the expansion of RE sources as well. Some RE applications, such as rooftop PV and solar thermal as well as bioenergy cogeneration plants and onshore wind, are often decentralized energy production facilities and may be located near or even at demand centres. Other RE applications are more likely to involve industrial-scale energy production facilities located at some distance from demand centres and requiring large-scale transmission, for example, large onshore wind parks, offshore wind energy, concentrated solar power in deserts, hydrothermal geothermal plants, and hydropower. In both cases, public acceptance concerns can constrain development if not carefully managed. The use of biomass has been especially controversial recently, as issues have arisen over competition with other land uses, food production and ecosystem preservation, as well as possible direct or indirect GHG emissions due to land use change (see Sections 2.5, 9.3.4 and 10.6). On the other hand, RE deployment is positively driven by sustainability criteria since it has the potential to provide energy access in remote areas without some of the environmental and health impacts usually associated with fossil fuels (see Sections 9.3.2, 9.3.4 and 10.6). Therefore, non-economic criteria have a significant influence on the resulting RE deployment and corresponding assumptions are crucial for scenario results.

Table 10.3 | Overview of key parameters of the illustrative scenarios based on assumptions that are exogenous to the models' respective endogenous model results. Dark grey marks exogenous input; dark yellow marks endogenous model results. Note that the concentration categories are defined in terms of CO_2 (only) concentrations, while other metrics, predominantly CO_2-equivalent concentrations—of Kyoto gases or of all forcing agents—are used in the literature. (Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010)).

Category	Units	Status Quo	Baseline		Category III+IV (440 - 600ppm)		Category I+ II (< 440ppm)		Category I+ II (< 440ppm)	
Scenario name			IEA-WEO2009-Baseline		ReMind-RECIPE		MiniCAM-EMF22		ER-2010	
Model					ReMind		MiniCAM		MESAP/PlaNet	
	yr	2007	2030	2050[1]	2030	2050	2030	2050	2030	2050
Techology pathway[2]										
Renewables			all[3]	all	solar: PV and CSP not differentiated		solar: PV and CSP not differentiated, ocean energy not included		all	all
CCS			+	+	+	+	+	+	-	-
Nuclear			+	+	+	+	+	+	+	-
Population	billion	6.67	8.31	9.15	8.32	9.19	8.07	8.82	8.31	9.15
GDP/capita[4]	thousand USD_{2005}/capita	10.9	17.4	24.3	12.4	18.2	9.7	13.9	17.4	24.3
Energy Demand (direct equivalent)	EJ/y	469	645	749	590	674	608	690	474	407
Energy Intensity	MJ/USD_{2005}	6.5	4.5	3.4	5.7	4.0	7.8	5.6	3.3	1.8
Renewable Energy	%	13	14	15	32	48	24	31	39	77
Fossil & Industrial CO_2 Emissions	Gt CO_2/y	27.4	38.5	44.3	26.6	15.8	29.9	12.4	18.4	3.7
Carbon Intensity	kg CO_2/GJ	58.4	57.1	56.6	45.0	23.5	49.2	18.0	36.7	7.1

Notes: 1. IEA (2009) does not cover the years 2031 until 2050. As the IEA's projection only covers a time horizon up to 2030 for this scenario exercise, an extrapolation of the scenario has been used that was provided by the German Aerospace Agency (DLR) by extrapolating the key macroeconomic and energy indicators of WEO 2009 forward to 2050 (Teske et al., 2010). 2. (-): Technology not included; (+): Technology included. 3. This includes: Solar photovoltaics, CSP, solar water heating, wind (on- and offshore), geothermal power, heating and cogeneration, bioenergy power, heating and cogeneration, hydropower, ocean energy. 4. The data are either input for the model or endogenous model results.

Last but not least, climate and energy policy frameworks are highly relevant to RE deployment in scenario analysis. Market forces and constraints are relevant for the deployment of RE and determine the market potential. As market potential also includes opportunities, it may in theory be larger than the economic potential due to support programs, but usually the market potential is lower because of a variety of constraining market failures for RE and other new technologies (Sections 1.4.2 and 11.4). Market potential analyses have to take into account the behaviour of private economic agents under their specific conditions, which are partly shaped by public authorities (see Sections 11.5 and 11.6). In this context, the energy policy framework has a profound impact on the expansion of RE sources respective to corresponding assumptions for the scenario results.

RE deployment is driven and hindered by a variety of factors and very much depends on how the different determinants and their impacts are being assessed; uncertainties about future development are generally high and determined by specific assumptions. In this context, energy scenarios bundling a consistent set of specific assumptions are an approximation of what can be expected for the future under specific conditions. As a comparison of different scenarios spans a range of possible futures, it can show overarching commonalities and trends and can make differences and uncertainties visible and more transparent.

Selection of four illustrative scenarios for an in-depth analysis

Scenario results are determined not only by parameter assumptions, but also by the underlying modelling architecture and model-specific restrictions (e.g., upper deployment bound for specific RE technologies). The four scenarios were selected to present a wide range of different modelling architectures, demand projections and technology portfolios for the supply side (see Box 10.2). The IEA-WEO2009-Baseline Reference Scenario (IEA, 2009; extension to 2050: Teske et al., 2010) (henceforth IEA-WEO2009-Baseline) is the only baseline scenario in this set, that is, it does not incorporate any climate policy targets beyond those implemented by 2009. It is characterized by a comparatively high demand projection with low RE deployment. In two of the three mitigation scenarios, ReMIND RECIPE 450 ppm Stabilization Scenario (Luderer et al., 2009) (henceforth ReMIND-RECIPE) and MiniCAM EMF 22 first-best 2.6 W/m[2] Overshoot Scenario (Calvin et al., 2009) (henceforth MiniCAM-EMF22), high demand expectation and a significant increase in RE is combined with the possibility of employing CCS and nuclear power plants. Low demand (e.g., due to a significant increase in energy efficiency) is combined with high

Box 10.2 | Overview of the four illustrative scenarios and their underlying models.

IEA-WEO2009-Baseline: This scenario uses a typical baseline scenario approach. As such, it calculates the possible energy pathway without any substantial change in government policy (IEA, 2009, p. 44) and under the assumption of a minimal to moderate fossil fuel cost increase. The scenario does not include specific GHG emissions constraints. As the IEA (2009) projection only covers a time horizon up to 2030 for this scenario exercise, an extrapolation of the scenario has been used that was provided by the German Aerospace Center (DLR) that uses the key macroeconomic and energy indicators of IEA (2009) and brings them forward to 2050 (Teske et al., 2010). Regarding fossil and industrial CO_2 emissions, the baseline scenario expects an increase from 27.4 Gt CO_2/yr in 2007 to 44.3 Gt CO_2/yr by 2050. (Scenario 'IEA WEO 2009 Reference Scenario' from IEA (2009) extended beyond 2030 by Teske et al. (2010).)

ReMIND-RECIPE: This scenario describes a mitigation path aiming to stabilize atmospheric CO_2 (only) concentration at 450 ppm (corresponding to fossil and industrial CO_2 emissions of 15.8 Gt CO_2/yr by 2050). It was generated with the energy-economy-climate model ReMIND-R, which computes welfare-optimized transformation trajectories under full 'where-flexibility' (emission reductions are performed where it is cheapest), 'when-flexibility' (emission reductions are performed when they are cheapest) and 'what-flexibility' (emission reductions are performed by choosing the least expensive combination of technologies) conditions. Another crucial assumption is perfect foresight: investment decisions are made knowing in advance the future changes in prices and technology developments. The model is characterized by a high level of integration: the macro-economy and the energy system are treated within an integrated optimization framework, thus fully accounting for the macro-economic feedbacks of the climate mitigation effort. The complex integrated formulation requires compromises in terms of the sectoral and technological resolution of the energy system. ReMIND-RECIPE accounts for a variety of RE sources (wind, solar, biomass, hydro and geothermal) and conversion technologies. Wind power and solar PV are parameterized as learning technologies. RE technologies can be deployed at the industrial scale at optimal sites and be transported within world regions (up to continental scale) to demand centres, whereby the model implicitly assumes that bottlenecks (e.g., with respect to grid infrastructure) are avoided by early and anticipatory planning. (Scenario '450 ppm stabilization scenarios' from Luderer et al. (2009).)

MiniCAM-EMF22: The MiniCAM-EMF22 scenario was developed as part of the Energy Modelling Forum study 22 (EMF 22), which looks at possible approaches to long-term climate goals. The scenario was generated using the MiniCam integrated assessment model, the precursor to the Global Change Assessment Model (GCAM) integrated assessment model. The scenario is an overshoot scenario that reaches 450 ppm CO_2eq (Kyoto gases)[1] by 2100, after peaking at 525 ppm CO_2eq in 2050, and assumes full international participation in emissions reductions. The specific concentration levels correspond with fossil and industrial CO_2 emissions of 12.4 Gt CO_2/yr by 2050. The underlying characteristics of the scenario include global population growth that peaks at approximately 9.0 billion people in 2070 and then declines to 8.7 billion in 2100. The scenario considers the availability of a wide range of energy supply options, including major RE options, nuclear power and both fossil energy and bioenergy equipped with CCS technology. The presence of bioenergy with CCS is particularly important in the scenario because it allows for the option to create negative emissions, primarily in electricity production (Calvin et al., 2009; Clarke et al., 2009). (Scenario 'First-best 2.6 W/m^2 Overshoot Scenario' from Calvin et al. (2009).)

ER-2010: The ER-2010 scenario (Teske et al., 2010) is based on the socioeconomic assumptions of the IEA-WEO2009-Baseline scenario, but assumes an increase in fossil fuel costs and a price for carbon from 2010 onwards. The scenario has a key constraint that limits worldwide CO_2 emissions to a level of 3.7 Gt CO_2 per year by 2050. To achieve this, the scenario is characterized by significant efforts to fully exploit the large potential for energy efficiency, using currently available best practice technology, and to foster the use of RE. In all sectors, the latest market development projections and the resulting cost reductions for the RE industry have been taken into account, and a stable development of the RE sector is pursued. To accelerate the market penetration of RE, various additional measures have been assumed, such as a speedier introduction of electric vehicles combined with the implementation of effective communications systems and technologies, smart meters and faster expansion of super grids to allow a higher share of variable RE power generation (PV and wind) to be employed. The methodological background of the scenario is the simulation model PlaNet of the energy and environmental planning package MESAP (see Krewitt et al. (2009), which was created for long-term strategic planning on a national, regional or local level. The model is characterized by a very detailed technology breakdown for each sector. Following the simulation approach, activities and drivers of demand (e.g., mobility demand), as well as relevant market shares of technologies, amongst other factors, are specified exogenously by the user. (Scenario 'Advanced Energy [R]evolution 2010' from Teske et al. (2010).)

Note: 1. Note that atmospheric CO_2 (only) concentrations reach about 385 ppm by 2100, that is, the scenario falls into concentration category 1 (<400 ppm); see also Table 10.2.

RE deployment, no employment of CCS and a global nuclear phase-out by 2045 in the third mitigation scenario, Advanced Energy [R]evolution 2010 (Teske et al., 2010) (henceforth ER-2010).

Table 10.3 shows key parameters for the four illustrative scenarios. Depending on the model, some of the assumptions may be exogenously applied or be determined endogenously. All scenarios project a significant increase in global population and assume or calculate a significant increase in GDP. The IEA-WEO2009-Baseline GDP projections are based on forecasts by the International Monetary Fund (IMF, 2009) and the OECD. Those GDP projections have been used as input parameters for the ER-2010 model as well. In contrast, GDP projections from MiniCAM-EMF22 and ReMIND-RECIPE are endogenously determined. Both population and GDP changes are major driving forces for future energy demand (which is endogenously calculated in all models) and therefore at least indirectly determine the resulting shares of RE.

For the set of the four illustrative scenarios, the following sections give an overview of the available data for each of the different sectors. Global energy scenarios often provide detailed information on RE electricity generation. Information about the current and future RE power market is often publicly accessible, while suitable data sets about the RE heating sector and RE application in the transport sector are often not available or less detailed than for the power sector. These sectors deserve more attention, particularly because RE heating shows a significant technical potential and is in many cases already cost-effective (Aitken, 2003; Seyboth et al., 2007).

10.3.1.1 Renewable energy deployment in the electricity sector

The RE electricity sector scenarios analyzed here show more dynamic development and larger RE shares over the midterm compared to either the heating or transport sector scenarios.

Factors for market development in the RE electricity sector
Technology cost and performance assumptions are among the most influential variables affecting energy deployment in the scenarios. The largest variations in the cost assumptions can be found for solar PV, CSP, and ocean energy. As an illustrative example: for 2020, the highest cost projections for solar PV in the analyzed scenarios was USD_{2005} 5,406/kW and the lowest projection was less than half of that at USD_{2005} 2,177/kW. The upper limit is in the range of current market prices (see Section 3.8.3), although all scenarios assume cost reductions in the future. This demonstrates a typical problem in scenario analysis covering a new technology market where numbers in scenarios are often superseded by recent developments. The different cost assumptions lead to very different market development pathways in the scenarios, spanning a range for solar PV-based electricity generation, even in the mitigation-oriented scenarios, from 115 TWh (414 PJ) up to 594 TWh (2,138 PJ) in 2020 (see Table 10.4), corresponding to annual market growth rates of between 18% and 42%, respectively.

However, cost projections for installed PV systems in 2050 had a significant lower level of variability, ranging from USD_{2005} 753/kW in the low case to USD_{2005} 1,125/kW in the high case. Nevertheless, the expected deployment rates in the scenarios are quite different. With regard to the PV-based electricity generation in 2050, there is a 25-fold difference between two of the mitigation oriented scenarios: 20,790 TWh/yr (74,844 PJ/yr) in the ReMIND-RECIPE scenario versus 822 TWh/yr (2,959 PJ/yr) in MinCam-EMF22. This example illustrates the complexity of the analysis, as the resulting deployment path for PV depends not only on cost assumptions, but also on many other factors (e.g., availability and characteristics of alternative mitigation technologies like CCS and nuclear power in the case of MinCam-EMF 22).

Among all RE technologies for electricity generation, onshore wind energy saw the least variation in cost projections among the models, ranging around ±10% over the entire time frame. Cost-optimization energy models use cost assumptions for each technology as one of the main determinants of market expansion or reduction, and the input cost assumptions will therefore play a major role in determining the scenario energy mix.

Annual market potential for the RE electricity sector
Based on the energy parameters of the analyzed scenarios, the required annual production capacity (representing the annual market volume) has been either calculated ex-post (IEA-WEO2009-Baseline, ReMIND-RECIPE, MinCam-EMF 22) or has been provided by the scenario authors (ER-2010). These calculated manufacturing capacities (Table 10.4) do not include the additional needs for re-powering (i.e., replacement of old wind turbines with new ones). Annual market growth rates in the analyzed scenarios are very different, as are the expectations about how the current dynamic of the market might change. In some cases, drastic reductions in the current average market growth rates have been outlined, even in those scenarios aiming for an ambitious GHG stabilization level. The global PV industry had an average annual growth rate of 35% between 1998 and 2008 (EPIA, 2008). The wind industry experienced a 30% annual growth rate over the same time period (Sawyer, 2009). While the advanced technology roadmaps from the PV, CSP and wind industry indicate these annual growth rates can be maintained over the next decade (Sawyer, 2009; EPIA, 2010) and will decline later, most of the analyzed integrated energy scenarios expect much slower annual growth for all RE electricity supply technologies. The MiniCAM-EMF22 scenario, in particular did not project a stabilization of the growth rates at the current level, but instead found alternative non-RE mitigation technologies or other RE options (like biomass technologies) to be more cost-competitive than solar PV. Furthermore, as MiniCAM-EMF22 is representing an overshoot scenario in the medium term, the pressure to further deploy RE is much lower than in scenarios with more ambitious GHG stabilization levels for 2030 (e.g., ER-2010). Additionally, while MiniCAM-EMF22 and ReMIND-RECIPE are predominantly cost driven, in the ER-2010 scenario the market development is simulated and based on exogenous settings. With these settings, ER-2010 seeks to avoid large fluctuations in annual RE markets in order to achieve stable development and employment in the RE sector.

Table 10.4 | Overview of scenario results for four illustrative scenarios: renewable electricity generation, resulting RE market shares, annual market growth rates and required annual manufacturing capacity. Both the IEA-WEO2009-Baseline and ER-2010 have a separate category for bioenergy and geothermal combined heat and power (CHP) and power-generation-only power plants—heat generation is excluded and listed in Table 10.5. "N/A": data not available, "NSM": not specifically modelled. Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).

	Energy Parameter								Market Development									
	Generation [EJ/y]				Percent of global demand based on the demand projection of the analysed scenario [%]				Annual Market growth [%/y]					Annual Market Volume [GW/y]				
	IEA-WEO2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010	IEA-WEO 2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010	> 600 ppm IEA WEO 2008	IEA-WEO 2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010	IEA-WEO 2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010
Total projected energy demand by scenario:																		
2020	98.1	117.9	103.4	92.9														
2030	123.5	146.3	124.8	111.2														
2050	167.6	228.2	222.4	158.1														
Solar																		
PV 2020	0.4	0.8	0.4	2.1	0.4	0.7	0.4	2.3		17	27	18	42	5	12	6	36
PV 2030	1.0	9.3	1.0	7.0	0.8	6.4	0.8	6.3		11	32	10	14	18	163	17	120
PV 2050	2.3	74.8	3.0	24.6	1.4	32.8	1.3	15.6		4	12	6	7	40	651	25	211
CSP2020	0.1		0.7	2.5	0.1		0.7	2.7		17		40	62	1		3	12
CSP2030	0.4	N/A	2.0	9.8	0.4	N/A	1.5	8.8		14	N/A	13	17	2	N/A	9	45
CSP2050	0.9		5.6	32.4	0.5		2.5	20.5		4		6	6	4		11	66
Wind																		
on+offshore2020	3.6	16.7	8.6	10.3	3.7	14.2	8.4	11.0		12	33	23	26	26	175	83	101
on+offshore2030	5.5	35.2	15.8	21.1	4.5	24.0	11.9	19.0		5	9	7	8	60	381	171	229
on+offshore2050	9.1	51.4	28.3	39.0	5.4	22.6	12.5	24.7		3	2	3	3	93	262	146	202
Geothermal																		
for power generation																		
2020	0.4			1.3	0.4			1.4		6			20	1			4
2030	0.6	NSM	NSM	4.6	0.5	NSM	NSM	4.1		4	NSM	NSM	15	2	NSM	NSM	18
2050	1.0			10.7	0.6			6.8		2			5	4			21
heat & power																		
2020	0.0			0.2	0.0			0.3		13			47	0			1
2030	0.0	NSM	NSM	0.9	0.0	NSM	NSM	0.8		5	NSM	NSM	16	0	NSM	NSM	5
2050	0.1			4.5	0.0			2.9		4			9	0			11

In addition to the specific RE cost projections and assumptions for other supply side mitigation technologies (e.g., CCS, nuclear power), the future of electricity demand may help determine the future role of RE sources in terms of absolute market share. In all scenarios, high energy demand does not necessarily coincide with high deployment of RE. ReMIND-RECIPE and MiniCAM-EMF22 both project a large increase in electricity demand, but whereas MiniCAM-EMF22 predicts a low RE market share, ReMIND-RECIPE expects a high one. The ER-2010 has the lowest demand projection of all analyzed scenarios and the highest RE share. However, the RE market projections of the ER-2010 (in absolute numbers) for solar and wind are amongst the scenarios in the medium and high range, respectively, but in the lower range for hydro and biomass. High electricity demand in some of the scenarios arises from relatively low expectations about the role that energy (electricity) efficiency is expected to play in the future.

The underlying assumptions for future RE deployment growth in the scenarios do not always correspond with current manufacturing capacity and thus are not able to reflect the market behaviour (interactions) in practice. The IEA-WEO2009-Baseline scenario, for example, expects lower global deployment of wind power in 2020 than currently available manufacturing capacity,[5] which could lead to overcapacity and lower market prices for wind turbines. Lower prices for wind would, all else being equal, lead to greater deployment. This shows once more the problem of dealing with a very dynamic (and in this case policy-driven) sector using scenario analysis. On the other hand, the high scenario for wind in ReMIND-RECIPE requires an annual production capacity of 175 GW by 2020, which would represent a four-fold increase in production capacity at a global level. Both the ER-2010 and MiniCAM-EMF22 scenarios require this production capacity about a decade later (by 2030), leading to a global wind power share of 12 to 19% under the demand projections of these scenarios. The highest global wind share occurs in the ReMIND-RECIPE scenario, with a 24% portion by 2030, a share that is reached in the ER-2010 scenario only by 2050. One reason the ReMIND-RECIPE scenario projects such a high share of RE penetration is because it allows for RE learning and therefore endogenously considers technological progress as well as cost reduction effects. Moreover, the underlying model assumes perfect foresight and assumes potential bottlenecks with regard to RE integration to be resolved by anticipatory planning of grid infrastructure and storage (see Box 10.2). The deployment of wind in 2030 is lower in ER-2010 as the scenario limits the expansion of wind due to long-term integration costs and the limited possibility to reallocate the labour force between the renewable energy sector and the rest of the economy.

Figure 10.13 summarizes the resulting range of electricity generation by RE sources in the different scenario projections for 2050. Solar PV, CSP and wind power have the largest expected market potential beyond 2020. Hydropower remains at a relatively high and stable level in almost all scenarios (10 to 15% by 2030), indicating a high correlation among projections. The total renewable electricity generation market potential in the lowest case (IEA-WEO2009-Baseline) is 9% above the 2008 level with a 24% share by 2050. The highest RE electricity shares are 95% (ER-2010) and 72% (ReMIND-RECIPE) by 2050, while the MiniCAM-EMF22 scenario achieves a global renewable electricity share of 35%.

Hence, all scenarios project a significant increase in RE electricity generation. The required increase in manufacturing capacities for RE electricity generation technologies has not been identified as a fundamental barrier to growth, but certainly could represent a challenge to the growth envisioned by some of the scenarios. The availability of different mitigation technologies besides RE (e.g., fossil CCS and nuclear) and corresponding policy pathways lead to significantly different—in most cases lower—renewable energy deployment.

10.3.1.2 Renewable energy deployment in the heating and cooling sector

The heating sector is one of the largest demand sectors and the RE share—mainly traditional bioenergy—is currently high, especially in non-Annex I countries. RE for heating could also be used for cooling, which offers new and additional market opportunities for countries with Mediterranean, subtropical, or tropical climates. RE for cooling—in combination with solar architecture—can be applied for instance for air-conditioning and would in that context reduce electricity demand for electric air-conditioning significantly. RE heating and cooling technologies represent a variety of different technology pathways and require different infrastructure. Electricity-based geothermal heat pumps, small- and large-scale solar collectors and district heating with a network of bioenergy cogeneration plants are to some extent competing technologies. Low-energy buildings, for example, are a limiting factor for cogeneration networks and could make electrical heating systems such as heat pumps the preferred choice (see Section 8.2.2).

Factors for market development in the RE heating and cooling sector

Besides cost aspects, policy choices in favour of specific RE technologies and associated infrastructure (e.g., district heating networks) as well as oil and gas price projections have a significant impact on the projected deployment for each RE heating technology. Only the ER-2010 scenario indicates a significant increase in the global RE share, from 24%[6] in 2007 (IEA-WEO2009-Baseline) up to 90% by 2050, while the other of the four illustrative scenarios expect only a slight increase of RE heat to a maximum of 30% (MiniCAM-EMF22) by 2020 and a decrease again to 2007 levels by 2050. All studies indicate that electricity demand increases in the heating sector at the expense of fuel consumption.

5 Global annual installation of wind turbines in 2009 was 38.3 GW according to the Global Wind Report 2009 of the Global Wind Energy Council (GWEC).

6 Excluding traditional biomass for cooking and heating, RE provides around 5 to 6% of total global heating demand and very little cooling (Seyboth et al., 2007).

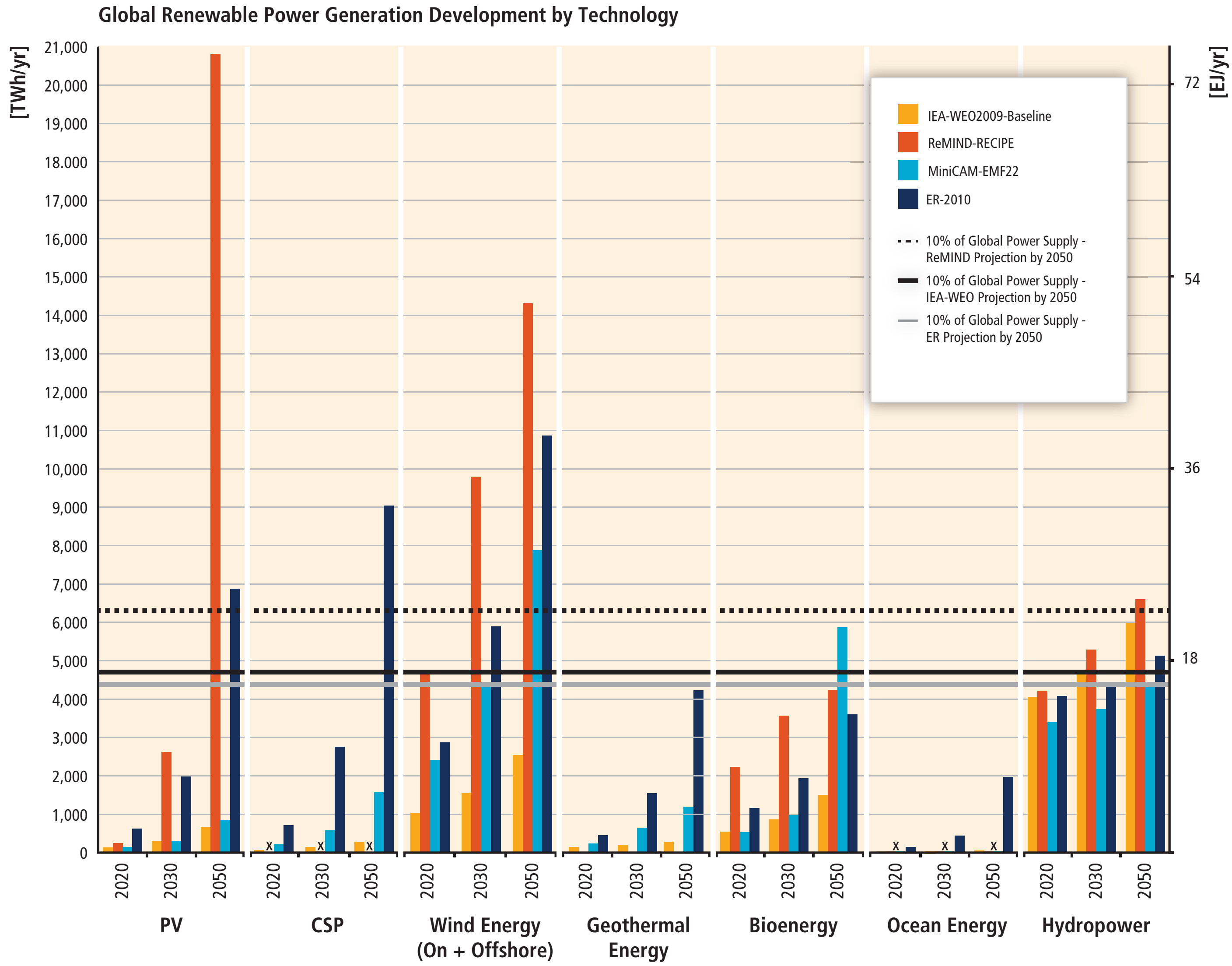


Figure 10.13 | Global RE electricity generation (development projections by technology and shares of global power generation for the four illustrative scenarios for comparison). The total renewable power generation by 2050 is 11,159 TWh/yr (IEA-WEO2009-Baseline), 63,384 TWh/yr (ReMIND-RECIPE), 21,660 TWh/yr (MiniCAM-EMF22) and 41,500 TWh/yr (ER-2010) respectively. Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).

Annual market potential for RE heating and cooling

The RE heating sector shows for the various technologies much lower growth rate projections than outlined for the electricity sector. The highest growth rates are expected for solar heating—especially solar collectors for water heating and space heating—followed by geothermal heating. Geothermal heating includes heat pumps, while geothermal cogeneration plants are presented in Section 10.3.2.1 under RE electricity generation.

In the ER-2010 scenario, solar heating systems show a significant increase with market growth rates of above 35% until 2020 and a minimum of 10% afterwards up to the end of the projection in the year 2050 (see Section 3.4).

A shift from the traditional and sometimes unsustainable use of bioenergy for heating towards modern and more sustainable uses of bioenergy heating such as wood pellet ovens or biogas burners are assumed in all scenarios. The more efficient use of biomass would increase the share of biomass heating without the necessity to increase the overall demand for biomass. However, only one of the analyzed scenarios provides information about the specific breakdown of traditional versus modern biomass use. Therefore, it is not possible to estimate the real annual market development of the different bioenergy heating systems.

The market potential at both domestic and industrial scales for RE heating technologies such as solar collectors, geothermal heat pumps or pellet heating systems overlaps with the market potential analysis of the RE power sector. While the solar collector market is independent from the electricity sector, biomass cogeneration provides electricity as well as heat. Geothermal heat pumps use electricity for their operation and therefore increase the demand for electricity. RE heating and cooling is more dispersed than RE electricity generation, which, together with lack of metering, is why statistical data are poor and further research is needed. Based on the energy parameters of the four scenarios analyzed, the required annual market volume has been calculated in order to identify the needed manufacturing capacities and how they relate to current capacities. Table 10.5 provides an overview of the projected annual market volumes.

Manufacturing capacities for all RE heating and cooling technologies must be expanded significantly in order to realize the projected RE heat production in all scenarios. The annual market volume for solar collectors is projected to triple from less than 35 PJ/yr in 2020 to 100 PJ/yr in 2030 in the IEA-WEO2009-Baseline case and up to 1,162 PJ/yr in the ER-2010 case. Due to the diverse technology options for bio- and geothermal energy heating systems and the low level of information in all analyzed scenarios, it is not possible to provide here a full set of specific market size data by technology.

The total share of RE heating systems in all scenarios by 2050 significantly varies, from a market share of around 23% (IEA-WEO2009-Baseline, ReMIND-RECIPE and MiniCAM-EMF22) to 91% (ER-2010). The resulting shares for RE technologies for heating and cooling are significantly driven by the scenario assumptions (including assumptions about infrastructure changes such as the expansion of district heating networks, as well as improvements in building efficiency and industrial processes). The large share of RE heating systems in ER-2010 depends, for instance, on the assumption that district heating systems for the distribution of solar-, geothermal- and bioenergy-generated heat would be available and competitive after 2020 (see Table 10.5).

10.3.1.3 Renewable energy deployment in the transport sector

The use of RE in the transport sector in all analyzed studies was limited to liquid biofuels, biomethane from biogas and RE-based electric vehicles for private use or public transport. Most of the scenario literature does not take into account new technologies such as second-generation sails for ships. Additionally, different reporting and categorization within the underlying scenario models do not support a stringent comparison of scenario results. However, even this comparison shows the substantial influence of driving forces (e.g., GHG stabilization levels) on the resulting RE share, which differs between scenarios by up to an order of magnitude (see Table 10.6).

10.3.1.4 Global renewable energy primary energy contribution

Figure 10.14 provides an overview of the projected primary energy production (using the direct equivalent methodology, see Section 1.1.8) by source for the four selected scenarios for 2020, 2030 and 2050, and compares the numbers with different projected global primary energy demands. Bioenergy has the highest market share, on average, across all of the scenarios, followed by solar energy, though scenario-specific results vary. This is largely driven by the fact that bioenergy (see Chapter 2) can be used across all sectors (electricity, heating and cooling as well as transport) in combination with the selected primary energy accounting methodology. As the available land for bioenergy is limited and competition with nature conservation issues as well as food and materials production is crucial, the sectoral use for the available bioenergy significantly depends on scenario assumptions and underlying priorities (see Sections 2.2, 2.5 and 9.3.4). Solar energy can be used in direct form for heating and cooling and electricity generation (and indirectly via electricity for transport purposes), but solar technology starts from a relatively low level. The relatively lower average primary energy share for wind and hydropower may in part be due to their exclusive use in the electricity sector, though some scenarios show substantial contributions from wind in particular.

The total RE share in the primary energy mix by 2050 has a substantial variation across all four scenarios. With 15% by 2050—compared to 12.9% in 2008—the IEA-WEO2009-Baseline projects the lowest primary RE share, while ER-2010 reaches 77%, the MiniCAM-EMF22 achieves 31% and ReMIND-RECIPE 48% of the worlds primary energy demand with RE. While it is not surprising that without constraining GHG concentration levels, RE deployment rates are rather low (IEA-WEO2009-Baseline), it is worth mentioning that there is even a significant difference (more than a factor of two with regard to the relative RE shares) between the mitigation-oriented scenarios. Once more, this is a result of many aspects; that is, technology-specific assumptions (e.g., costs) and model characteristics (e.g., inclusion of endogenous learning), assumptions about the availability of other mitigation technologies and the expected energy demand. The overall total global RE deployment by 2050 in all analyzed scenarios represents less than 2% of the available technical RE potential (see Section 10.3.2.2). The wide range of RE shares is a function of different assumptions about policy, technology costs, chosen mitigation technologies (e.g., availability of CCS) and future energy demand projections.

10.3.2 Regional breakdown – technical potential versus market deployment

This section focuses on the regional perspective and provides an overview of the regional market penetration paths given in the four scenarios. A comparison with the technical potential per region for each technology indicates to what level the regional technical potentials will be exploited. Additionally, an in-depth cost curve analysis of three regions (China, India and Europe) provides deeper insights into the assumed cost development of renewable electricity generation.

10.3.2.1 Regional renewable energy supply curves

Regional energy supply cost curves can serve as ‘snapshots’ of the selected scenarios and are thus an alternative perspective on scenario

Table 10.5| Projected RE heat production, possible market shares, annual growth rates and annual market volumes for the four illustrative scenarios—excluding additional needs for re-powering. "N/A": data not available. Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER- 2010 (Teske et al., 2010).

	Energy Parameter								Market Development							
	Generation [EJ/yr]				Percent of global demand based on demand projections of the scenarios (incl. CHP) [%]				Annual Market growth [%/yr]				Annual Market Volume [PJ/yr]			
	IEA-WEO 2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010	IEA-WEO 2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010	IEA-WEO 2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010	IEA-WEO 2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010
Total projected heat demand by scenario:																
2020	158	190	135	152												
2030	174	198	145	156												
2050	205	160	151	152												
Solar																
Solar Thermal 2020	0.8	N/A	N/A	6.5	0.5	N/A	N/A	4.5	10	N/A	N/A	39	32	N/A	N/A	409
Solar Thermal 2030	1.6	N/A	N/A	15.8	0.9	N/A	N/A	12.2	8	N/A	N/A	12	100	N/A	N/A	1162
Solar Thermal 2050	3.1	N/A	N/A	38.7	1.5	N/A	N/A	33.7	3	N/A	N/A	5	187	N/A	N/A	1568
Geothermal heating																
2020	0.6	0.1	N/A	4.4	0.4	0.1	N/A	3.0	14	-6	N/A	41	6	-1	N/A	63
2030	0.9	0.2	N/A	9.3	0.5	0.1	N/A	7.0	4	7	N/A	10	12	3	N/A	149
2050	1.6	4.6	N/A	26.5	0.8	2.8	N/A	26.4	3	18	N/A	7	22	66	N/A	283
Bioenergy heating																
2020	36.2	40.8	40.4	41.7	23.0	21.5	30.0	27.6	not specifically modelled				28	112	104	130
2030	38.2	39.8	39.0	45.4	22.0	20.1	27.0	29.7					678	698	686	811
2050	43.6	32.4	31.7	48.1	21.3	20.2	21.0	31.7					270	191	186	295
Total renewables heating																
2020	37.7	40.9	40.4	52.6	23.9	21.6	20.0	35.0	1	N/A	N/A	5	66	N/A	N/A	601
2030	40.7	40.0	39.0	70.5	23.4	20.2	27.0	48.7	1	N/A	N/A	4	791	N/A	N/A	2122
2050	48.4	37.0	31.7	113.3	23.6	23.1	21.0	90.8	1	N/A	N/A	3	479	N/A	N/A	2146

Table 10.6 | Projected RE shares in the transportation sector for the four illustrative scenarios. (Note: The electricity share includes RE- and non-RE-based electricity as well as hydrogen produced with electricity. For the IEA-WEO2009-Baseline, MiniCAM-EMF22 and ER-2010 the RE share in the electricity sector has been used to identify the RE share of the electricity used for the transport sector. Therefore the total RE share within the transport sector is lower than the sum of the percentages.) Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).

RE share in Transport Sector		IEA-WEO2009-baseline (%)	ReMIND-RECIPE (%)	MiniCAM-EMF22 (%)	ER-2010 (%)
Biofuels	2020 2030 2050	4.3 4.6 5.0	2.2 12.9 26.8	6.8 9.5 10,2	5.4 9.3 14.0
Electricity (including conventional generation+ hydrogen)	2020 2030 2050	1.4 1,5 1,6	0.1 1.0 6.7	2.5 4.1 11.2	4.4 14.7 57.4
Total RE share	2020 2030 2050	4.6 4.9 5.4	2.3 13.9 33.6	7.5 10.8 15.6	7.3 19.1 68.9

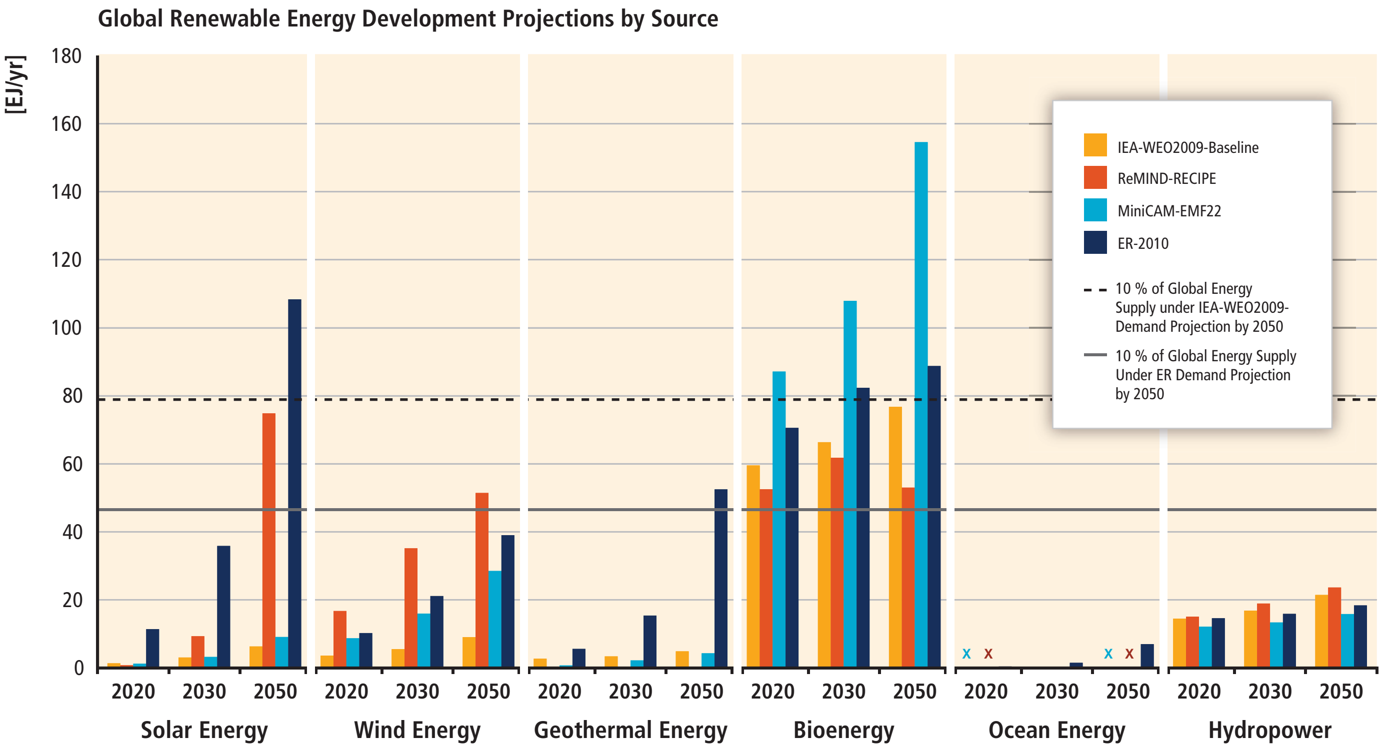


Figure 10.14 | Global RE development projections by source and global renewable primary energy shares (direct equivalent) by source for a set of four illustrative scenarios. The total renewable energy deployment projected for 2050 is 117 EJ/yr (IEA-WEO2009-Baseline), 214 EJ /yr (ReMIND-RECIPE), 323 EJ/yr (MiniCAM-EMF22) and 314 EJ/yr (ER-2010) respectively. Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).

results. The following curves (see Figures 10.15, 10.16 and 10.17) are illustrative examples and represent a cross-section of three of the four scenarios (specific data for MiniCAM-EMF22 are not available for this exercise).[7] The regional energy supply cost curves focus on a specific target year and relate the deployment of certain RE electricity technologies in the different regions (as a result of the specific scenarios) to their cost levels in discrete steps. Thus, the curves report scenario results (potential deployment) and are not a reflection of RE technical potentials.

This presentation alleviates two major shortcomings of the cost curve method (which are discussed in a more general and comprehensive way in Section 10.4). First, recognizing the crucial determinant role of carbon emission factors, energy pricing and fossil fuel policies in the ultimate shape of abatement cost curves, only RE supply cost curves are created (and not mitigation cost curves). Second, in order to capture the uncertainties in cost projections, several scenarios were reviewed. Using dynamic scenarios that span a longer time horizon to create the curves as done here also prevents the problem of following a static perspective.

Beyond the general issues about cost curves detailed in Section 10.4, it is important to note a few points for proper interpretation of the curves.

7 Unlike other parts of this section, IEA-WEO2008-Baseline and not IEA-WEO2009-Baseline is used to represent a baseline scenario here due to data constraints.

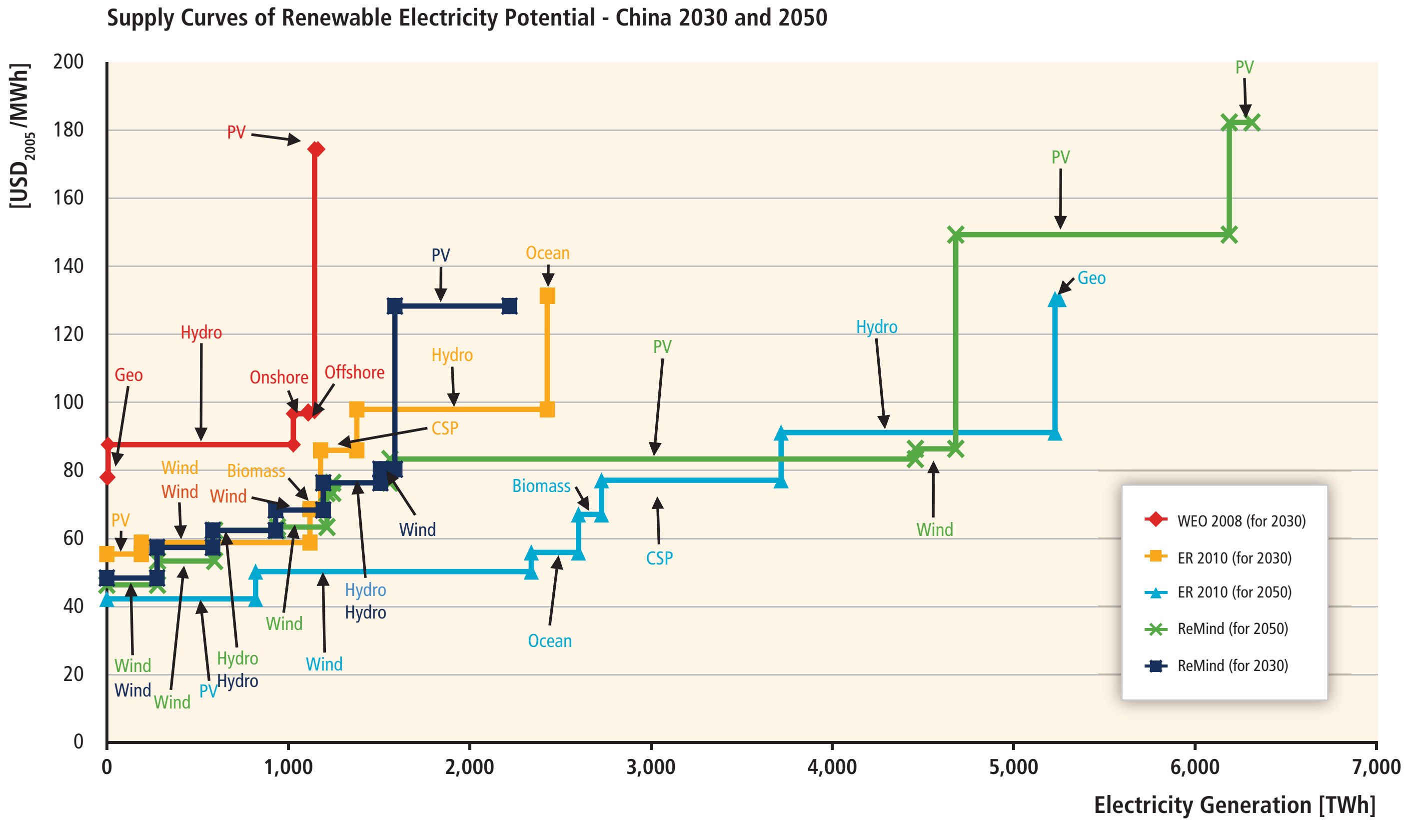


Figure 10.15 | Illustrative RE electricity supply curves for China for the years 2030 and 2050. The curves report scenario results (level of deployment) and are not a reflection of RE technical potential.

First, the ER-2010 and the IEA-WEO2008-Baseline scenario data were not as detailed in cost data as was the ReMIND-RECIPE scenario. For the former two scenarios, each technology in a region is represented by a single average cost. Second, average costs for a technology for a whole region can mask the more cost-effective sub-categorization of technologies and sites into an average. Thus, with this approach it is not possible to highlight the cheaper (or more expensive) sites and sub-technologies.

It was not possible to deduct existing capacity from the RE deployment by cost level. Thus, values include all capacity that can be installed in the target year allowed by the different constraints assumed. Due to space and data constraints, only curves for the three regions and the electricity sector are shown.

The figures illustrate several important trends. Perhaps the most important message is the importance of a long-term vision for RE. RE deployment is consistently and significantly larger for 2050 than for 2030 in all regions and scenarios (caused by cost degression effects), often doubling at medium cost levels, except for OECD Europe. Even in this region, there is a large increase in RE deployment between these two time periods, although the ER-2010 scenario does not envision a larger than approximately 50% increase in RE deployment at most cost levels. On the other hand, a more than doubling of the potential deployment in both China and India in both scenarios during this period can be seen.

When comparing the three models, the IEA-WEO2008-Baseline projects the highest costs and lowest RE deployment in all three regions, while typically the ReMIND-RECIPE scenario envisions the lowest cost levels and highest RE deployment.[8] While in some regions the curves from different models are close to each other and project similar deployment levels at similar cost levels, the technologies they consider the most promising are often different. For instance, the ReMIND-RECIPE scenarios see the largest promise in PV and in 2050 the lion's share of its cost-effective RE deployment comes from this technology in all three regions. Projected RE deployment in the ER-2010 scenario consists of a balance of wind (on- and offshore), PV, concentrating solar power (CSP), hydropower and geothermal energy. The IEA-WEO2008-Baseline projects mainly wind and hydropower through 2030, and considers PV as too expensive in all regions. This is the technology for which the scenarios differ the most both in terms of costs and deployment level. For instance, the ReMIND-RECIPE's highest PV cost band for 2050 in OECD Europe is approximately one-fourth of the average PV cost projected by the IEA-WEO2008-Baseline by 2030,

8 ReMIND-RECIPE assumes that RE technologies will be deployed at the industrial scale at optimal sites and transported over large distances (up to continental scale) to demand centres. It implicitly assumes that bottlenecks, for example, with respect to grid infrastructure, are avoided by early and anticipatory planning. This results in high capacity factors in ReMIND-RECIPE compared to other scenarios, which in turn has a strong effect on electricity generation costs and deployment levels.

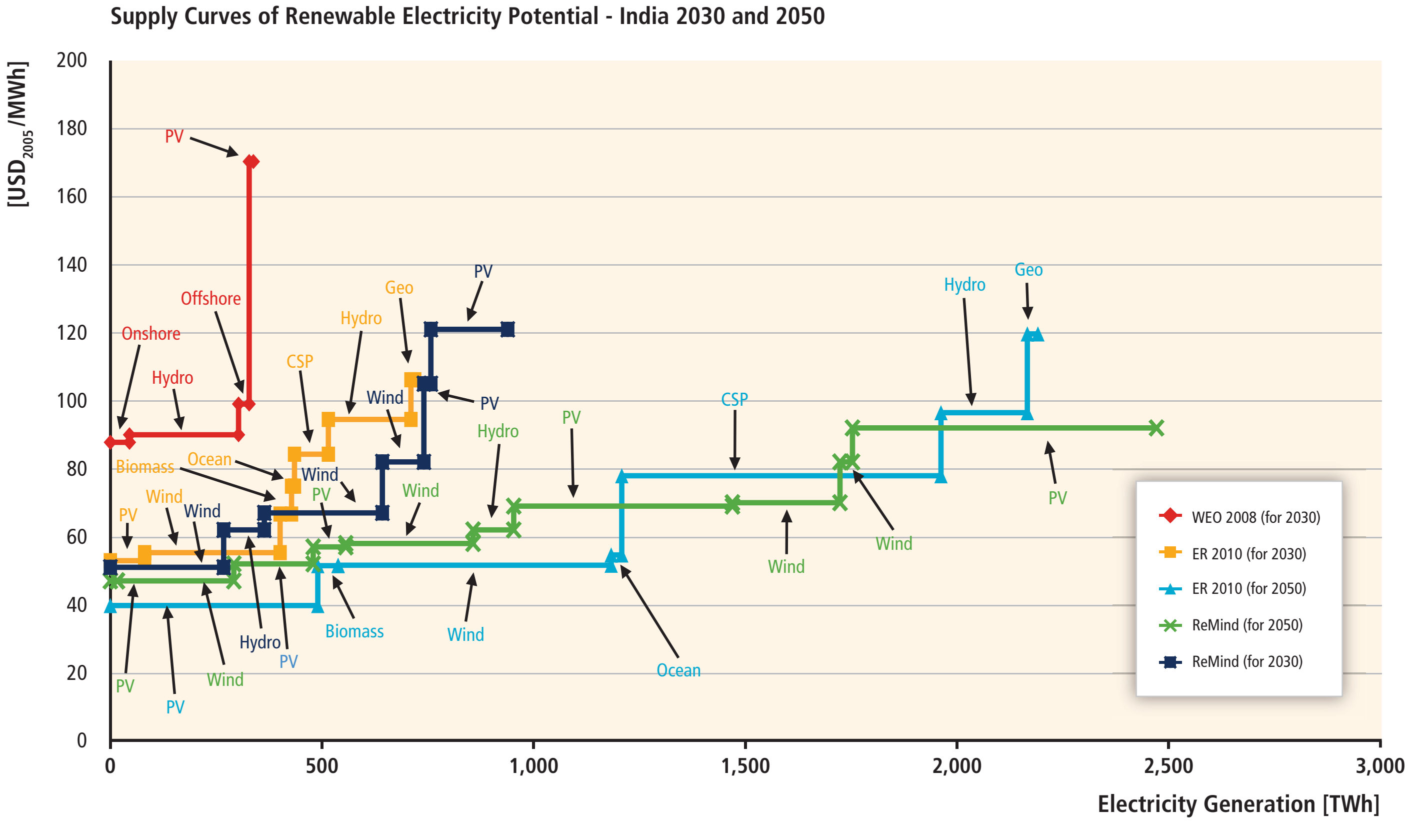


Figure 10.16 | Illustrative RE electricity supply curves for India for the years 2030 and 2050. The curves report scenario results (level of deployment) and are not a reflection of RE technical potential.

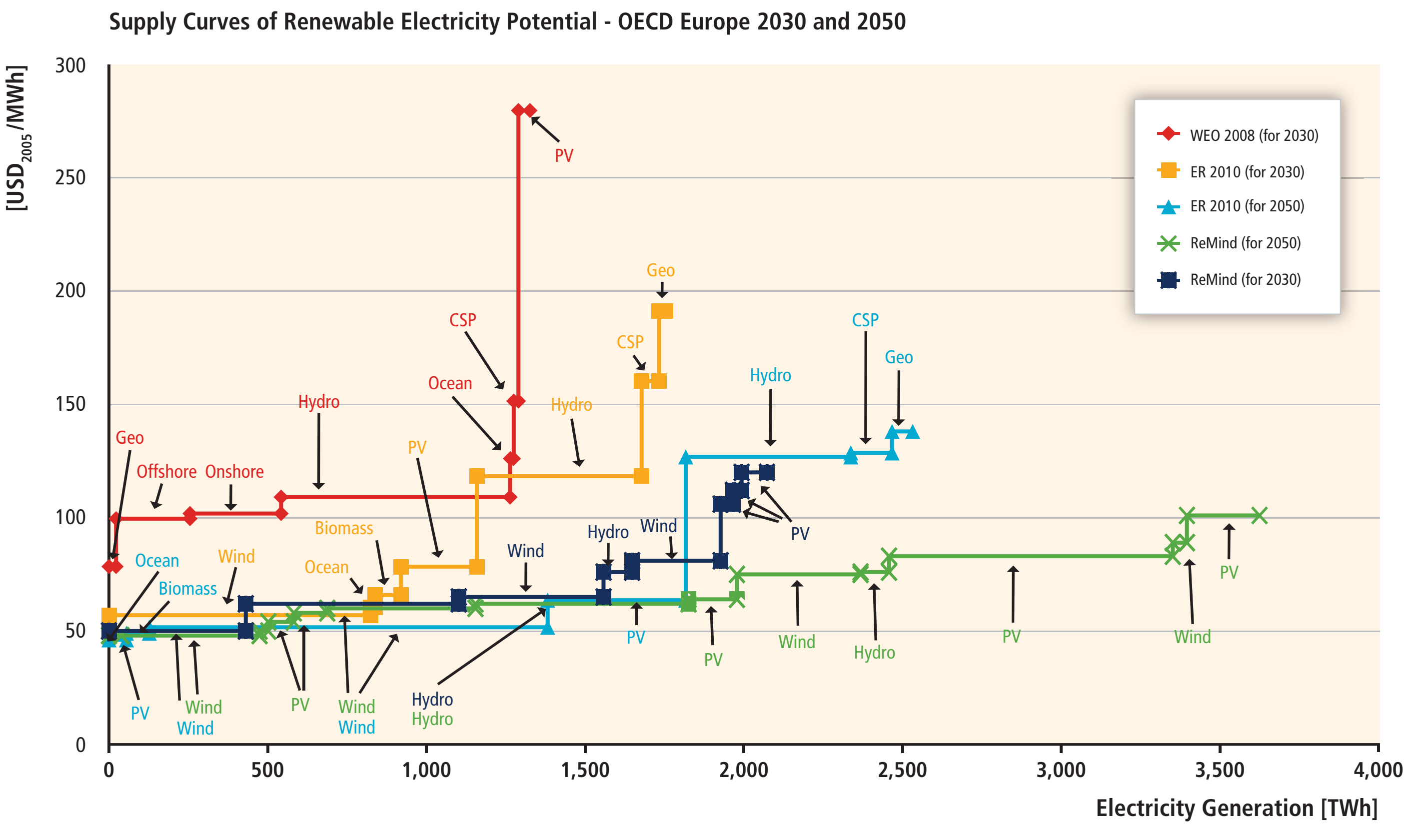


Figure 10.17 | Illustrative RE electricity supply curves for OECD Europe for the years 2030 and 2050. The curves report scenario results (level of deployment) and are not a reflection of RE technical potential.

and even the highest cost band in 2030 is half the average PV cost projected by that same study.

The different scenarios see different roles and costs for CSP. ReMIND-RECIPE considers a generic solar technology parameterized based on PV, and thus this technology was not specifically modelled in this scenario. The ER-2010 scenarios see a larger role for CSP than for PV in both China and India in the longer term, albeit at a higher cost. Neither of the models attributes a major deployment of geothermal energy, but they see its costs very differently. The costs of this electricity generation source in the IEA-WEO2008-Baseline is approximately half of that in the ER-2010 scenarios for the same target year (2030), and even in 2050 the ER-2010 cost projections are significantly higher for this technology than in the IEA-WEO2008-Baseline scenario in 2030—although the deployment levels at this cost are several times higher than projected by the other scenarios, making a noticeable contribution to the total deployment in 2050 in India and OECD Europe from among the examined regions. The ReMIND-RECIPE scenarios do not consider geothermal power.

With regard to the quality of electricity supply, it is also important to keep in mind that the presented supply curves do not distinguish between highly variable, and sometimes unpredictable, energy sources and dispatchable energy sources. In this context, a cost premium due to a higher reliability level that might be needed is also not considered as additional backup costs for highly variable RE sources.

10.3.2.2 Primary energy by region, technology and sector

This section provides an overview of the potential deployment paths given in the four scenarios versus the technical potential per region. For each technology, deployment shares indicate to what level the regional technical potential has been exploited. Figure 10.19 compares the resulting primary energy contribution of RE in relation to the technical potential by region and technology for the four scenarios, while Figure 10.18 gives an overview for all scenarios, but for RE as a whole by region, compared to the demand projections by 2050 and the current regional primary energy demand.

The maximum deployment share out of the overall technical potential for RE in 2050 was found for India with a total of 22.1% (ER-2010), followed by China with a total of 17.7% (ER-2010) and OECD Europe 15.3% (ER-2010). Two regions had deployment rates of about 5 to 7% of the regional available technical RE potential by 2050: 6.9% in developing Asia (MiniCAM-EMF22) and 5.5% for OECD North America (ER-2010). The remaining five regions used less than 4.5% of the

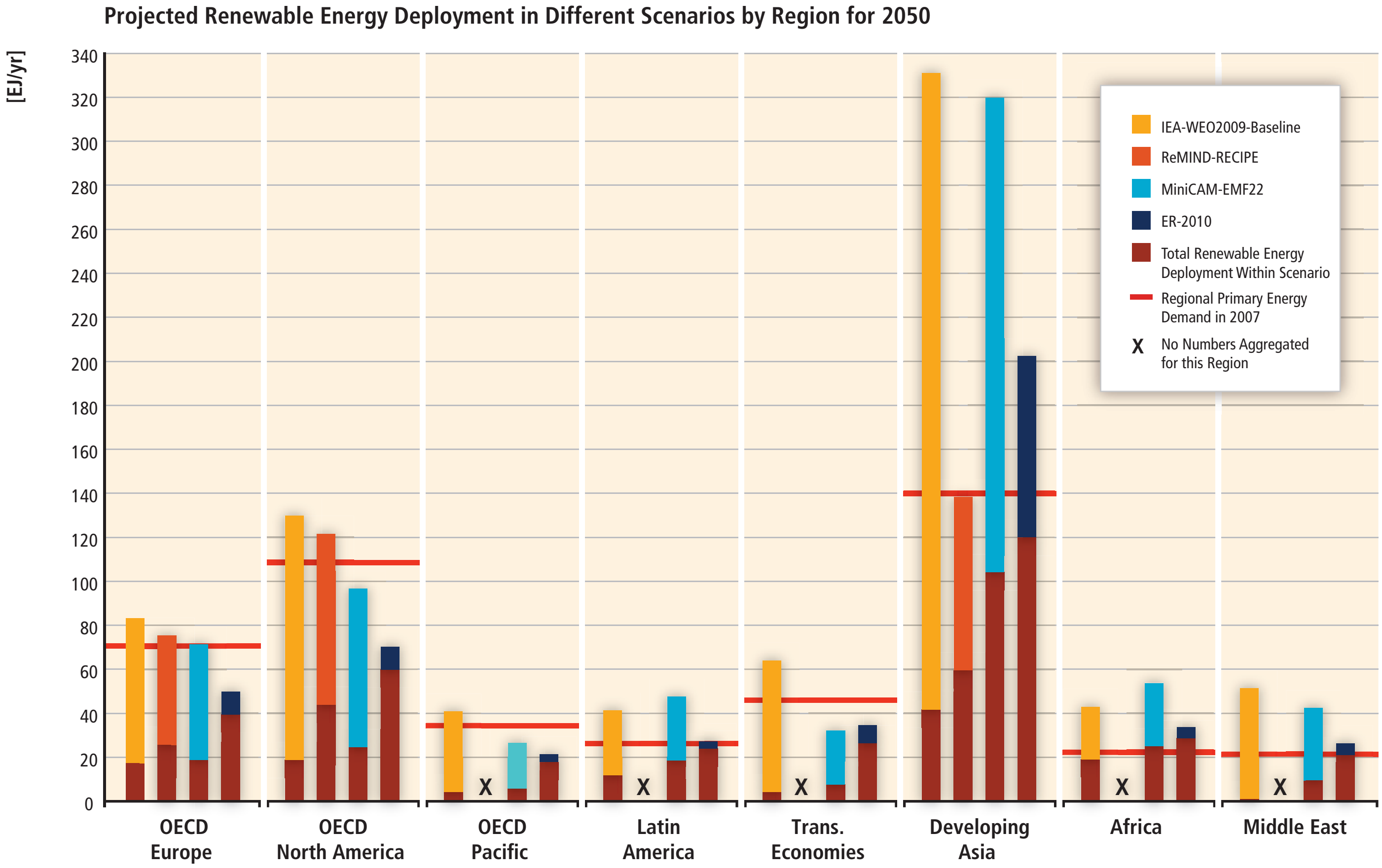


Figure 10.18 | Regional breakdown of possible energy demand and RE potential deployment for the selected set of four scenarios in 2050 (direct equivalent). Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010). For comparison, total primary energy demand in 2007 is given (IEA, 2009).

available technical potential for RE. Wind energy has been exploited to a much larger extent in all regions than solar energy. Geothermal energy does not reach the technical potential limit in any of the scenarios analyzed, with the deployment rate remaining below 5% at both the regional and global level. Apart from some specific regions (e.g., China, India and Europe), the same is the case for ocean energy as a very young technology form. The established hydropower potential deployment at a global level covers roughly one-third of the technical potential, while in some specific regions the estimated capacity for 2050 is already very close to the maximum possible capacity.

While the overall technical potential for RE exceeds current global primary energy by an order of magnitude (see Chapter1), even the two most ambitious scenarios in terms of RE deployment with comparable high growth rates for RE did not exceed 2.5% (ER 2010: 2.3%; MiniCAM-EMF22: 1.8%) of the given technical RE potential for 2050 at a global level.

10.3.3 Greenhouse gas mitigation potential of renewable energy in aggregate and as individual options

This section focuses on the question of how much RE can contribute to climate change mitigation, both in aggregate and as individual technologies. The numbers given in this section are derived from the results of the four illustrative scenarios (e.g., the underlying deployment paths of different RE technologies). As the amount of GHGs mitigated by renewable technologies greatly depends on the GHG intensity of the energy mix and on whether it is assumed that RE substitutes for fossil fuels only or also possibly other energy generation technologies (e.g., nuclear, other REs), the GHG mitigation potentials are provided over a range in this section to reflect the given uncertainties. Note that besides the fact that numbers are shown only for a limited number of scenarios, the following calculation is necessarily based on simplified assumptions and can only be seen as indicative.

For the power sector, the range is defined by the following three cases:

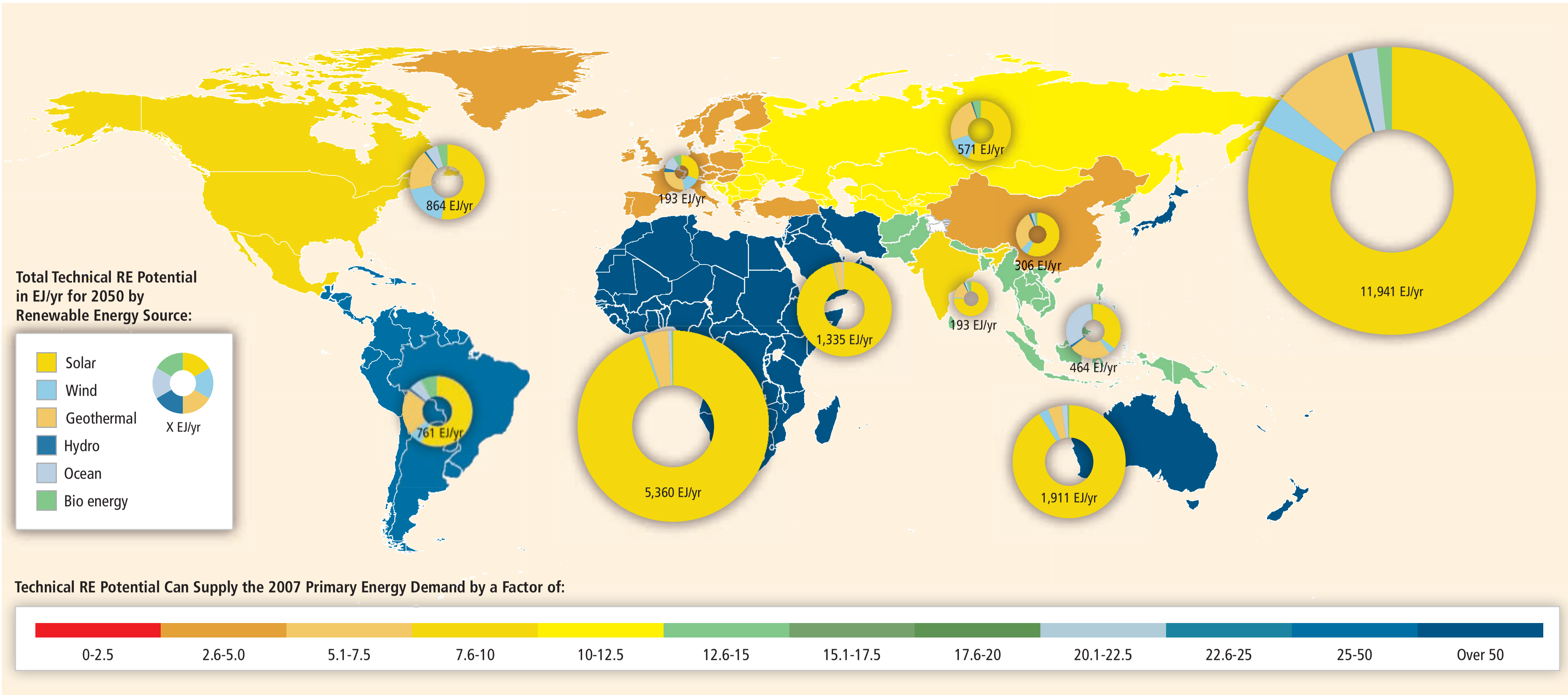
- Upper case: Substitution of the specific average CO_2 emissions of the fossil generation mix under the baseline scenario.
- Medium case: Substitution of the specific average CO_2 emissions of the overall generation mix under the baseline scenario.
- Lower case: Substitution of the specific average CO_2 emissions of the generation mix of the particular analyzed scenario.

For the electricity sector, Table 10.7 shows the underlying assumptions for the calculation of the CO_2 mitigation potential. The specific carbon

Table 10.7 | Assumptions for the CO_2 mitigation potential calculation: average specific CO_2 emissions from electricity generation or heat supply being substituted in the different scenarios. Sources for the underlying RE deployment: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).

Average specific CO_2 Emissions		IEA-WEO2009-Baseline	ReMIND-RECIPE	MiniCAM-EMF22	ER-2010
Power Sector					
Upper Case	2020 [g CO_2/kWh]	812			
	2030 [g CO_2/kWh]	768			
	2050 [g CO_2/kWh]	716			
Medium Case	2020 [g CO_2/kWh]	625			
	2030 [g CO_2/kWh]	580			
	2050 [g CO_2/kWh]	531			
Lower case	2020 [g CO_2/kWh]	599	543	487	544
	2030 [g CO_2/kWh]	564	370	374	345
	2050 [g CO_2/kWh]	500	190	147	123
Heating + Cooling Sector					
Upper Case (Medium + 10%)	2020 [kt CO_2/PJ]	78.1[(1)]			
	2030 [kt CO_2/PJ]	78.1[(1)]			
	2050 [kt CO_2/PJ]	78.1[(1)]			
Medium Case	2020 [kt CO_2/PJ]	72[(2)]			
	2030 [kt CO_2/PJ]	72[(2)]			
	2050 [kt CO_2/PJ]	72[(2)]			
Lower Case (Medium -10%)	2020 [kt CO_2/PJ]	63.9[(3)]			
	2030 [kt CO_2/PJ]	63.9[(3)]			
	2050 [kt CO_2/PJ]	63.9[(3)]			

Notes: The medium case for the power sector was defined by taking the average of the baseline scenarios of the studies IEA-WEO2009, ReMIND-RECIPE and MiniCAM-EMF22 (ER-2010, being based on IEA-WEO2009, has no baseline of its own). The upper case is defined by only taking the fossil fuel component of the above baseline scenarios. The lower case assumes the substitution of the specific average CO_2 emissions of the generation mix of the particular analyzed scenario. As a pragmatic assumption for direct heat bioenergy 50% of the emission factor for heating and cooling have been applied to consider that relevant GHG emission occur in the process chain.(1) 39 kt CO_2/PJ (2) 36 kt CO_2/PJ (3) 32 kt CO_2/PJ.

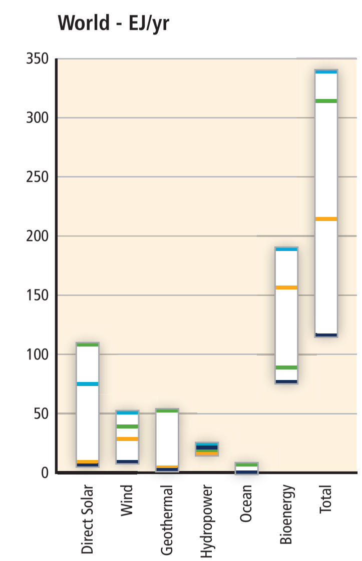


RE potential analysis: Technical RE potentials reported here represent total worldwide and regional potentials based on a review of studies published before 2009 by Krewitt et al. (2009). They do not deduct any potential that is already being utilized for energy production. Due to methodological differences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

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

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

IEA-WEO2009-Baseline
ReMIND-RECIPE
MiniCAM-EMF22
ER-2010
Range



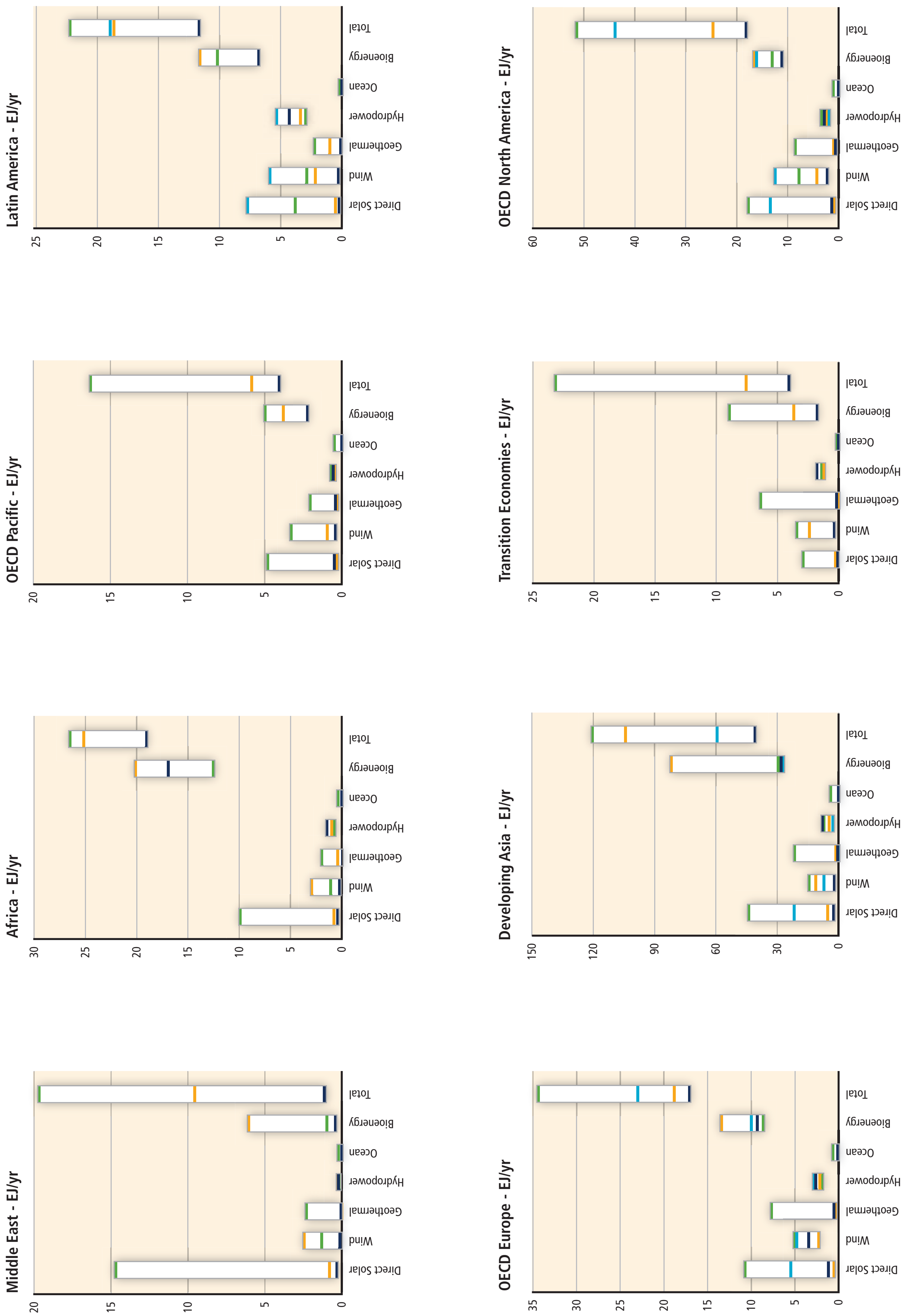

Latin America - EJ/yr
OECD North America - EJ/yr
OECD Pacific - EJ/yr
Transition Economies - EJ/yr
Africa - EJ/yr
Developing Asia - EJ/yr
Middle East - EJ/yr
OECD Europe - EJ/yr
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total

Figure 10.19 | (Preceding pages) Overview of the relation between the primary energy contribution of RE (direct equivalent) and the corresponding technical potential for different technologies and regions for 2050 for the selected set of four scenarios. Due to differences in regional aggregation not all models provide data for all regions.

Note: Data for technical potential presented in Chapters 2 through 7 may disagree with the figures in Krewitt et al. (2009) due to differences in assessed studies and the underlying methodologies (see also Chapter 1, in which Krewitt et al. (2009) worldwide RE technical potential estimates are compared to a range of values in the literature presented in Chapters 2 through 7).

emissions factor for the year 2050 ranges from 716 g CO_2/kWh (199 g CO_2 /kJ) (upper case) to between 123 and 190 g CO_2/kWh (34 to 53 g CO_2/kJ) (lower case) for the selected mitigation scenarios. As noted in the table, a range of emission factors was also assumed for RE used in heating and cooling applications. In contrast to electricity generation, no specific information for these applications was available from the different scenarios. Against that background for the calculation, a pragmatic approach was selected for the underlying emission factors starting with a substitution of oil for the medium case and considering an uncertainty range.

Biofuels and other RE options for transport are excluded in the calculation due to limited data availability. To reflect the embedded GHG emissions saved due to bioenergy used for direct heating, only half of the theoretical CO_2 savings have been considered in the calculation. Given the high uncertainties and variability of embedded GHG emissions (see Chapter 2 for the discussion of indirect GHG emissions from the whole biomass process chain and Chapter 9 for a more general discussion on lifecycle assessment of different RE sources) this is necessarily once more a simplifying assumption.

Figure 10.20 shows the resulting annual CO_2 reduction potential by RE source for all scenarios for 2030 and 2050. The black line at 2.9 Gt CO_2/yr identifies 10% of the global energy-related CO_2 emissions; the red line here indicates 33% of total energy-related CO_2 emissions (base year for both lines is 2008).

The three mitigation scenarios of the illustrative scenarios show a wide range of possible RE contribution. While in all three, hydropower and wind energy play leading roles in 2030, in two of the scenarios (ReMIND-RECIPE, ER-2010) solar energy supersedes the other technologies by 2050. In contrast, as discussed earlier, due to the specific primary energy accounting approach the primary energy share ranking is led by bioenergy (see Section 10.3.1.4). This shows that the contributions (and effectiveness) of RE technologies vary by what perspective is taken (GHG mitigation or primary energy perspective). Further, the dependence of the resulting impacts on underlying assumptions is of great importance.

The resulting GHG reduction potential of all RE technologies heavily depends on the complex system behaviour determining the substituted

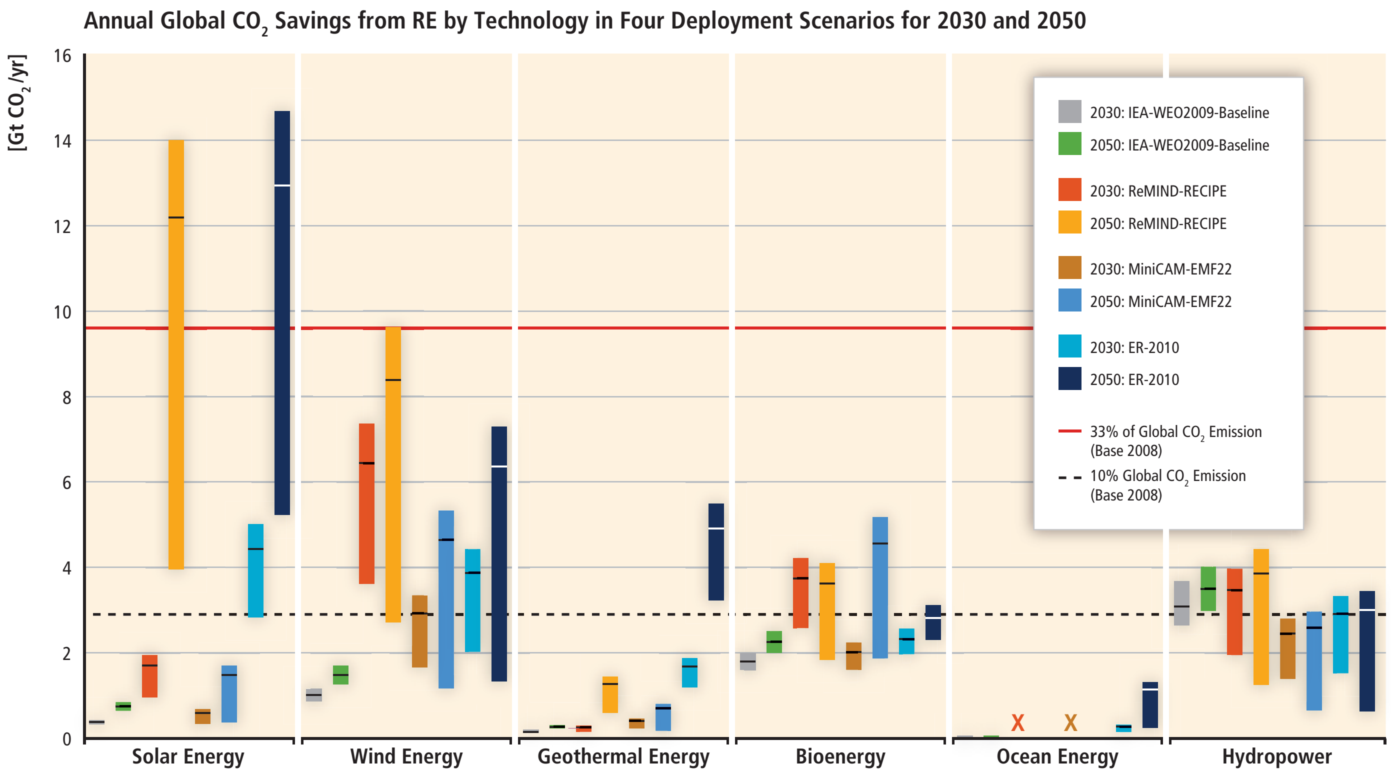


Figure 10.20 | Expected range of annual global CO_2 savings from RE for the four illustrative scenarios for 2030 and 2050. Biofuels for transport are excluded, and biomass used for direct heating only accounts for half the CO_2 savings due to imbedded GHG emissions from bioenergy. The presented range marks the high uncertainties regarding the substituted energy source: While the upper limit assumes full substitution of high-carbon fossil fuels, the lower limit considers specific CO_2 emissions of the analyzed scenario itself. Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).For comparison, global CO_2 emissions in 2008 are given (IEA 2010d).

energy sources. Considering the limitations of the rough approximations applied here, in the four scenarios the corresponding annual CO_2 reduction potential in 2050 reaches from 4.2 Gt CO_2/yr (MiniCAM-EMF22 lower case) to 35.3 Gt CO_2/yr (ER-2010 upper case) (Figure 10.21). At the upper level, this is equal to approximately 80% of the energy-related CO_2 emissions of the analyzed baseline scenario (IEA-WEO2009-Baseline) in the year 2050.

Cumulative CO_2 reduction potentials from RE sources up to 2020, 2030 and 2050 (Figure 10.22) have been calculated on the basis of the annual average CO_2 savings shown in Figure 10.21.[9] Based on this, the analyzed scenarios would have a cumulative reduction potential (2010 to 2050) in the medium case approach of between 244 Gt CO_2 (IEA-WEO2009-Baseline) under the baseline conditions, 297 Gt CO_2 (MiniCAM-EMF22), 482 Gt CO_2 (ER-2010) and 490 Gt CO_2 (ReMIND-RECIPE scenario). The full range across all calculated cases and scenarios for the cumulative CO_2 savings is between 218 Gt CO_2 (IEA-WEO2009-Baseline) and 561 Gt CO_2 (ReMIND-RECIPE), compared to about 1,530 Gt CO_2 cumulative fossil and industrial CO_2 emissions in the IEA-WEO2009-Baseline scenario during the same period.

Again, these numbers exclude CO_2 savings from RE use in the transport sector (including biofuels and electric vehicles). The overall CO_2 mitigation potential can therefore be higher.

10.3.4 Comparison of the results of the in-depth scenario analysis and knowledge gaps

All in-depth scenarios analyzed here show an increase in RE sources across all sectors. However, the electricity sector is in the forefront of all sectors and here the most dynamic increase in RE capacity is projected. Hydropower is expected to play the dominant role in the RE electricity sector in the near term and on a global basis, but based largely on already-existing installed generation capacity. Wind is expected in all three mitigation scenarios to overtake hydropower in terms of global electricity supply by 2030. The results for all other technologies are far more diverse. Two scenarios see solar PV as an important player in the electricity sector after 2030, with a share of more than 10% by 2050, while the baseline scenario projects PV remaining at marginal levels. In all but the ER-2010 scenario, the foreseen role for geothermal energy remains low at levels

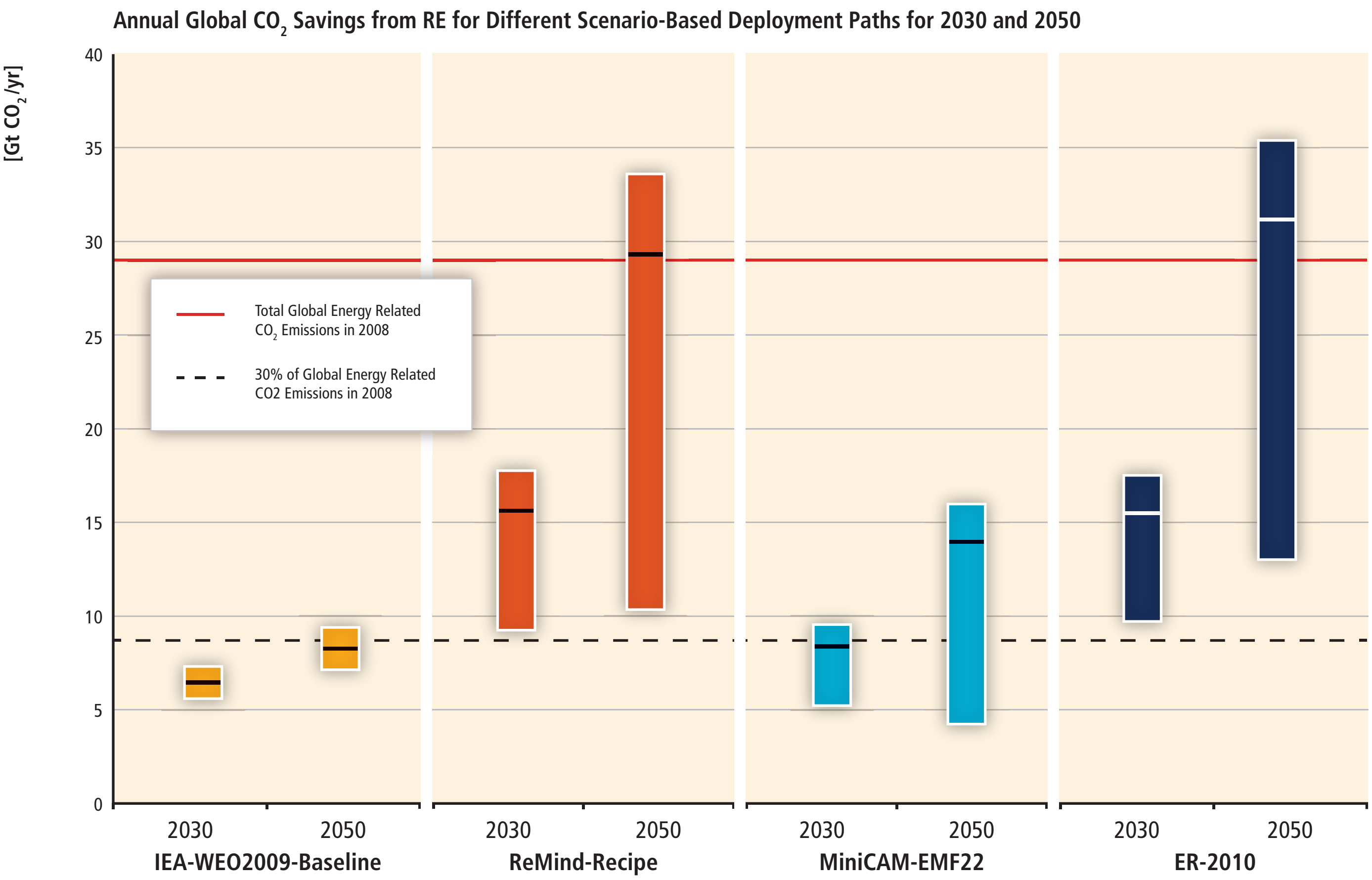


Figure 10.21 | Range of annual global CO_2 savings from RE in total for a set of four illustrative scenarios for 2030 and 2050 (Note: biofuels for transport are excluded, and biomass used for direct heating only accounts for half the CO_2 savings due to embedded GHG emissions from bioenergy). (The presented range marks the high uncertainties regarding the substituted energy source: while the upper limit assumes a full substitution of high-carbon fossil fuels, the lower limit considers specific CO_2 emissions of the analyzed scenario itself.) Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).

9 For the integration, the time periods 2020 to 2030 and 2030 to 2050 were linearly interpolated.

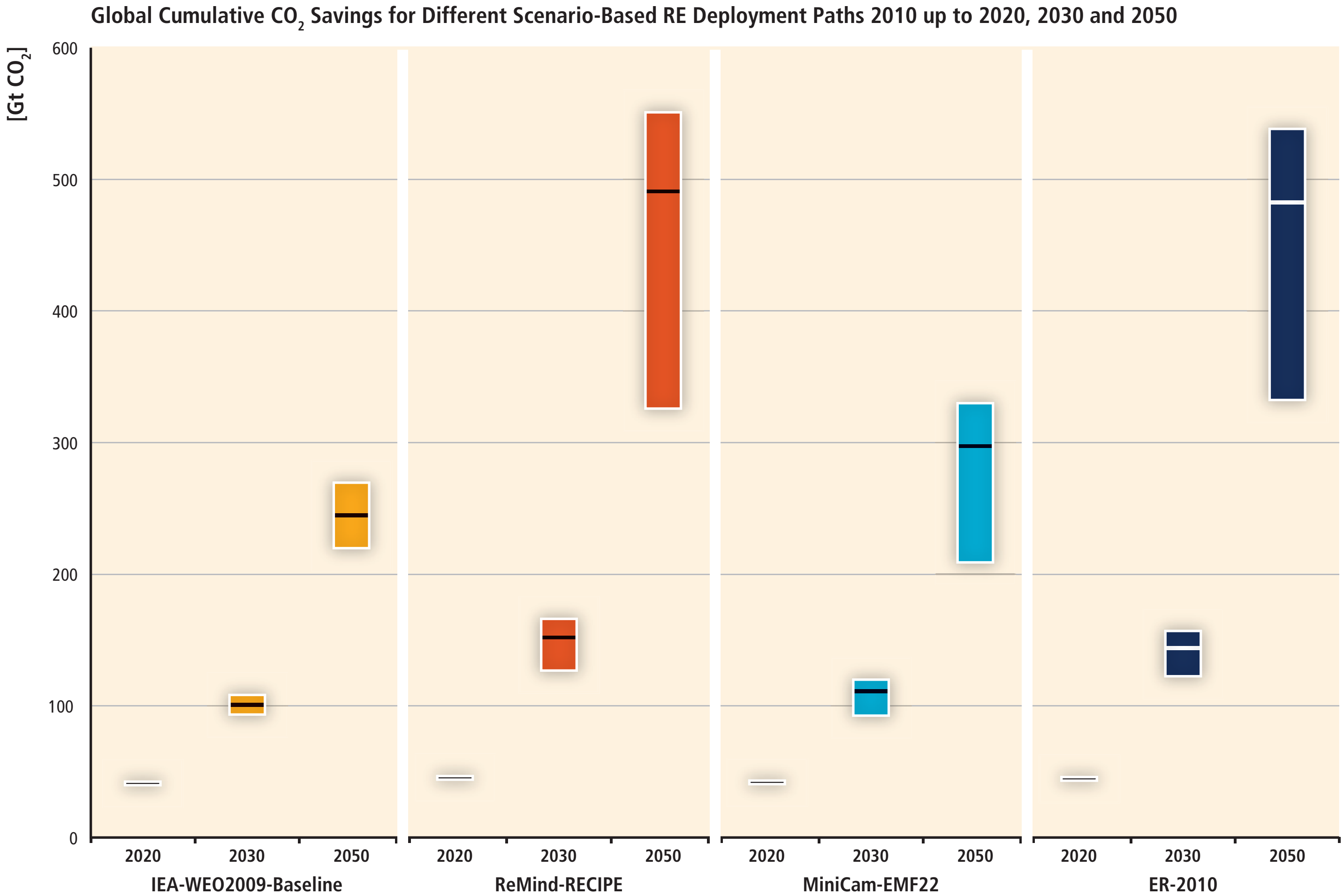


Figure 10.22 | Expected range of global cumulative CO_2 savings up to 2020, 2030 and 2050. The presented range marks the high uncertainties regarding the substituted conventional energy source: while the upper limit assumes a full substitution of high-carbon fossil fuels, the lower limit considers specific CO_2 emissions of the analyzed scenario itself. Sources: IEA-WEO2009-Baseline (IEA, 2009; Teske et al., 2010), ReMIND-RECIPE (Luderer et al., 2009), MiniCAM-EMF22 (Calvin et al., 2009), ER-2010 (Teske et al., 2010).

well below 5% of the global electricity supply. The scenario results for the heating and cooling sector include significant uncertainties as the models use different accounting methods, for example, for geothermal heat pumps. In terms of primary energy share, bioenergy has the greatest share—especially in the heating sector. Wind and solar energy are projected to become important players by and after 2030.

As already stressed in the comprehensive scenario survey (see Section 10.2), there are many reasons why the investigated scenarios reach different results. Each of the in-depth scenarios follows a different strategy. Significant differences in the demand projections and whether or not a shift towards more electricity within the transport and/or heating sector are projected to have a significant impact on the selected technologies and their deployment rates. Moreover, other mitigation technologies, such as CCS and/or nuclear, have a significant impact on the resulting role of RE sources in a future energy mix. In practice, a high RE deployment can only be achieved if system-relevant policy decisions are made many years ahead of the intended market penetration. The assumptions of expanded energy infrastructure such as transmission grids (see Chapter 8) or district heating networks can change the RE deployment of the scenario entirely. Even if the analyzed models do not include grid modelling via system integration aspects, these issues are at least covered implicitly in the scenarios (integration restrictions).

Due to comparably long lifetime expectations, the energy system is relatively inflexible and investment decisions have long-lasting impacts. A high share of relatively inflexible 'base load' power plants—such as coal, lignite and nuclear power plants, for instance—will reduce the technical and economic 'space' of variable renewable electricity generation like solar photovoltaic and wind. Technology choices and preferences predetermine the future RE deployment as well as the assumed RE cost developments and corresponding fossil fuel price projections. The overall share of RE in primary energy demand within the three in-depth mitigation scenario ranges from 24% (MiniCAM-EMF22) to 39% (ER-2010) by 2030 and 31% (MiniCAM-EMF22) to 77% (ER-2010) by 2050. Lower RE shares are due to the availability of competing low-carbon technologies such as CCS and nuclear, while scenarios not allowing access to these technologies expect higher RE shares, but not necessarily higher absolute numbers.

In addition to the comprehensive scenario survey in the previous section (see Section 10.2), the in-depth analyses of the four illustrative scenarios could deliver further specific insights into the specific RE technology deployment and the corresponding driving forces. However, often data availability limits detailed investigations. Against that background the following knowledge gaps can be identified:

- Lack of consistent RE technical potential estimates across the globe, and especially in developing countries (consistent economic potential estimates are an important input basis for the models).
- Modelling of the heating and transport sectors in most of the existing models is less detailed than modelling of the electricity sector, although both sectors are substantially contribute to GHG emissions. More generally, there is a severe lack of data for the heating and transport sector especially on a sectoral or regional basis.
- New RE technologies, such as ocean energy, are not represented in most of the current energy scenarios.
- The reporting system, for example, for geothermal heat pumps, is very different in all scenarios and sometimes not transparent, which makes it difficult to compare the results.
- The interaction of the technology pathways with the effects on deployment costs (learning effects) are treated differently in the scenarios and underlying assumptions or implemented calculation rules are sometimes not very well reported.
- Simplified calculations of the resulting CO_2 mitigation potential of RE deployment can give an orientation, but are associated with severe shortcomings. Comparative model runs (with and without RE) are necessary to consider the energy system behaviour in an appropriate way.

10.4 Regional cost curves for mitigation with renewable energies

10.4.1 Introduction

Governments and decision makers face limited financial and institutional resources and capacities for mitigation, and therefore tools that assist them in strategizing how these limited resources are prioritized have become very popular. Among these tools are abatement cost curves—a tool that relates the mitigation potential of a mitigation option to its marginal cost. Recent years have seen a major interest among decision- and policymakers in abatement cost curves, witnessed by the proliferation in the number of such studies and institutions/companies engaged in preparing such reports (e.g., Next Energy, 2004; Creyts et al., 2007; Dornburg et al., 2007; McKinsey&Company, 2007, 2008a, 2009b,c; IEA, 2008b). However, while abatement curves are very practical and can provide important strategic overviews, it is pertinent to understand that their use for decision making has many limitations.

The aims of this section are to: (a) review the concept of abatement cost curves briefly and appraise their strengths and shortcomings (Section 10.4.2); (b) review the existing literature on regional abatement cost curves as they pertain to mitigation using RE (Section 10.4.3); and (c) review the literature on (regional) RE technology resource supply cost curves (Section 10.4.4). The section thus covers supply curves of RE on the one hand, which evaluate the unit costs of energy generation and the possibilities of utilizing the technical potential depending on the technology deployed, and on the other hand carbon abatement cost curves, which describe the mitigation potentials and marginal costs of emission mitigation (usually per tonne of CO_2eq.) through the deployment of renewable energy sources.

10.4.2 Cost curves: concept, strengths and limitations

10.4.2.1 The concept

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

Supply curves of conserved energy were first introduced by Arthur Rosenfeld (see Meier et al., 1983) and became a popular concept in the 1980s (Stoft, 1995). The methodology has since been revised and upgraded, and the field of its application extended to energy generation supply curves including RE cost curves; as well as carbon abatement from the 1990s (Rufo, 2003). One of the benefits of the method was that it provided a framework for comparing otherwise different options, such as the cost-effectiveness of different energy supply options compared to energy conservation options, and therefore was a practical tool for some decision-making approaches, such as integrated resource planning. Although Stoft (1995) explains why the supply curves used in the studies by Meier et al. (1983) cannot be regarded as 'true' supply curves, including the fact that markets associated with the different types of options depicted in them, such as energy efficiency and energy supply markets, differ in many aspects, he maintains that they are useful for their purpose.

Despite the widespread use of supply curves and their advantages discussed above, there are some inherent limitations to the method that have attracted criticism from various authors that are important to review before reviewing the literature on them or presenting the regional cost curves.

10.4.2.2 Limitations of the supply curve method

The concept of abatement, energy and conservation supply curves has common and specific limitations. Much of the criticism in the early and some later literature focuses on the notion of options with negative costs. For instance, IEA (2008b) raises an objection based on the perfect market theory from neoclassical economics, arguing that it is not possible to have negative cost options as under perfect market conditions someone must have realized those options complying with rational economic behaviour. The existence of untapped 'profitable' (i.e., negative cost) opportunities represents a realm of debates ongoing for decades between different schools of thought (e.g., see Carlsmith et al., 1990; Sutherland, 1991; Koomey et al. 1998; Gumerman et al., 2001). Those accepting negative cost opportunities argue, among other things, that certain barriers prevent those investments from taking place on a purely market basis, but policy interventions can remove these barriers and unlock these profitable opportunities. Therefore the barriers prevailing in RE markets, detailed in other sections of this report, such as insufficient information, limited access to capital, uncertainty about future fuel prices (e.g., in the case of fossil fuels or biomass) or misplaced incentives (e.g., fossil fuel subsidies for social or other reasons) hinder a higher rate of investments into RE technologies, potentially resulting in negative cost options (Novikova, 2009).

A further concern about supply curves is raised by Gordon et al. (2008), who argue that the methodology simplifies reality. In their view, the curves do not reflect the real choices of actors, who accordingly do not always implement the available options in the order suggested by the curve. Both Gordon et al. (2008) and IEA (2008b) agree that there is the problem of high uncertainty in the use of supply curves for the future. This uncertainty is related to both economic and technological perspectives. Additional uncertainty arising from the methodology is the sensitivity of mitigation curves relative to the baseline assumption of the analysis (Kuik et al., 2009). Baker et al. (2008) have demonstrated that aggregation may also trigger significant uncertainty in abatement cost curves. For any given hour with given load and fuel prices, the expected monotonically rising (although not necessarily convex) relationship between price and abatement can be observed. However, when hours are aggregated into days, weeks, months and years, the constancy of the relationship will be completely lost. Perhaps one of the key shortcomings of the cost curves are that they consider and compare mitigation options individually (whereas typically a package of measures are applied together), therefore potentially missing synergistic and integrational opportunities, or potential overlaps. Optimized, strategic packages of measures may have lower average costs than the average of the individual measures applied using a piecemeal approach. Conversely, some measures may be more expensive or even become unviable when other measures are implemented. Any measures that compete against each other are substitutable, in some part or entirely (Sweeney and Weyant, 2008).

For GHG abatement cost curves, a key input that largely influences the results is the carbon intensity, or emission factor, of the country or area to which it is applied, and the uncertainty in projecting this into the future. This may lead to a situation where the option in one locality is shown to be a much more attractive mitigation measure as compared to an alternative than in another locality simply as a result of the differences in emission factors (Fleiter et al., 2009). As a result, a carbon abatement curve for a future date may say more about expected policies for fossil fuels than about the actual measures analyzed by the curves, and the ranking of the individual measures is also very sensitive to the developments in carbon intensity of energy supply.

Some concerns are emerging in relation to abatement cost curves that are not yet fully documented in the peer-reviewed literature (see Box 10.3). For instance, the costs of a RE technology in a future year largely depend on the deployment pathway of the technology in the years preceding—that is, the policy environment in the previous decades. The abatement cost of a RE option heavily depends also on the prices of fossil fuels, which are also very uncertain to predict. Furthermore, for variable (and sometimes to a degree unpredictable) RE generation technologies, the additional costs associated are not just a function of the amount of technology deployed. They are also a function of the fraction of the load met by the technology (higher fractions require more ancillary services, e.g., operating reserves), the flexibility of the existing generation portfolio, the location of the technology deployed relative to loads and existing transmission lines, etc.

Economic data, such as technological costs or retail rates, are derived from past and current economic trends that may obviously not be valid for the future, as sudden technological leaps, policy interventions or unforeseeable economic changes may occur—as has often been observed in the field of RE technology proliferation. These uncertainties can be mostly alleviated through the use of scenarios, which may result in multiple curves, such as for example in van Dam et al., (2007), and as presented in Sections 10.2 and 10.3. Some of the key uncertainty factors are the discount rates used and energy price developments assumed. The uncertainty about discount rates stems both from the fact that it is difficult to project them for the future, and because it is difficult to decide what discount rate to use, that is, social versus market discount rates (e.g., see Dasgupta et al., 2000). A number of studies (see e.g., Nichols, 1994) have discussed that in the case of investments in energy efficiency or RE, individual companies or consumers often use higher discount rates than would be otherwise expected for other types of, for example, financial investments. On the other hand, as Fleiter et al. (2009) note, society faces a lower risk in the case of such investments, therefore a lower discount rate could be considered appropriate from that perspective. Kuik et al. (2009) demonstrated that depending on the method used to construct them, abatement cost

Box 10.3 | Overview of selected key limitations of the cost/supply curve method:

- Controversy among scientists about opportunities at negative costs;
- Strong focus on costs as selection criteria, while in reality actors base their decisions also on other criteria than those reflected in the curves;
- Economic and technological uncertainty inherent to predicting the future, including energy price developments and discount rates;
- Further uncertainty due to strong level of aggregation of the databases used (e.g., site- and technology-specific differences);
- High sensitivity relative to baseline assumptions and the whole future generation and transmission portfolio;
- Consideration of individual measures separately, ignoring interdependencies between measures applied together or in different order (including path dependency issues and treatment of transmission and integration aspects); and
- For carbon abatement curves, high sensitivity to (uncertain) emission factor assumptions.

curves are affected by policies abroad. Essentially, policies abroad create a shift in the baseline for a country through changes in prices in energy markets as well as in price developments in RE technologies.

While several of these shortcomings can be addressed or mitigated to some extent in a carefully designed study, including those related to cost uncertainty, others cannot, and thus when cost curves are used for decision making, these limitations need to be kept in mind while discussing regional cost curves reviewed from the literature in the following section as well as regarding the regional cost curves out of the scenario results in Section 10.3.

10.4.3 Review of regional energy and abatement cost curves from the literature

10.4.3.1 Introduction

This section reviews key studies that have produced national or regional cost curves for RE and its application for mitigation. First, the section reviews work that looks at RE supply curves, followed by a review of the role of RE in overall abatement cost curves—since designated cost curves for RE alone are rare.

10.4.3.2 Regional and global renewable energy supply curves

In an attempt to review the existing literature on regional and global RE supply curves, a number of studies were identified, as summarized in Table 10.8. As discussed in the previous section, the assumptions used in these studies have a major influence on the shape of the curve, ranking of options and the opportunities identified by the curves. Therefore, the table also reviews the most important characteristics and assumptions of the models/calculations as well as their key findings.

In general, it is very difficult to compare data and findings from different RE supply curves, as there have been very few studies using a comprehensive and consistent approach and detailing their methodology, and most studies use different assumptions (technologies reviewed, base resource data, target year, discount rate, energy prices, deployment dynamics, technology learning etc.). Therefore, country or regional findings in Table 10.8 need to be compared with caution, and for the same reasons findings for the same country can be very different in different studies.

One of the weaknesses of many regional or technology studies is that they usually do not account for the competition for land and other resources among the various energy sources (except for probably the various plant species in the case of biomass). In studies that do take this into account (such as de Vries et al., 2007), technical potentials substantially decline in case of exclusive land use.

10.4.3.3 Regional and global carbon abatement cost curves

Table 10.9 summarizes the findings and characterizes the assumptions in the studies reviewed that construct regional/national/global carbon abatement cost curves with the perspective of the role of RE technology deployment. They have a different focus, goal and approach as compared to RE supply curve studies, and are broader in scope, examining RE within a wider portfolio of mitigation options.

Table 10.8 | Summary of RE supply curves for world, regions and countries, with the data grouped into cost categories. Baseline refers to the expected projection of the energy type, the details of which are described in the notes by the target year; most typically the projected total primary energy supply for the particular country, unless otherwise noted in the notes. Currency values are given as in the respective sources as base years are often not specified and conversion to USD_{2005} is not possible.

Country/region		Cost (USD/MWh)	Total RE (TWh/yr) [EJ/yr]	Percent of baseline (%)	Discount rate (%)	Notes	Source
Global		<100	200,000–300,000 [720–1,080]	>100	10	• Combined data for onshore wind, solar PV and biomass given land use constraints and technology scenarios • Sources of uncertainty considered	de Vries et al. (2007), baseline: WEC (2004b) and Hoogwijk et al. (2004). Target year: 2050
Global (Biomass)		<100	97,200 [350]	N/A	10	• Study claims biomass production under this price can exceed present electricity consumption multiple times	Hoogwijk et al. (2003). Target year not specified
Global	**Wind**	<40 <60 <80 <100	2,000 [7.2] 23,000 [83] 39,000 [140] 42,000 [151]	6 72 123 133	10	• Liquid transport fuel and electricity from biomass, onshore wind, PV • Capacity calculated for the whole world; grid connections, supply-demand relationships etc. not incorporated • Global technical potential for electricity generation • High technology development scenario (IPCC SRES (IPCC, 2000) A1 scenario) with stabilizing world population and fast and widespread yield improvements.	RE data: de Vries et al. (2007) Target year: 2050 Baseline data: IEA (2003)
	Biomass	<60	59,000 [212]	187			
	PV	<80 <100	400,000 [1,440] 1,850,000 [6,660]	1,268 5,868			
Global		<70 <100	21,000 [76] 53,000 [191]	600–700 -	10	• Technical potential for onshore wind based on wind strength and land use issues; grid availability, network operation and energy storage issues are ignored • Baseline refers to 2001 world electricity consumption	Hoogwijk et al. (2004) Based on 2001 state of technology, no target year specified.
	Former USSR	<70 <100	2,000 [7.2] 7,000 [25]	160 550			
	USA	<70 <100	3,000 [11] 13,000 [47]	80 350			
	East Asia	<70 <100	0 [0] 50 [.2]	0 3			
	Western Europe	<70 <100	1,000 [3.6] 2,000 [7.2]	40 80			
Global		<50	121,805 [438]	N/A	10	• Biomass energy from short-rotation crops on abandoned cropland and unused rest land • Four IPCC SRES (2000) land use scenarios for the year 2050 • Land productivity improvement over time, cost reductions due to learning and capital-labour substitution • Present world electricity consumption (20 PWh/yr) may be generated at costs below USD 45/MWh (IPCC SRES (IPCC, 2000) A1 B1 scenarios) and USD 50/MWh (IPCC SRES (2000) A2 B2 scenarios) in 2050	Hoogwijk et al. (2009). Target year: 2050
	Former USSR		23,538 [85]				
	USA		9,444 [34]				
	East Asia		17,666 [64]				
	OECD Europe		3,194 [12]				
Central and Eastern Europe		<100	3,233 [12]	74	N/A	• Biomass only, best scenario with willow being the selected energy crop (highest yield) • Countries: Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia • Baseline data includes Slovenia, however, its share is rather low, therefore resulting distortion is not so high.	RE data: van Dam et al. (2007) Target year: 2030 Baseline data: Solinski (2005)
Czech Republic		<100	101 [.4]	20	4	• Only biomass production • Best-case scenario where future yields equal the level of the Netherlands	RE data: Lewandowski et al (2006) Target year: 2030 Baseline data: IEA (2005)

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Country/region	Cost (USD/MWh)	Total RE (TWh/yr) [EJ/yr]	Percent of baseline (%)	Discount rate (%)	Notes	Source
India	<100	56 [.2]	3.4	10	• Small hydro • Grid availability not expected to be a serious concern • Baseline refers to 2005 electricity consumption	Pillai and Banerjee (2009) Target year: 2030
	<200	90 [.3]	5.6		• Wind • Grid availability not expected to be a serious concern • Baseline refers to 2005 electricity consumption	
Netherlands	<100	22 [.08]	2.1	N/A	• Included: onshore and offshore wind, PV, biomass and hydro • Discount rate is not available, however, this option is a scenario where sustainable production is calculated. Therefore they use 5% internal rate of return (IRR) assuming that there are governmental support • Baseline is total primary energy supply forecast for 2020 by IEA	RE data: Junginger et al., 2004 Target year: 2020 Baseline data: IEA (2006)
	<200	23 [.08]	2.2			
	<300	24 [.09]	2.3			
UK	<100	81 [.3]	22	7.9	• Included: 'Low-cost technologies' (landfill gas, onshore wind, sewage gas, hydro) • Costs: capital, operating and financing elements • Baseline is all electricity generated in the UK forecasted for 2015	RE data: Enviros Consulting Ltd. (2005) Target year: 2015 Baseline data: UK SSEFRA (2006)
	<200	119 [.4]	33			
USA	<100	3,421 12]	15	N/A	• Wind energy only	RE data: Milligan (2007) Target year: 2030 Baseline data: EIA (2009)
USA (WGA)	<100	177 [.6]	0.77	N/A	• Only the WGA region • CSP, biomass, and geothermal • Geothermal reaches maximum capacity under USD 100/MWh • CSP has a large technical potential, but full range is between USD 100 and 200/MWh	RE data:(Mehos and Kearney, 2007; Overend and Milbrandt, 2007; Vorum and Tester, 2007) Target year: 2030 Baseline data: EIA (2009)
	<200	1,959 [7]	8.5			
	<300	1,971 [7]	8.6			
USA (Arizona 2025)	<100	0.28 [.001]	N/A	Biomass and PV: 7.5 Rest: 8	• State of Arizona, USA • RE: wind, biomass, solar, hydro, geothermal • Discount rates vary between energy sources	RE data: Black & Veatch Corporation (2007) Target year: 2025
	<200	10.5 [.04]	N/A			
	<300	20 [.07]	N/A			

One general trend can be observed based on this illustrative sample of a limited number of selected studies. Abatement cost curve studies tend to find lower potentials for mitigation through RE than those focusing on RE for energy supply. Even for the same country these two approaches may find very different mitigation potentials.

One factor contributing to this general trend is that RE supply studies typically examine a broader portfolio of RE source technologies, while the carbon mitigation studies reviewed focus on selected resources/technologies to keep models and calculations within reasonable complexity levels.

The highest figure in carbon mitigation potential share by the deployment of RE, as shown in Table 10.9, is for Australia: 13.4% under USD 100/t CO_2eq by 2030. This has to be seen in contrast with the much higher shares as a percentage of national total primary energy supply (TPES) reported in the previous section (data from McKinsey&Company, 2008a). Besides Australia, countries with the most promising abatement potentials through RE sources identified in the sample of studies are China and Poland—both having high emission factors.

10.4.4 Review of selected technology resource cost curves

The energy and abatement cost curves discussed above provide a more aggregated picture (see Sections 10.4.2 and 10.4.3). For selected technologies, this section ends with the discussion of illustrative examples of resource cost curves. In this context, some studies are highlighted that were already part of the general overview in Section 10.4.3.

Table 10.9 | Summary of carbon abatement cost curves for world, regions and countries (cells including grey literature are coloured in grey).

Country/region	Year	Cost (USD/tCO_2eq)	Mitigation potential (Mt CO_2)	Percent of baseline (%)	Discount rate (%)	Notes	Source
Global	2050	<200	46,195	85	N/A	• Key sensitivities: lower technical potential for wind, hydro or CCS, lower uranium resources raise abatement costs by 2 to 5%	Syri et al. (2008) Baseline model: global ETSAP/TIAM Baseline Scenario: IEA (2009)
Global	2030	<100	6,390	9.1	4	• Scenario A (maximum growth of RE and nuclear) • Scenario B (50% growth of RE and nuclear)	McKinsey&Company (2009b)
		<100	4,070	5.8			
Annex I	2020	<100	2,818	20	N/A	• Different abatement allocations analyzed depending (equal marginal cost, per capita emission right convergence, equal percentage reduction) • CO_2 equivalent emissions six Kyoto GHGs, but exclude LULUCF • Costs in 2005 USD	den Elzen et al. (2009) Baseline Scenario: IEA WEO (IEA, 2009)
Australia	2020	<100	74	9.5	N/A		(McKinsey&Company, 2008a)
Australia	2030	<100	105	13			
Australia (NSW Region)	2014	<100	8.1	1.0	N/A	• New South Wales region • Includes governmental support for RES	Abatement data: Next Energy (2004) Baseline data: McKinsey&Company (2008a)
		<300	8.5	1.1			
China	2030	<100	1,560	11	4		(McKinsey&Company, 2009a)
China	2030	<50	3,484	27	N/A	• Storylines do not describe all possible development (e.g., disaster scenarios, explicit new climate policies) • Main abatement (half of total) is efficiency, the rest is renewable and fuel switch from coal	van Vuuren et al. (2003) Baseline Scenario: ERI 2009
China	2030	<100	2,323	18	N/A	• Main factor influencing abatement cost is constraints on the rollout of nuclear power • Baseline seems to be underestimated as 2010 power consumption is 40% below fact.	Chen, 2005 Baseline Scenario: ERI (2009)
Czech Republic	2030	<100	9.3	6.2	N/A	• Scenario with maximum use of RE sources	McKinsey&Company (2008b)
		<200	11.9	8.0			
		<300	16.6	11			
Germany	2020	<100	20	1.9	7	• Societal costs (governmental compensation not included)	McKinsey&Company (2007)
		<200	31	3.0			
		<300	34	3.2			
Poland	2015	<100	50	11	6	• Only biomass • Best case scenario	Abatement data: Dornburg et al. (2007) Baseline data: EEA (2007)
		<200	55.9	12			

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Country/region	Year	Cost (USD/tCO_2eq)	Mitigation potential (Mt CO_2)	Percent of baseline (%)	Discount rate (%)	Notes	Source
Switzerland	2030	<100	0.9	1.6	2.5	• Base case scenario	McKinsey&Company (2007)
South Africa	2050	<100	83	5.2	10	• Renewable electricity to 50% scenario	Hughes et al. (2007)
Sweden	2020	<100	1.26	1.9	N/A		McKinsey&Company (2008c)
USA	2030	<100	380	3.7	7		Creyts et al. (2007)
UK	2020	<100	4.38	0.46	N/A		Confederation of British Industry (CBI, 2007)
		<200	8.76	0.93			
UK	2020	<100	7	4.0	3.5		Committee on Climate Change (2008)
		<200	33	18.8			

Resource cost curves have to be seen in context with the discussion of the energy and cost aspects in the various technology chapters (Chapters 2 through 7).

Summary of biomass resource cost curves.[10] The analyses of biomass resource cost curves in the literature use typically different land use scenarios (de Vries et al., 2007; Hoogwijk et al., 2009). They take into account geographical specificities (crop productivity and land availability) as well as capital and labour input. Hoogwijk et al. (2009) find that biomass can supply about 40 to 70% of the present primary energy consumption (130 to 270 EJ/yr) by 2050 at costs below USD 2/GJ/yr, which is the present lower limit of the cost of coal (see Figure 10.23).

Regions of low production cost and relatively high technical potential are the former USSR, Oceania, eastern and western Africa and East Asia. Cost reductions are due to land productivity improvements over time, learning and capital-labour substitution. Biomass-derived electricity costs are at present slightly higher than electricity base-load costs. The present world electricity consumption of around 20 PWh/yr (72 EJ/yr) may be generated in 2050 at costs below USD 12.5/GJ in two scenarios,

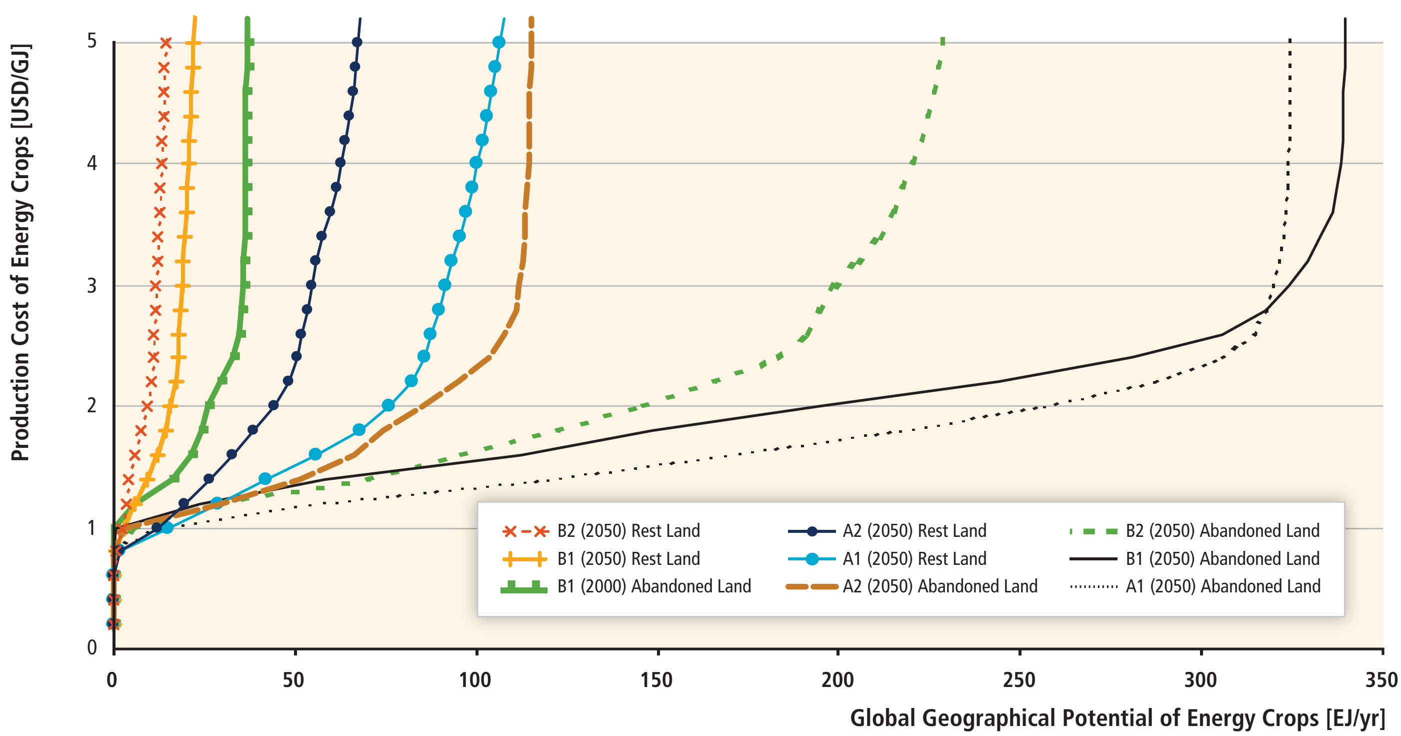


Figure 10.23 | Global average cost-supply curve for the production of bioenergy plants on the two land categories 'abandoned land' (agricultural land not required for food) and 'rest land' in 2050. The curves are generated based on IMAGE 2.2 modelling of four SRES scenarios. The cost supply curve for abandoned agricultural land in 2000 (SRES B1 scenario) is also shown. Source: Hoogwijk et al. (2009). The scenarios A1, A2, B1 and B2 correspond to the storylines developed for the IPCC Special Report on Emission Scenarios (IPCC, 2000).

10 For further details, see Section 2.2.

while below USD 15.3/GJ in two others. At costs of USD 16.7/GJ, about 18 to 53 PWh/yr (65 to 191 EJ/yr) of electricity can be produced in 2050. The global curve that sums all regional curves is found to be relatively flat up to 300 EJ/yr; land rental costs and the substitution of capital for labour represent the highest sensitivity.

In the study of de Vries et al. (2007), another trade-off is addressed: food versus energy. The authors assess four land use scenarios, each corresponding to different levels of food trade, technology development and population. A low technical potential estimate in the A2 scenario is a direct consequence of more people, hence higher food demand and lower yield (improvement), hence more land demand for food production (see Figure 10.24).

For a cost range of electricity from biomass of USD 13.9 to 27.8/GJ, there were 7 PWh (25 EJ) of technical potential in the year 2000, while for a projected cost range between USD 8.3 and 27.8/GJ, there is an estimated technical potential of 59 PWh (212 EJ) by 2050 (with a sensitivity of 30 to 85 PWh/yr (108 to 310 EJ/yr), depending upon discount rates, land use patterns, technology assumptions and land use implementation fractions).

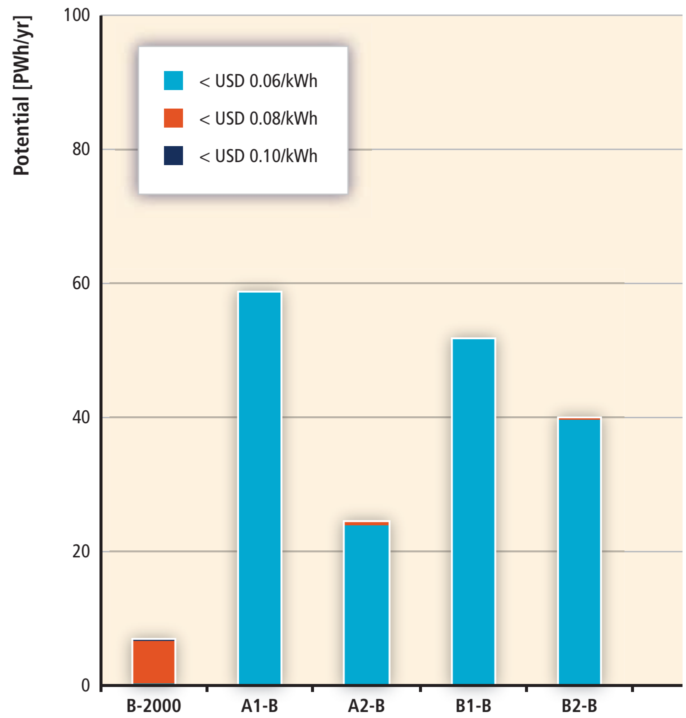


Figure 10.24 | The global technical potential for electricity from biomass in 2000 and in four IPCC SRES (IPCC, 2000) scenarios for 2050 for four production categories (de Vries et al., 2007).

Summary of PV resource cost curves. De Vries et al. (2007) estimate PV electricity generation technical potential at 4,105 PWh/yr (4,778 EJ/yr) in 2050 at the cost of USD 16.7 to 69.4/GJ. Since the technical potential for the year 2050 depends primarily on cost-reducing innovations, for a cut-off cost level of USD 27.8/GJ, a non-zero technical potential emerges only under specific scenario conditions (e.g., high economic growth vs. low population growth, or medium economic and population growth), as in the IPCC (2000) A1 and B1 scenarios (see Figure 10.25).

In this particular study, solar PV economic potential is sensitive to competition for land. If the technological breakthroughs do not take place, a large part of the major technical potential is unlikely to become economic. Its capital-intensive nature also makes it sensitive to changes in discount rates. High or low exclusion factors also affect the solar PV technical potential. For the technical potential, land is not a constraint as even with a high exclusion factor, the technical potential is over 20 times the 2000 world electricity demand (de Vries et al., 2007).

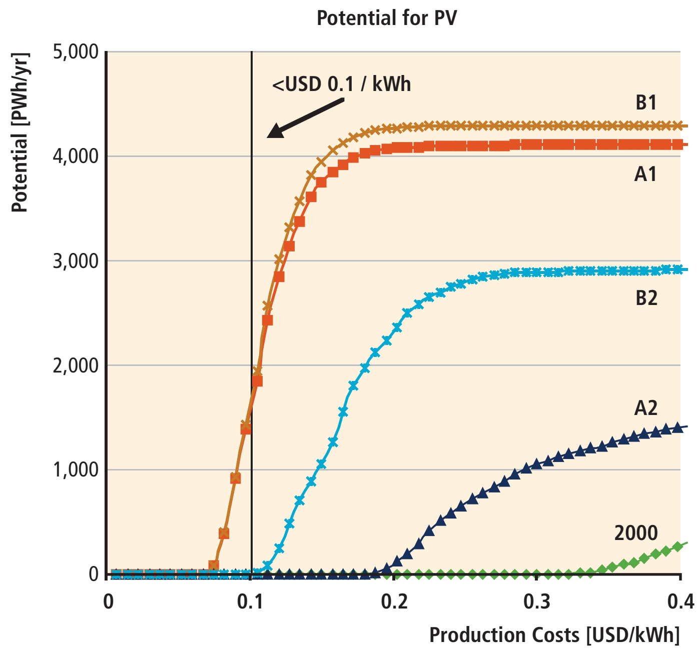


Figure 10.25 | Resource supply cost curve for PV for four IPCC SRES (IPCC, 2000) scenarios in 2050. The figure also shows the USD 0.1/kWh (USD 0.03/MJ) line used in the paper as the cut-off cost in determining the economic potential (de Vries et al., 2007).

Summary of onshore wind cost curves. Papers assessing wind technical potentials usually base their data on climatic models of wind speeds or interpolation of wind speed measurements (Hoogwijk et al., 2004; de Vries et al., 2007; Changliang and Zhanfeng, 2009). Hoogwijk et al. (2009) have made explicit assumptions about the average turbine availability, wind farm array efficiency and spacing, and, related to this, power density; this has not differentiated across grid cells, that is, one global parameter has been used. The estimated global technical potential that can be realized at relatively low cost is largely confined to three regions (Figure 10.26). These are the USA, the Former USSR and Oceania (Hoogwijk et al., 2004; McElroy et al., 2009). Wind power might even be generated at costs below USD 11.1/GJ in scenarios assuming either high economic growth and low population growth or medium economic and population growth (IPCC SRES (IPCC, 2000) A1 and B1 scenarios), which is significantly lower than the current cost level (see Chapter 7).

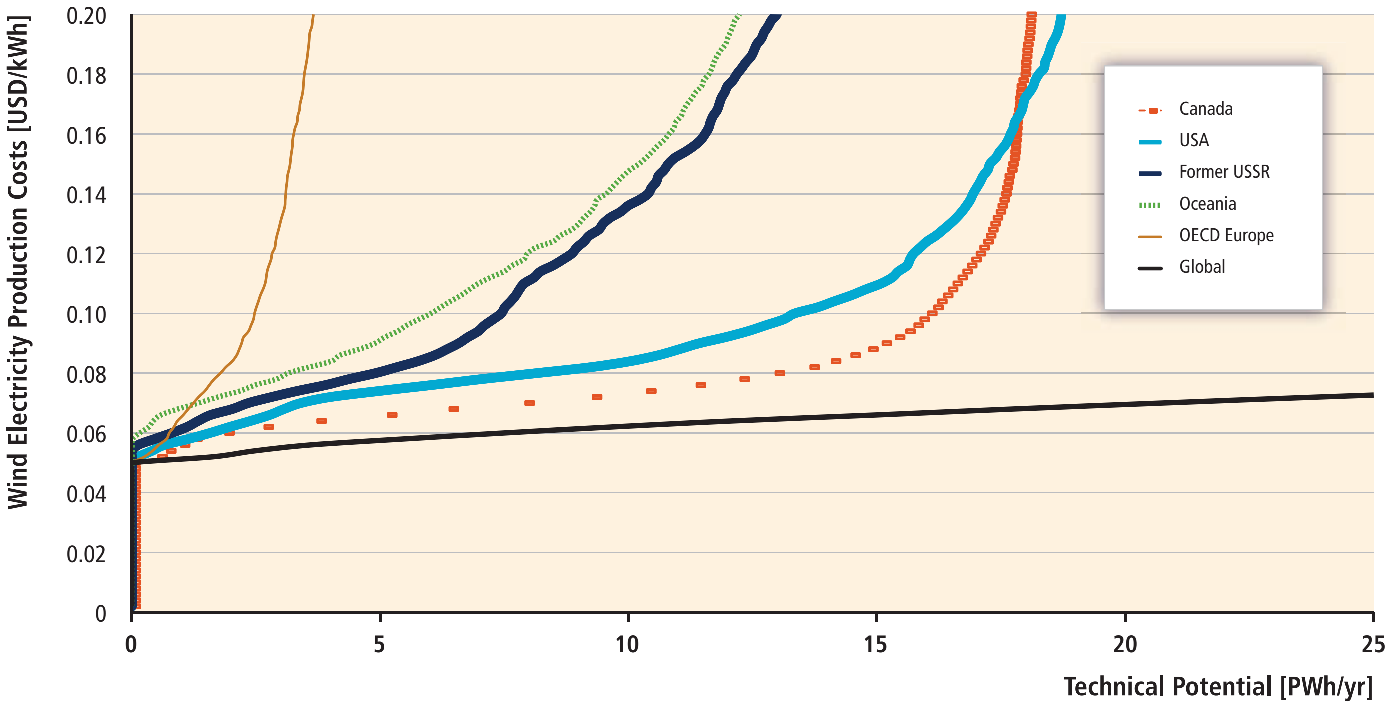


Figure 10.26 | Global, regional and country cost-supply curves for wind energy (USD/kWh versus PWh/yr) (Hoogwijk et al., 2004).

Finally, none of the studies reviewed here fully consider transmission and integration issues (see Chapter 8). In one study that did seek to account for these factors, wind remains an important contributor to the worldwide economic potential at less than USD 27.8/GJ, with an economic potential between 8 and 43 PWh/yr (29 and 155 EJ/yr)—or 50 to 300% of the 2000 world electricity demand (de Vries et al., 2007).

Summary of offshore wind cost curves. For offshore wind, the technical potential and costs are strongly determined by the distance of the installation from the shore and the water depth. In a recent study by EEA (2007), the lower limit of wind speed at hub height has been set to 5.0 m/s to consider the wind power plant economically viable. At an average production cost of USD_{2005} 0.024/MJ (6.9 Eurocents/kWh) in 2030, 5,800 GW of offshore wind power could be developed in Europe (Figure 10.27).

Various studies have assessed the technical potential for offshore wind. Nevertheless, only Fellows (2000) presents the assessments at a global level (except Norway and Canada), including cost estimates for the time frame to 2020. Hoogwijk and Graus (2008) have added values for Canada and updated the data for the technological development for 2020 to 2050. High technical potentials are found in OECD Europe and Latin America, the latter having high shares of unexplored low-cost technical potentials. An economic potential of 1.2 PWh/yr (4.3 EJ/yr) for OECD Europe and Latin America is found at costs lower than USD 27.8/GJ. At costs above USD 13.9/GJ, 0.3 PWh/yr (1 EJ/yr) is available in OECD Europe, and 0.55 PWh/yr (1.98 EJ/yr) in Latin America. The lowest technical potentials are found in the Middle East, where even at less than USD 27.8/GJ only 0.18 PWh/yr (0.65 EJ/yr) capacity is available (Hoogwijk and Graus, 2008).

Summary of technology resource cost curves. This section has reviewed selected resource cost curves for selected RE technologies for which such curves were found. It is important to emphasize that such studies are comparable only to a limited extent due to the use of different methodologies and potentially conflicting assumptions (such as related to land use), thus they should not be directly used for potential summation or comparison purposes. These results also significantly differ from the integrated technology cost curves produced based on scenarios presented in Section 10.3.2.1, since these present potential deployment levels taking into account many more constraints than the technical potential/cost studies in Section 10.3.

10.4.5 Gaps in knowledge

There is a major gap in knowledge for RE heat and transport fuel technical potentials on a regional basis, especially as a function of cost. Additionally, the real benefit of the cost curve method (to identify the really cost-effective opportunities) in practice cannot be fully utilized with the given data sets. Average costs for a technology for a whole region mask the really cost-effective technical potentials and sites into an average, compromised by the inclusion of less attractive sites or sub-technologies. Therefore, significant, globally coordinated further research is needed for refining these curves into sub-steps by sites and sub-technologies in order to identify the most attractive opportunities

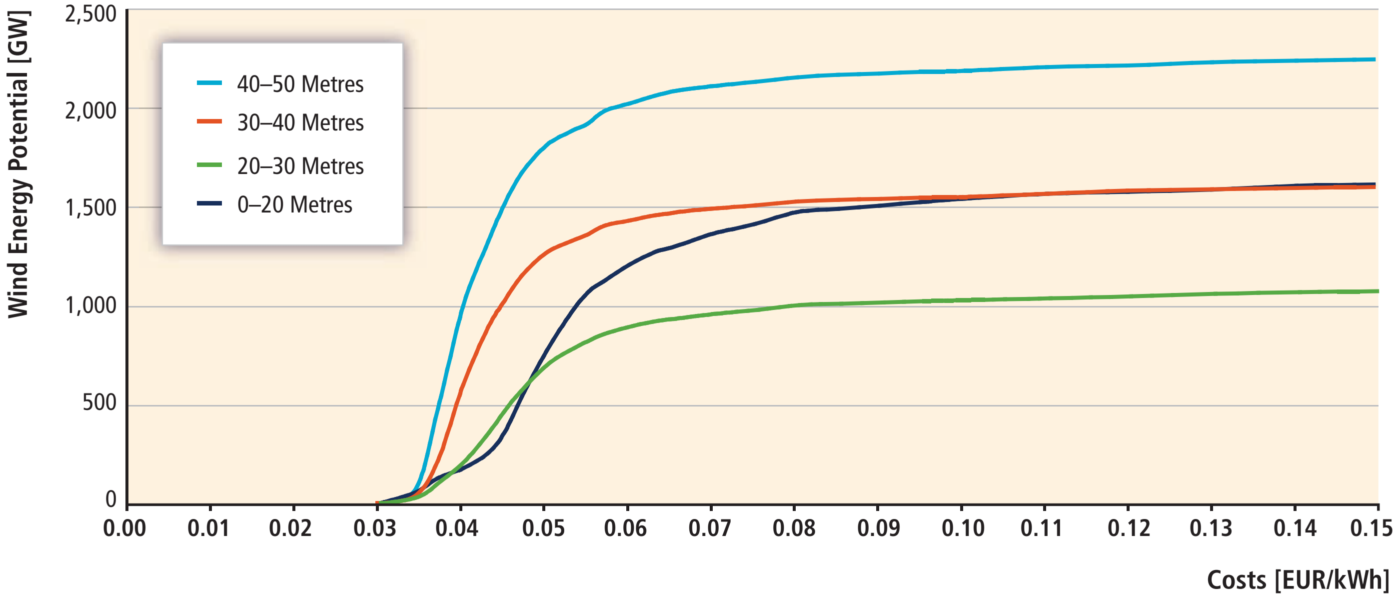


Figure 10.27 | Technical potential for offshore wind energy generation at different water depths in 2030 for Europe (EEA, 2009).

broken out of otherwise less economic technologies (such as more attractive wind sites, higher productivity biomass technologies/plants/sites, etc.). Finally, global data sets on deployment rates as a function of energy production costs as well as the cost of additional system balancing and transmission are a key requisite for integrated assessment modelling studies. The lack of such comprehensive data sets (with the laudable exception of Hoogwijk and Graus data) is striking, and is an important knowledge gap.

10.5 Costs of commercialization and deployment

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

The aforementioned statement, which is consistent with recent publications of the IEA (IEA, 2007a, 2010a,d), is based on a consideration of the resource base, the energy services requested as well as technology-specific assessments of current costs of investment, financing, operation and maintenance as presented in the cost sections of the various technology chapters (see Sections 2.7, 3.8, 4.7, 5.8, 6.7 and 7.8).

Under favourable conditions, inter alia, modern combustible biomass to produce heat (IEA, 2007a), solar thermal energy (e.g., solar water heaters in China (IEA, 2010d)), selected off-grid PV applications (IEA, 2010c), large-scale hydropower (IEA, 2008a), larger geothermal projects (>30 MWe (IEA, 2007b)) and (if the cost of carbon is reflected in the markets) wind onshore power plants (IEA, 2010a) are already competitive. Provided that sufficient policy support is available, grid parity of PV (i.e., competitiveness with grid retail prices) is envisioned in many countries by 2020 (IEA, 2010c). Other technologies, such as CSP and offshore wind power, will require further support in order to compete with wholesale prices in the long term.

Currently and in the mid-term, the application of RE technologies can result in additional private costs compared to energy supply from other sources.[11] Starting with a review of present technology costs (i.e., current costs observed and published in the last few years), the remainder of this section will focus on expectations about how these costs might decline in the future, for instance, due to extended R&D efforts, technological learning associated with increased deployment, or spill-over effects (see IPCC, 2007). In addition, historic R&D expenditures and future investment needs will be discussed. It must be emphasized that Section 10.5 focuses on technology costs only. Integration aspects are discussed in Chapter 8; externalities and the associated social costs in Chapter 9 and Section 10.6.

10.5.1 Introduction: Review of present technology costs

In the field of RE, energy supply costs are mainly determined by investment costs. Nevertheless, operation and maintenance costs (O&M costs), and—if applicable—fuel costs (in the case of biomass), may play an important role as well. The respective cost components are discussed

11 Within this section, the external costs of other technologies are not considered. Although the term 'private' will be omitted in the remainder of this section, the reader should be aware that all costs discussed here are private costs in the sense of Section 10.6. Externalities therefore are not taken into account.

in detail in the technology chapters (Sections 2.7, 3.8, 4.7, 5.8, 6.7 and 7.8) and recent values are summarized in Annex III (Tables 1 through 3), where, inter alia, technology-specific values for typical device sizes (in MW), recent specific investment costs (in USD/kW), annual O&M costs (in USD/kW or US cents/kWh), capacity factors (in %) and economic lifetimes (in years) can be found. At a global scale, the respective values are highly uncertain for the various RE technologies. As recent years have shown, investment costs, for instance, might be considerably influenced by changes in material (e.g., steel) and engineering costs as well as by technological learning and mass market effects (IEA, 2010a,b).

Levelized costs of energy (LCOE, also called levelized unit costs or levelized generation costs; see Annex II for more information and illustrative calculations) are defined as 'the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent' (IEA, 2005, p.174). LCOE therefore capture the full costs (i.e., investment costs, O&M costs, fuel costs and decommissioning costs) of an energy conversion installation and allocate these costs over the energy output during its lifetime. In general, LCOE do not take into account subsidies, policy incentives or integration costs.

The LCOE that can be derived from the values given in Annex III (Tables 1 to 3) are shown in Figures 10.28 through 10.31. Though these represent LCOE estimates for recent renewable energy plants, LCOE are different at different locations as discount rates, investment cost, O&M costs, capacity factors (especially due to the local RE resource availability) and fuel prices are site dependent (Heptonstall, 2007; IEA, 2010b).

The cost ranges in the background of Figure 10.28 display the global ranges of indicative values for the cost of energy supply options using fossil fuels. For electricity, the range is based on a recent assessment of LCOE for new coal and gas-fired power plants (IEA, 2010b). The values refer to centralized power plants. In contrast to IEA (2010b), a carbon price mark-up has not been included.

Following IEA (2007a), the (levelized) cost of oil and gas based heat supply options are estimated by taking into account retail fuel prices and conversion losses only. The investment costs for conventional boilers were neglected, because their contribution to overall LCOH is small (and because conventional heating facilities are often needed as a back-up for RE conversion technologies). Retail prices are used as most RE heating technologies have to compete at the final consumer level. For conversion efficiencies the values proposed by IEA (2007a) are applied. The indicative cost range depicted in Figure 10.28 is based on differing national retail prices (including taxes) for light fuel oil and natural gas as reported in the recently published IEA Key World Energy Statistics (IEA, 2010f). The lower bound of the range refers to natural gas-fired industrial heating applications; the higher bound to light fuel oil use in households.

According to the IEA (2010d), the cost of conventional transport fuels is strongly correlated with the underlying (historical) Brent crude oil spot price. In order to facilitate an investigation of the competitiveness of biofuels in times of highly fluctuating crude oil prices, the indicative transport fossil fuel cost range depicted in Figure 10.28 refers to a variation in the underlying crude oil spot price between USD 40 and 130/barrel.

As RE technologies are often characterized by high shares of investment costs relative to O&M costs and fuel costs, the applied discount rate has a prominent influence on the LCOE (see Figures 10.29, 10.30 and 10.31). The discount rate itself refers to a risk-free rate of return (assessed to be broadly of the order of 3%/yr) adjusted by a project-dependent risk premium (IEA, 2005, Appendix 6). According to IEA (2010b) (see Chapter 8 in this report), a discount rate of 5% is typically adopted by US investors facing a low risk in a fairly stable environment. Prominent examples are a public monopolist acting in a regulated market or a private investor investing in a low-risk technology in a favourable market environment. In the case where the investor is facing substantially greater financial, technological and price risks, a real discount rate of 10% can be justified (IEA, 2010b, p.154). As discussed in Appendix II, this report uses three values of real discount rates (3, 7 and 10%) in order to allow for an easy comparison between different projects and/or technologies. Note that in liberalized markets, private investors might ask for a higher real rate of returns than those characterized by a discount rate of 10% (IEA, 2005).

The LCOE ranges depicted in Figures 10.28 through 10.31 can be traced back to variations in the underlying parameters, which, in turn, can be grouped into:

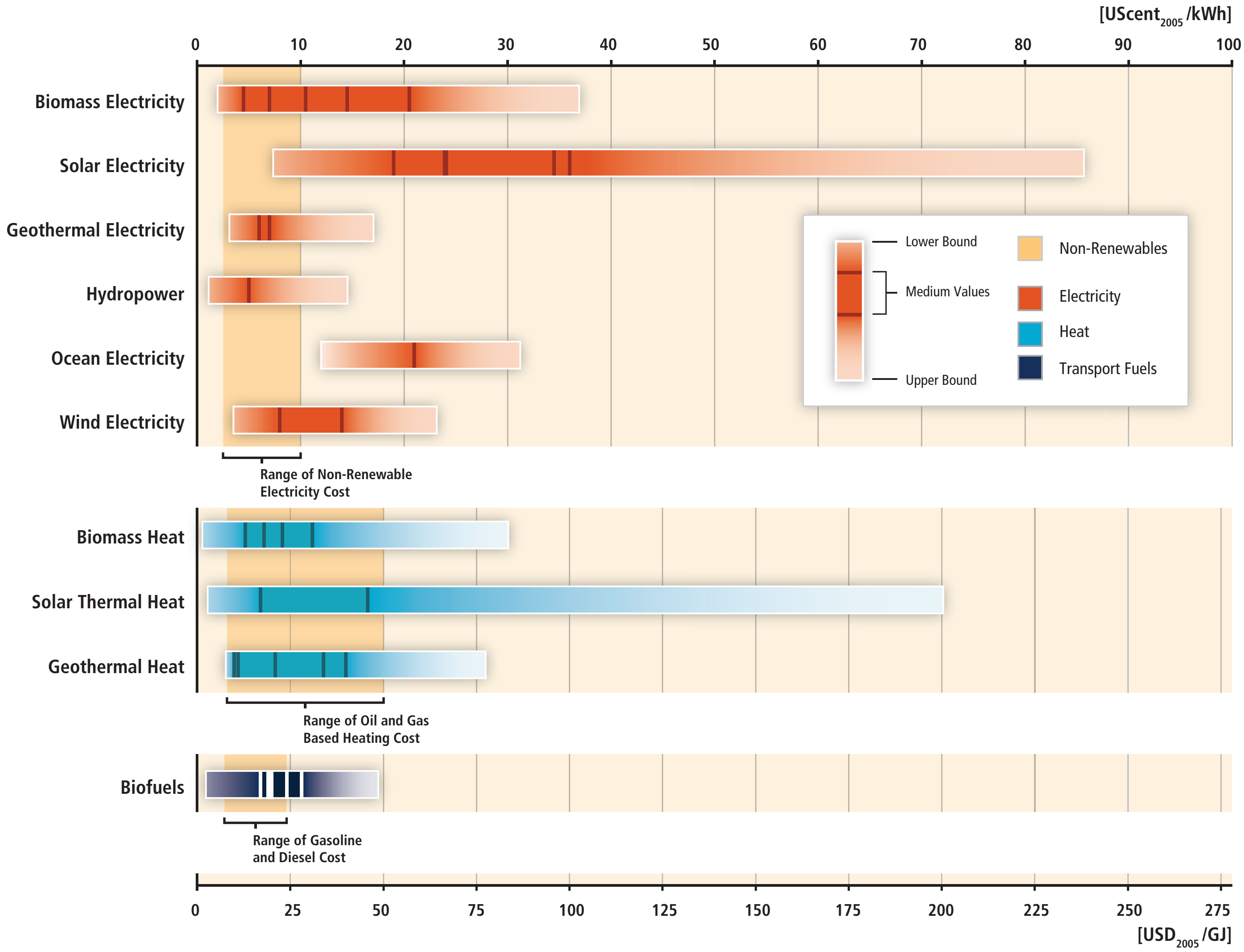
a) The considered range of the performance parameter (characterized by the capacity factor) that heavily depends on the local resource base (e.g., wind velocities or solar radiation).

b) The global spread of the technology-dependent parameters (i.e., lifetime as well as investment and O&M costs) that are influenced by local technology maturity, market conditions and wages.

c) The range of the different real discount rate selected for this study (3 to 10%).

The lowest LCOE values depicted in Figures 10.28 through 10.31 correspond to best-case conditions (highest achievable capacity factor and highest lifetime, lowest investment and O&M costs, and lowest bound on the discount rate). The upper range of the LCOE is characterized by high, but still reasonable values for costs; low, but still realistic values for the lifetime; low, but still observed capacity factors; and a discount rate of 10% (if not indicated otherwise). Less favourable conditions can yield substantially higher costs compared to those shown in the figures.

The results presented in Figures 10.28 through 10.31 warrant some discussion in comparison to the cost data presented in other chapters. Most of the technology chapters show the levelized cost as a function of a) the capacity factor, b) the investment costs and c) the discount rate (Sections 2.7, 3.8, 4.6, 5.8, 6.7 and 7.8). In order to facilitate a comparison between different technologies, Figures 10.28 through 10.31 do not repeat showing the respective sensitivities in an explicit way. As discussed above, the



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

Electricity

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

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

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

Hydropower:
1. All types

Ocean Electricity:
1. Tidal barrage

Wind Electricity:
1. Onshore
2. Offshore

Heat

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

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

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

Transport Fuels

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

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

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

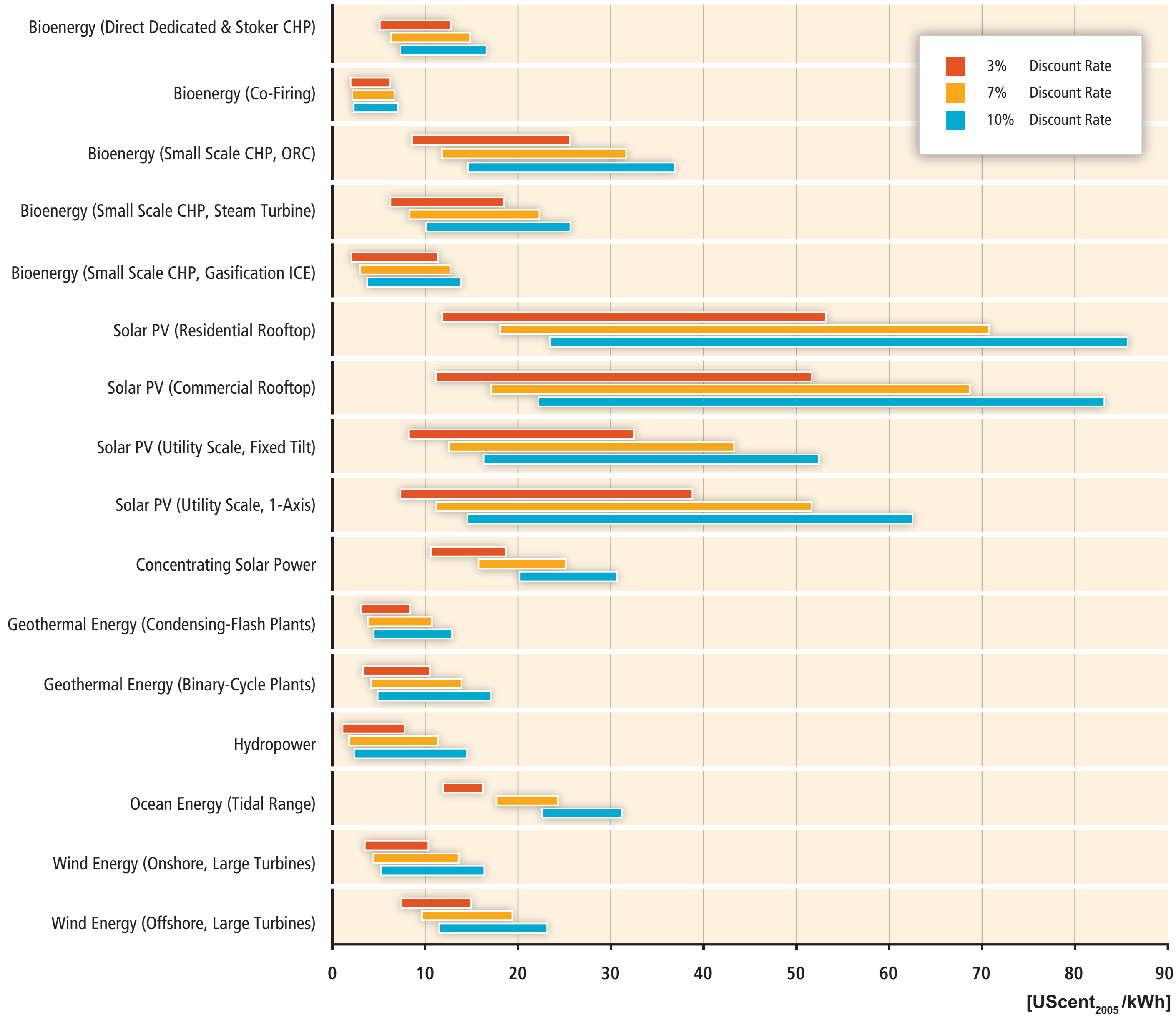


Figure 10.29 | Levelized cost of electricity for commercially available RE technologies at 3, 7 and 10% discount rates. The levelized cost estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range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

figures nevertheless show the range of LCOE that originates from varying the capacity factors and investment costs within reasonable bounds.

In contrast to the aforementioned LCOE sensitivity diagrams that are contained in the technology chapters, the supply cost curves presented in Section 10.4.4 (Figures 10.23, 10.25, 10.26 and 10.27) provide additional information about the available resource base. Instead of showing the sensitivity with respect to the capacity factor, they allow an insight into the amount of RE that can be harnessed up to a prescribed level of the LCOE. This additional information comes from studies that made their own assumptions about other factors (beyond site-dependent capacity factors) that have an influence on the LCOE (e.g., discount rates, investment and O&M costs, and lifetimes). As a result, these results might not be fully compatible with the LCOE calculations summarized in Annex III.

The supply cost curves discussed in Section 10.3.2.1 (Figures 10.15 through 10.17) exhibit the amount of RE that is harnessed (once again as a function of the associated LCOE) in different regions once specific

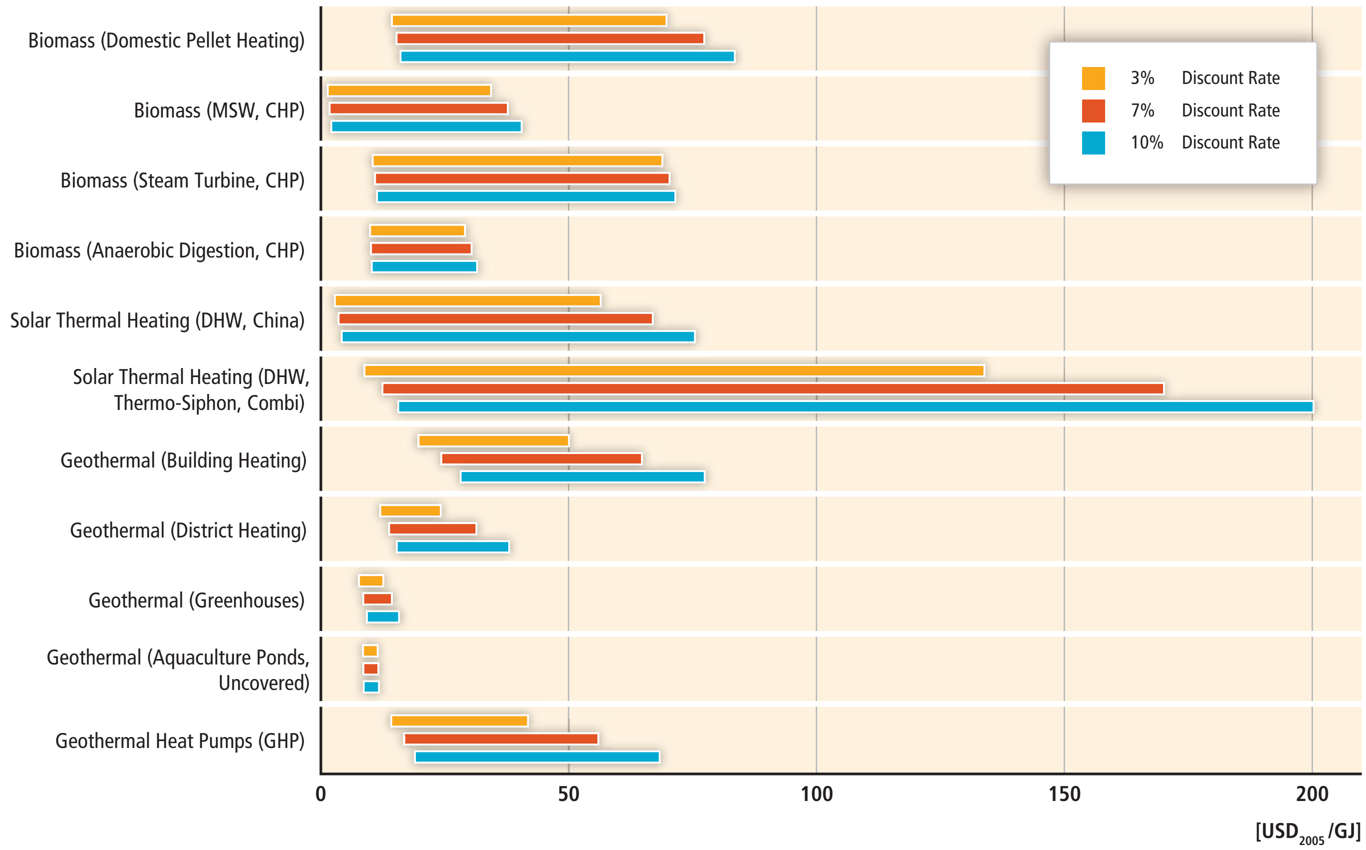


Figure 10.30 | Levelized cost of heat (LCOH) for commercially available RE technologies at 3, 7 and 10% discount rates. The LCOH estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based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

trajectories for the expansion of RE are followed. As the results clearly show, the respective numbers are heavily dependent on the peculiarities (e.g., applied assumptions) of the underlying models.

In addition, it must be emphasized that most of the supply cost curves refer to future points in time (e.g., 2030 or 2050), whereas the levelized costs given in the cost sections of the technology chapters as well as those shown in Figures 10.28 through 10.31 (and in Annex III) refer to current costs.

The LCOE presented in Figures 10.28 through 10.31 are based on literature reviews and represent the most current cost data available. The corresponding data are summarized in Tables 1 to 3 of Annex III. The LCOE ranges are rather broad as the values vary across the globe depending on the RE resource base and the local costs of investment, financing, operation and maintenance. Comparison between different technologies therefore should not be based on the cost data provided here; instead, site-, project- and investor-specific conditions should be taken into account. The technology chapters (Sections 2.7, 3.8, 4.6, 5.8, 6.7 and 7.8) provide useful sensitivities in this respect.

Similar to LCOE, wholesale and retail prices of electricity that might be used in order to assess the competitiveness of centralized and decentralized RE power plants are country specific as well. The same holds true for the cost of fuels used for heating and transport purposes. A comparison of RE LCOE with those of other technologies or market prices should therefore be project-based as well.

The LCOE of a technology is not the sole determinant of its value or economic competitiveness. In addition to integration and transmission costs, relative environmental impacts must be considered, as well as the contribution of a technology to meeting specific energy services, for example, peak electricity demands.

Nevertheless, and despite the existing uncertainties, summarizing the information contained in Figures 10.28 through 10.31, Sections 2.7, 3.8, 4.6, 5.8, 6.7 and 7.8 as well as in recent benchmark studies (IEA, 2010a,b,c,d), the following conclusions can be drawn:

A comparison of LCOE of RE technologies with those of other technologies (nuclear, gas and coal power plants) shows that—at least as long as

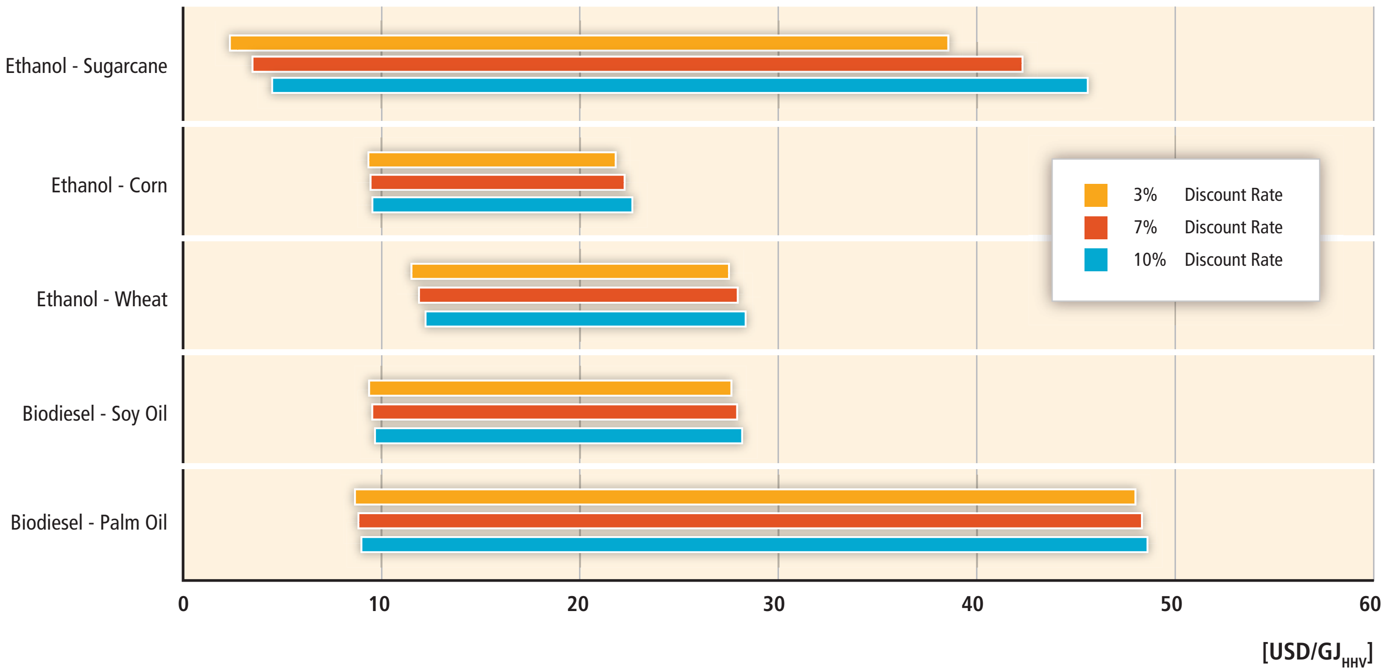


Figure 10.31 | Levelized cost of fuels (LCOF) for commercially available biomass conversion technologies at 3, 7 and 10% discount rates. LCOF estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost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

externalities are not taken into account—RE sources are often not yet competitive with other sources, especially if they both feed into the electricity grid. If the respective technologies are used in a decentralized mode, private investors would compare their production cost with the retail consumer power price, which is much higher. In this case, niche markets might exist that facilitate the market introduction of new technologies. The same holds true for applications in remote areas, where often no grid-based electricity is available (IEA, 2010c). Similar trends exist outside of the power sector for the use of RE in heating and transportation applications (IEA, 2007a).

Given suitable conditions, the lower end of the LCOE ranges indicate (see Figure 10.28) that some RE technologies already can compete with traditional forms at current energy market prices in many regions of the world. That said, the graphs provide no indication of the resource potential that can be utilized at low cost. Sections 10.3 and 10.4 provide more information in this regard.

10.5.2 Prospects for cost decreases

In the field of RE, significant opportunities exist to further improve the energy efficiencies and/or to decrease the costs of producing and installing the respective technologies (see Sections 2.7, 3.8, 4.7, 6.7 and 7.8). Together, these effects are expected to decrease the LCOE of many innovative RE sourcing technologies in the future (IEA, 2008b, 2010a). According to Junginger et al. (2006), the list of the most important mechanisms causing cost reductions comprises:

- *Learning by searching*, that is, improvements due to research, development and demonstration (RD&D)—especially, but not exclusively in the stage of invention;
- *Learning by doing* (in the strict sense), that is, improvements in the production process (e.g., increased labour efficiency, work specialization);
- *Learning by using*, that is, improvements triggered by user experience feedbacks occur once the technology enters (niche) markets;
- *Learning by interacting (or 'spill-overs')* (IPCC, 2007; Clarke et al., 2008), that is, the reinforcement of the above-mentioned mechanism due to an increased interaction among various actors in the diffusion phase;
- *Upsizing of technologies* (e.g., up-scaling of wind turbines); and
- *Economies of scale* (i.e., mass production) once the stage of large-scale production is reached.

The various mechanisms may occur simultaneously at various stages of the innovation chain. In addition, they may reinforce each other. As a consequence of the aforementioned mechanisms, many technologies applied in the field of RE sources showed a significant cost decrease in the past (IEA, 2000, 2008a). This empirical observation is highlighted by *experience (or 'learning') curves*, which describe how costs have declined with accumulated experience and corresponding cumulative production or installed capacity. An illustrative experience curve (referring to wind energy) is shown in Figure 10.32. Further examples concerning bioenergy use and photovoltaic modules can be found in Section 2.7.2 (Figure 2.21) and in Section 3.8.3 (Figure 3.17), respectively.

For a doubling of the (cumulatively) installed capacity, many technologies showed a more or less constant percentage decrease in the specific investment costs (or in the levelized costs or unit price, depending on the selected cost indicator). The corresponding *learning rate (LR)* is defined as the percentage cost reduction for each doubling of the cumulative capacity. A summary of observed learning rates is provided in Table 10.10. Occasionally, the *progress ratio (PR)* is used as a substitute for the learning rate. It is defined as PR = 1 - LR (e.g., a learning rate of 20% would imply a progress ratio of 80%). Frequently, energy supply costs (e.g., electricity generation costs) and the cumulative energy supplied

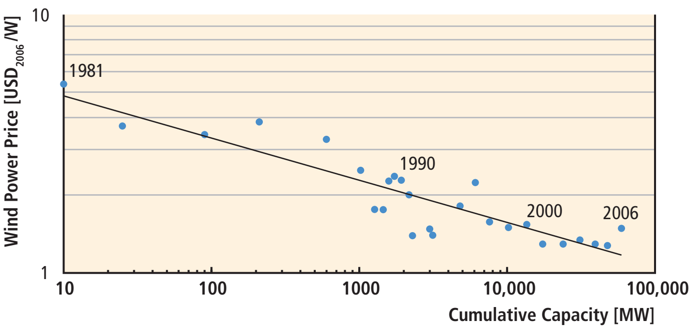


Figure 10.32 | Illustrative experience curve for wind turbines. Source: Nemet (2009).

by the respective technology (e.g., the cumulative electricity production) are used as substitutes for investment costs and the cumulative installed capacity, respectively. If the learning rate is time-independent, the empirical experience curve can be fitted by a power law. In this case, representing costs against cumulative installed capacity in a graph with double logarithmic scales shows the experience curve as a straight line (Junginger et al., 2010) (see Figure 10.32).

As there is no natural law that costs *have* to follow a power law (Junginger et al., 2010), care must be taken if historic experience curves are extrapolated in order to predict future costs (Nemet, 2009). Obviously, the cost reduction cannot go *ad infinitum* and there might be some unexpected steps in the curve in practice (e.g., caused by technology breakthroughs). As technologies mature, learning rates may fall (Ferioli et al., 2009; Nemet, 2009). In order to avoid implausible results, projections that extrapolate experience cost curves in order to assess future costs should therefore constrain the cost reduction by appropriate *floor costs* (see Edenhofer et al., 2006).

Concerning levelized costs or turnkey investment costs, a significant share of these floor costs might arise from balance of system and installation costs, which, in turn, are often dominated by labour costs. Although installers might gain experience, the future decrease in this cost component is limited (Yang, 2010). Unfortunately, *cost* data are not easily obtained in a competitive market environment. Indicators that are intended to serve as a substitute, for example, product *prices*, do not necessarily reveal the actual improvement achieved (Yu et al., 2011). Instead, they might be heavily influenced by an imbalance of supply and demand. This refers to both the final product itself (e.g., if financial support stipulates a high demand) and the cost of production factors, which might be temporarily scarce (e.g., steel prices due to supply bottlenecks). A deviation from price-based experience curves, as especially observed for PV modules in the years between 2004 and 2008 (see Section 3.8.3, Figure 3.17), therefore does not necessarily imply that a fundamental cost limit has been reached (Nemet, 2009). Instead, it might simply indicate that producers were able to make extra profits while the cost reduction takes place in the background. After a subsequent 'shakeout' phase, the short-term deviation from the long-term experience curve might be largely removed (Junginger et al., 2005b). In the field of solar PV, for instance, the recent development is characterized by overcapacities and a resulting increased competition between PV companies (see Chapter 3). As a result, PV system prices fell by 40% between 2008 and 2009 (IEA, 2010c; and see Section 3.8.3, Figure 3.17).

A summary of observed learning rates is provided in Table 10.10. Learning rates referring to investment costs (or turnkey investment costs) are often lower than those derived from electricity generation costs. Although the cost reduction in the specific investment costs of wind power plants, for instance, might be small, the scale-up results in higher hub heights and an associated significant increase in the capacity factor (and consequently in the amount of energy delivered). The ultimate goal of technological progress in the field of RE is a reduction of the energy production costs per kWh (in other words, the LCOE), not of the investment costs per se (see Section 7.8.4.1; EWEA, 2009; Ferioli et al., 2009).

Any efforts to assess future costs by extrapolating historic experience curves must take into account the uncertainty of learning rates as well as the caveats and knowledge gaps discussed in Sections 10.5.6 and 7.8.4.1. As a supplementary approach, expert elicitations could be used to gather additional information about future cost reduction potentials (Curtright et al., 2008), which might be contrasted with the assessments gained by using learning rates. Furthermore, engineering model analyses to identify technology improvement potentials could also provide additional information for developing cost projections (see Sections 2.6, 3.7, 4.6, 6.6 and 7.7)

Important potential technological advances and associated cost reductions, for instance, are expected in (but are not limited to) the following application fields: next-generation biofuels and bio-refineries (see Section 2.6); advanced PV and CSP technologies and manufacturing processes (see Section 3.7); enhanced geothermal systems (see Section

Table 10.10 | Observed learning rates for various electricity supply technologies. Source: IEA, 2008b, p. 205, extended and updated with a select list of additional literature (this report). (Note that values cited by older publications are less reliable as these refer to shorter time periods. In addition, only values for single-factor learning curves are shown. As a consequence there is some, albeit restricted, overlap with the learning rate information offered by Chapters 2 through 7.)

Technology	Source	Country / region	Period	Learning rate (%)	Performance measure
Onshore wind					
	Neij, 1997	Denmark	1982-1995	4	Price of wind turbine (USD/kW)
	Mackay and Probert, 1998	USA	1981-1996	14	Price of wind turbine (USD/kW)
	Neij, 1999	Denmark	1982-1997	8	Price of wind turbine (USD/kW)
	Durstewitz, 1999	Germany	1990-1998	8	Price of wind turbine (USD/kW)
	IEA, 2000	USA	1985-1994	32	Electricity production cost (USD/kWh)
	IEA, 2000	EU	1980-1995	18	Electricity production cost (USD/kWh)
	Kouvaritakis et al., 2000	OECD	1981-1995	17	Price of wind turbine (USD/kW)
	Neij, 2003	Denmark	1982-1997	8	Price of wind turbine (USD/kW)
	Junginger et al., 2005a	Spain	1990-2001	15	Turnkey investment costs (EUR/kW)
	Junginger et al., 2005a	UK	1992-2001	19	Turnkey investment costs (EUR/kW)
	Söderholm and Sundqvist, 2007	Germany, UK, Denmark	1986-2000	5	Turnkey investment costs (EUR/kW)
	Neij, 2008	Denmark	1981-2000	17	Electricity production cost (USD/kWh)
	Kahouli-Brahmi, 2009	Global	1979-1997	17	Investment costs (USD/kW)
	Nemet, 2009	Global	1981-2004	11	Investment costs (USD/kW)
	Wiser and Bolinger, 2010	Global	1982-2009	9	Investment costs (USD/kW)
Offshore wind					
	Isles, 2006	8 EU countries	1991-2006	3	Investment cost of wind farms (USD/kW)
Photovoltaics (PV)					
	Harmon, 2000	Global	1968-1998	20	Price PV module (USD/Wpeak)
	IEA, 2000	EU	1976-1996	21	Price PV module (USD/Wpeak)
	Williams, 2002	Global	1976-2002	20	Price PV module (USD/Wpeak)
	ECN, 2004	EU	1976-2001	20-23	Price PV module (USD/Wpeak)
	ECN, 2004	Germany	1992-2001	22	Price of balance of system costs
	van Sark et al., 2007	Global	1976-2006	21	Price PV module (USD/Wpeak)
	Kruck and Eltrop, 2007	Germany	1977-2005	13	Price PV module (EUR/Wpeak)
	Kruck and Eltrop, 2007	Germany	1999-2005	26	Price of balance of system costs
	Nemet, 2009	Global	1976-2006	15-21	Price PV module (USD/Wpeak)
Concentrating Solar Power (CSP)					
	Enermodal, 1999	USA	1984-1998	8-15	Plant investment cost (USD/kW)
Biomass					
	IEA, 2000	EU	1980-1995	15	Electricity production cost (USD/kWh)
	Goldemberg et al., 2004	Brazil	1985-2002	29	Prices for ethanol fuel (USD/m^3)
	Junginger et al., 2005b	Sweden, Finland	1975-2003	15	Forest wood chip prices (EUR/GJ)
	Junginger et al., 2006	Denmark	1984-1991	15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Sweden	1990-2002	8-9	Biomass CHP power (EUR/kWh)
	Junginger et al., 2006	Denmark	1984-2001	0-15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Denmark	1984-1998	12	Biogas plants (€/m^3 biogas/day)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	19	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1980-1985	7	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1985-2002	29	Ethanol from sugarcane (USD/m^3)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	20	Ethanol from sugarcane (USD/m^3)
	Hettinga et al., 2009	USA	1983-2005	18	Ethanol from corn (USD/m^3)
	Hettinga et al., 2009	USA	1975-2005	45	Corn production costs (USD/t corn)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	32	Sugarcane production costs (USD/t)

4.7); multiple emerging ocean technologies (see Section 6.6); and foundation and turbine designs for offshore wind energy (see Section 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 (see Sections 5.3, 5.7 and 5.8).

10.5.3 Deployment cost curves and learning investments

According to the definition used by the IEA (2008b, p. 208), "*deployment costs* represent the *total* costs of cumulative production needed for a new technology to become competitive with the current, incumbent technology." As the innovative technologies replace O&M costs, investment needs and fuel costs of other technologies, the *learning* investments are considerably lower. The *learning investments* are defined as the *additional* investment needs of the new technology. They are therefore equal to the deployment costs minus (replaced) cumulative costs of the incumbent technology.

Although not directly discussed in IEA (2008b)—to give the full picture—the cost difference could be extended to take into account variable costs as well (Figure 10.33). Because of fuel costs, the latter is evident for fossil fuel and biomass technologies. Once variable costs are taken into account, avoided carbon costs contribute to a further reduction of the *additional* investment needs (IEA, 2008b). Figure 10.33 shows a schematic presentation of experience curves, deployment costs and learning investments. The deployment costs are equal to the integral below the experience curve, calculated up to the break-even point.

In the beginning of the deployment phase, additional costs are expected to be positive ('expenditures'). Due to technological learning (in the broadest sense) and the possibility of increasing fossil fuel prices, additional costs could become negative after some decades (IEA, 2008b, 2010a). A least-cost approach towards a decarbonized economy therefore should not focus solely on the additional costs that are incurred until the break-even point with other technologies has been achieved (learning investments). After the break-even point, the innovative technologies considered are able to supply energy with costs lower than the traditional supply. As these costs savings occur then (after the break-even point) and indefinitely thereafter, their present value might be able to compensate the upfront investments (additional investment needs). Whether this is the case depends on various factors: the discount rate, the stringency of the selected climate stabilization goal and—most important—the future cost development of all its potentially competitive alternatives (see Section 10.2; Edenhofer et al., 2006; Clarke et al., 2009).

An answer to the question of whether or not upfront investments in a specific innovative technology are justified therefore cannot be given as long as this technology is treated in isolation (Kverndokk and

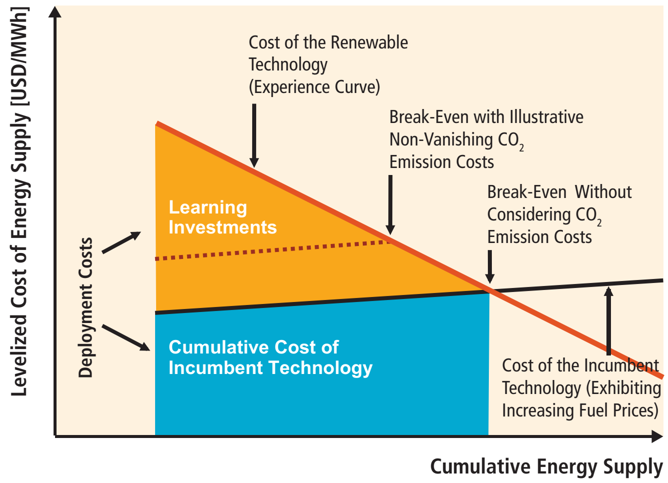


Figure 10.33 | Schematic representation of experience curves, deployment costs and learning investments (modified version of the diagram depicted in IEA, 2008b, p. 204).

Rosendahl, 2007). In a first attempt to clarify this issue and, especially, to investigate the mutual competition of prospective climate protection technologies, integrated assessment modellers have started to model technological learning in an endogenous way (Edenhofer et al., 2006, 2009, 2010; Clarke et al., 2009; Knopf et al., 2009). The results obtained from these modelling comparison exercises indicate that—in the context of stringent climate goals—upfront investments in learning technologies can be justified in many cases. However, as the different scenarios considered in Figure 10.34 and other studies clearly show, considerable uncertainty surrounds the exact volume and timing of these investments.

In reality, incentives for private investments in climate-friendly technologies are often low. In fact, private sector innovation market failures distort private sector investments in technological progress. The main problem is that private investors developing new technologies might not be able to benefit from the cost savings that are related to the application of these technologies in a couple of decades. Furthermore, as long as external environmental effects are not completely internalized, the use of fossil fuels appears to be cheaper than justified (Jaffe et al., 2005; Montgomery and Smith, 2007; van Benthem et al., 2008).

10.5.4 Time-dependent expenditures

A comprehensive survey of past investments in renewable energies is given in Section 11.2.2. This section therefore will constrain itself to a discussion of future investment estimates.

In Figure 10.34, future investments in different RE technologies are shown for the four illustrative scenarios discussed in detail in Section 10.3 (see Box 10.2). The resulting cumulative global investment estimates (in the power generation sector only) range from USD_{2005} 1,360 to 5,100 billion for the decade 2011 to 2020, and from USD_{2005} 1,490

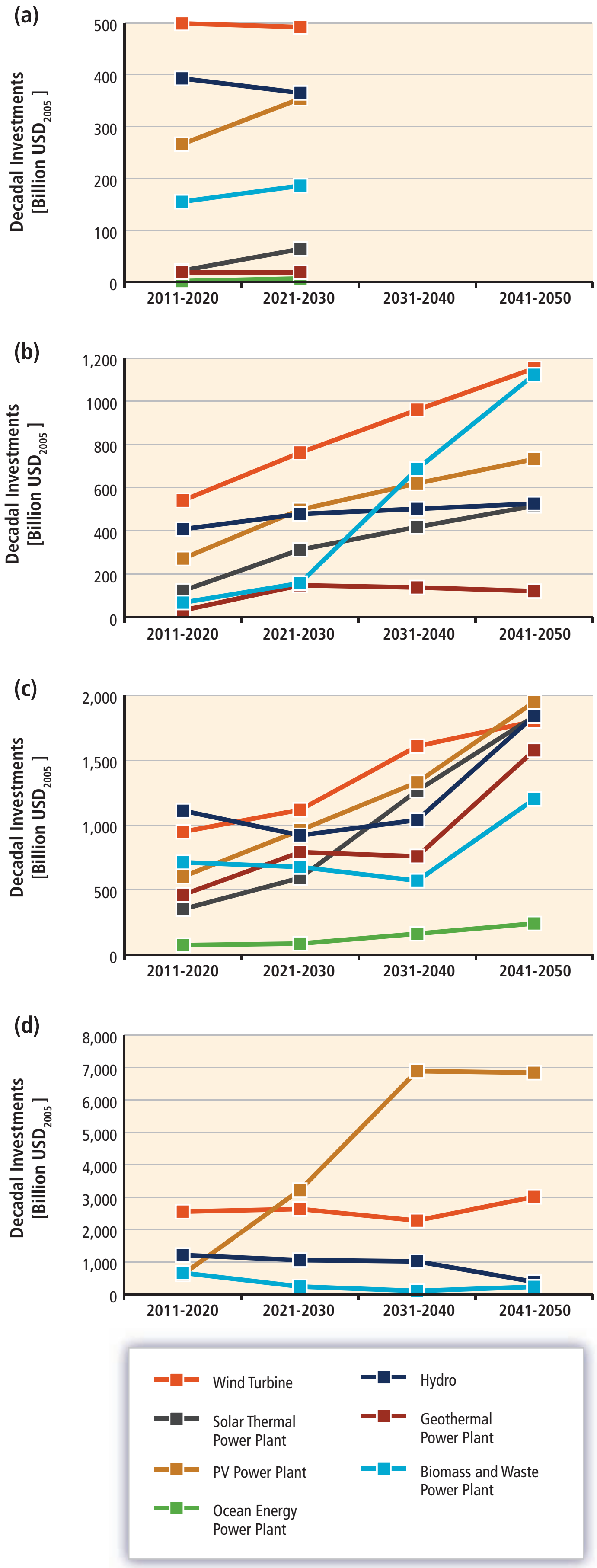


Figure 10.34 | Illustrative global *decadal* investments (in billion USD_{2005}) needed in order to achieve ambitious climate protection goals: (b) MiniCAM-EMF22 (first-best 2.6 W/m^2 overshoot scenario, nuclear and carbon capture technologies are permitted); (c) ER-2010 (450 ppm CO_2eq, nuclear and carbon capture technologies are not permitted); and (d) ReMIND-RECIPE (450 ppm CO_2, nuclear power plants and carbon capture technologies are permitted). Compared to the other scenarios, the PV share is high in (d) as concentrating solar power has not been considered. For comparison, (a) shows the IEA-WEO2009-Baseline (baseline scenario without climate protection). Sources: (a) IEA (2009); (b) Calvin et al. (2009); (c) Teske et al. (2010); and (d) Luderer et al. (2009).

to 7,180 billion for the decade 2021 to 2030. The lower values refer to the IEA World Energy Outlook 2009 Reference Scenario and the higher ones to a scenario that seeks to stabilize atmospheric CO_2 (only) concentration at 450 ppm. The average annual investments in the reference scenario are slightly lower than the respective investments reported for 2009 (see Section 11.2.2). Between 2011 and 2020, the higher values of the annual averages of the RE power sector investment approximately correspond to a three-fold increase in the current global investments in this field. For the next decade (2021 to 2030), a five-fold increase is projected. Even the upper level is smaller than 1% of the world GDP (IEA, 2009). Additionally, increasing the installed capacity of RE power plants will reduce the amount of fossil and nuclear fuels (and the related fuel costs) that otherwise would be needed in order to meet a given electricity demand. These numbers indicate how much money will be spent in the sector of RE sources if these scenarios materialize. The given numbers are useful to inform investors who are interested in the expected market volume. Data on energy delivered by the corresponding scenarios can be found in Sections 10.3 and 10.4.

Specific investment costs of RE sources are still often higher than those of other energy supply technologies. In order to assess the additional costs arising from using RE sources, two effects must be taken into account. Due to their capacity credit, investments in RE sources reduce investment needs for other technologies (see Sections 7.5.2.4 and 8.2.1.1). In addition, fossil fuel costs (and O&M costs) will be reduced as well. As a consequence, investment needs do not indicate the overall mitigation costs societies face if these scenarios materialize. In calculating the net total cost, replaced other investments and avoided variable costs must be considered as well (see IEA, 2008b, 2010a). As the latter are dependent on the development of fossil fuel prices, the overall net cost balance could be positive from a mid- or long-term perspective (for a national study, see Winkler et al., 2009).

Many integrated assessment models used to derive the scenarios considered in Section 10.2 consider avoided costs and take them into account during the respective calculation runs. However, the results for total avoided investments in other plants, and the overall avoided fuel costs are seldom published. In addition, there is a lack of global scenario exercises that attribute avoided costs to distinguished technologies—although this information would be extremely useful in order to carry out a fair assessment of learning investments or (net) deployment costs.

In the absence of technology-specific results, aggregated avoided costs will be discussed for an illustrative climate protection scenario (the BLUE

Map scenario) that has been designed by the International Energy Agency (IEA, 2010a). In order to deliver a 50% cut in CO_2 emissions by 2050 (compared to 2005), different technologies are applied. Their respective shares in delivering the requested emission reduction are: end-use fuel and electricity efficiency 38%, end-use fuel switching 15%, power generation efficiency and fuel switching 5%, CCS 19%, nuclear 6% wand RE 17%. Between 2010 and 2050, the additional investment of the BLUE Map scenario (compared to the Baseline scenario) is USD_{2005}41.72 trillion. In the same time period, the undiscounted fuel cost savings of this scenario are estimated to be USD_{2005} 101.59 trillion. Taken together, the total undiscounted net savings approach USD_{2005} 59.87 trillion. Even at a 10% discount rate, the fuel savings outweigh the additional incremental investment needs of the BLUE Map scenario.

Note that the results do not only take into account investments into RE sources. Other low-carbon technologies (energy efficiency improvements, nuclear energy, carbon capture and storage) are considered as well. Nevertheless, the results highlight the importance of comparing investment needs on the one hand and associated avoided (investment, O&M and fuel) costs of the substituted technologies on the other.

10.5.5 Market support and research, development, demonstration and deployment

Whereas the list in Section 10.5.2 summarizes different *causes* for technological progress and associated cost reductions, an alternative nomenclature focuses on how these effects can be *triggered*. Following this kind of reasoning, (Jamasb, 2007) distinguishes:

- *Learning by research* triggered by R&D expenditures that intend to achieve a *supply push* and
- *Learning by doing* (in the broader sense) resulting from capacity expansion promotion programs that intend to establish a *demand pull*.

Figure 10.35 depicts the historic RD&D support for RE research in relation to other technologies. Note that for fossil and nuclear technologies, the large-scale government support in the early stages of their respective innovation chain (i.e., well before the 1970s) is not shown.

As the IEA emphasizes, the role of governments is most effective if it combines 'supply push' and 'demand pull' programs depending on the position of the considered technology in the innovation chain (IEA, 2008b, 2010a). RD&D funding is particularly appropriate for infant technologies. Market entry support and demand pull programs (e.g., via norms, feed-in tariffs, renewable quota schemes, tax credits, bonus and malus systems) focus on the deployment and commercialization phase (Foxon et al., 2005; González, 2008), but can also help to trigger private investment in RD&D. A detailed description of corresponding policy options can be found in Chapter 11.

10.5.6 Knowledge gaps

At present, experience curves are often an integral part of integrated assessment models that seek to treat technological learning in an endogenous way. Unfortunately, small variations in the assumed learning rates can have a significant influence on the results of models that use experience curves. Empirical studies therefore should strive to provide error bars for the derived learning rates (van Sark et al., 2007; Mukora et al., 2009). In addition, a better understanding of the processes that result in cost reductions would be extremely valuable (Sagar and van der Zwaan, 2005; van den Wall-Bake et al., 2009). Furthermore, there is a severe lack of information that is necessary to decide whether short-term deviations from the experience curve can be attributed to supply bottlenecks, or whether they already indicate that the cost limit (in the sense of floor costs) is reached (Nemet, 2009). In addition, there is a need for studies that quantitatively investigate the extent to which spillovers to other firms are able to endanger the opportunity of innovating firms to harvest the innovation benefits (see Kverndokk and Rosendahl, 2007). If available at all, cost discussions in the literature mostly focus on investment needs. Unfortunately, many global studies neither display total cost balances (including estimates about operational costs and cost savings) nor externalities like social, political and environmental costs (e.g., side benefits like employment effects or the role of RE sources in reducing the risks associated with fossil fuel price volatility (Awerbuch, 2006; Gross and Heptonstall, 2008). Another crucial issue is that of optimal timing of RD&D versus demand pull programs as well as investigations into how a premature lock-in in sub-optimal technologies can be avoided (Sagar and van der Zwaan, 2005).

Although some assessments of externalities have taken place at a national level (see Chapter 9 and Section 10.6), a comprehensive global investigation and an associated cost-benefit analysis is highly recommended.

In addition, as Section 8.1 shows, there is a further need for comprehensive assessments of the additional costs arising from integrating RE sources into existing and future energy systems (Gross and Heptonstall, 2008).

10.6 Social and environmental costs and benefits

10.6.1 Background and objective

Energy production typically causes direct and indirect costs and benefits for the energy producer and for society. Energy producers, for instance, incur private costs, such as plant investment and operating costs, and receive private benefits, such as income from the energy market. Private costs and benefits are defined as costs or benefits accounted for by the

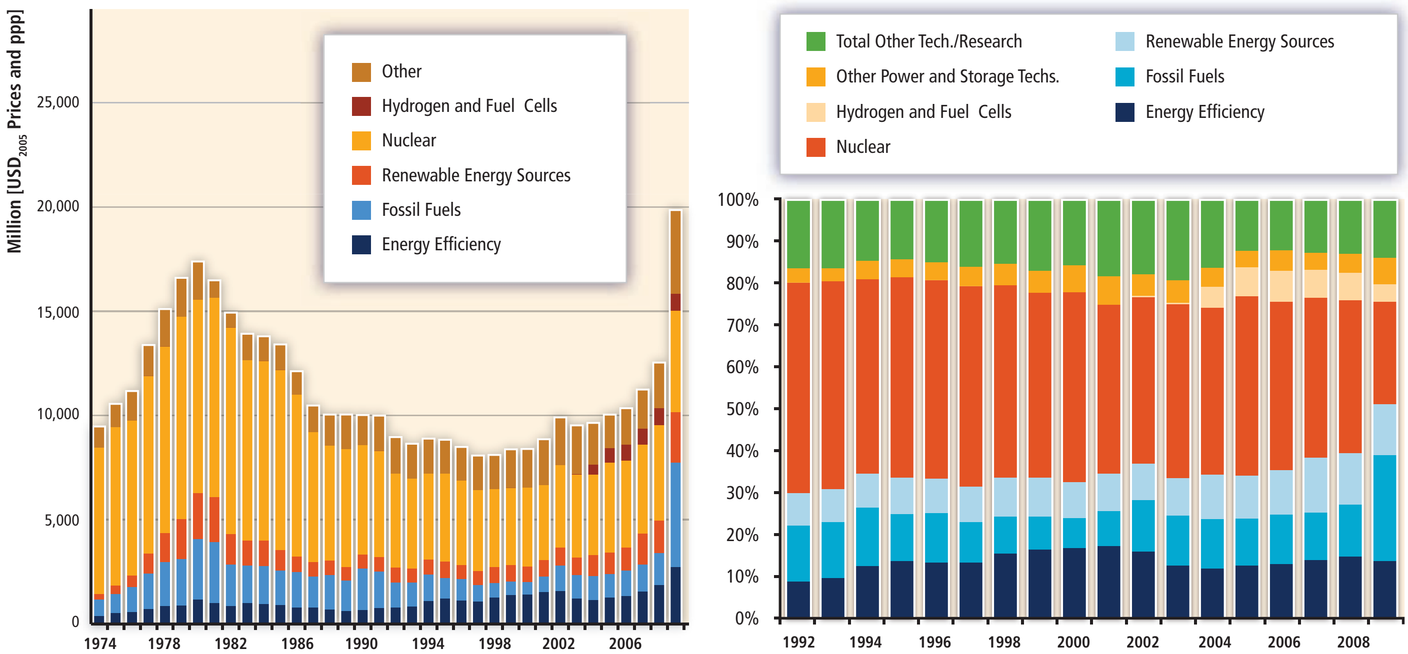


Figure 10.35 | Government budgets on energy RD&D of IEA countries (left panel) and technology shares of government energy RD&D expenditures in IEA countries (right panel) (IEA, 2008b, pp. 172-173, updated with data from IEA, 2010g).

agents responsible for the activity. The operations of energy producers often cause external impacts, which may be beneficial or detrimental but which are not covered by the energy producers or the price mechanisms. The costs and benefits due to external impacts are called external costs or external benefits, correspondingly (for the definition, see Annex I). External costs are usually indirect and they arise, for example, from pollutant emissions. The reduction of detrimental impacts caused by pollutant emissions can be seen as an external benefit from the system point of view when RE replaces some more harmful energy sources. Additionally, external benefits might occur if energy production and consumption result in positive effects for the society. Social costs are assumed to include here both private costs and external costs (Ricci, 2009a,b), although other definitions have also been used in the past (e.g., Hohmeyer, 1992).

In non-RE production, private costs are usually lower than the private benefits, which means that the energy production is normally profitable. On the other hand, the external costs can be high, on occasions exceeding the total (social) benefits. Alternatively, energy derived from RE technologies can often be unprofitable for the energy producer if not supported by incentive schemes. If the external costs (including environmental costs) are taken into account, the production of RE can, however, as a whole be more profitable from a social point of view than other energy production (Owen, 2006).

Typical factors causing external costs include atmospheric emissions from fossil fuel-based energy production, especially from combustion but also from other parts of the fuel chain. As shown in Chapter 9, the emissions can, among other things, consist of GHGs, acidifying emissions and particulate matter. These types of emissions can often but not always be lowered if RE is used to replace fossil fuels (Weisser, 2007).[12] Increasing the share of RE often contributes positively to access to energy,[13] energy security and the trade balance and it limits the negative effects from fluctuating prices of fossil-based energy (Section 9.3; Berry and Jaccard, 2001; Bolinger et al., 2006; Chen et al., 2007). However, various types of RE have their own private and external costs and benefits, depending on the energy source and the technology utilized. Chapter 9 addresses these issues comprehensively, based on the available literature.

Costs and benefits can be addressed in cost-benefit analyses to support decision making. However, the value of RE is not strictly intrinsic to renewable technologies themselves, but rather to the character of the energy system in which they are applied (Kennedy, 2005). The benefits of an increased use of RE are to a large part attributable to the reduced use of non-RE in the energy system.

The coverage and monetary valuation of the external impacts in general are difficult. The assessment of external costs is often tentative, may be inaccurate and might be seen impossible in many cases. As a result,

12 Note that in particular biomass applications can also cause particulate emissions.

13 About 1.4 billion people are still without access to electricity (Table 9.3.2); the RE sources due to their distributed character can at least to some extent help to alleviate this problem.

the cost-benefit analysis of some measure or policy, where the benefit arises from decreases in an environmental or external impact, is often contentious. In contrast, the difference between benefits and costs can be made clear even though the concrete numbers of the cost and benefit terms are uncertain. The long time spans associated with climate change and its impacts are not easy to consider in cost-benefit analyses. Discounting of impacts over long time horizons is at least to some extent problematic (Weitzman, 2007; Dietz and Stern, 2008). Further, many environmental impacts are not well understood or highly complex and their consideration and monetary valuation is difficult. Moreover, there are usually no compensation mechanisms that could balance costs and benefits among different stakeholders (Soderholm and Sundqvist, 2003). These aspects might limit the use of cost-benefit analysis and require other approaches, such as public consultation and direct setting of environmental targets and cost-benefit or cost-effectiveness analyses under these targets (Krewitt, 2002; Soderholm and Sundqvist, 2003; Grubb and Newbery, 2008).

Against this background, the objective of this section is to synthesize and discuss external costs and benefits of increased RE use in relation to climate change mitigation. The results are presented by technology at global and regional levels. Therefore, the section defines the cost categories considered and identifies quantitative estimates or qualitative assessments for costs by category type, by RE type, and as far as possible also by geographical area.

This section has links to the other chapters of this report, such as Chapters 1 and 9. Parts of this section consider the same topics, but from the viewpoints of external costs and benefits. The external costs and benefits considered in this section complement the cost considerations in the other parts of the chapter, forming a more holistic picture of costs from the social viewpoint.

10.6.2 Review of studies on external costs and benefits

Energy extraction, conversion and use cause significant environmental impacts and social costs. Many environmental impacts can be lowered by reducing emissions with advanced emission control technologies (Amann, 2008).

Although replacing fossil fuel-based energy with RE can reduce GHG emissions and also to some extent other environmental impacts and social costs caused by them, RE can also have environmental impacts and external costs, depending on the energy source and technology (da Costa et al., 2007). These impacts and costs should be lowered and of course should be considered if a comprehensive cost assessment is required.

This section considers studies in a cost and benefit category and presents a summary regarding energy sources as well. Some of the studies are global in nature, and to some extent regional studies, mostly for Europe and North America, will also be quoted. The number of studies for other regions is still limited. Many studies consider only one energy source or technology, but some studies cover a wider list of energy sources and technologies.

In the case of energy production technologies based on combustion, the impacts and external costs, in particular the environmental costs, mainly arise from emissions to air, especially if the greenhouse impact and health impact are considered. The lifecycle approach, including impacts via all stages of the energy production chain, is, however, necessary in order to recognize and account for total impact (Section 9.3.4). This holds true also in the case of non-combustible energy sources (WEC, 2004a; Kirkinen et al., 2008; Ricci, 2009a,b).

10.6.2.1 Climate change

The damage due to changing climate is often described by linking CO_2 emissions with the social costs of their impacts. This relation is called social costs of carbon (SCC), which is expressed as social costs per tonne of carbon or CO_2 released. A number of studies have been published on this subject and on the use of SCC in decision making (e.g., Anthoff, 2007; Grubb and Newbery, 2008; Watkiss and Downing, 2008).

The monetary evaluation of the impacts of the changing climate is difficult, however. To a large extent, the impacts manifest themselves slowly over a long period of time. In addition, the impacts can arise very far from a polluter in ecosystems and societies that are very different from the ecosystems and the society found at the polluter's location. It is for this reason that, for example, the methods used by the Stern (2007) review for damage cost accounting on a global scale are criticized, but they can also be seen as a choice for producing reasonable qualitative estimates. Apart from the question about discount rate, which is quite relevant considering the long term impacts of GHG emissions, considerable uncertainty exists in areas such as climate sensitivity, damages due to climate change, valuation of damages and equity weighting (Watkiss and Downing, 2008).

A German study (Krewitt and Schlomann, 2006) addressing external costs uses the values of USD 17/t CO_2, USD 90/t CO_2 and USD 350/t CO_2 (€ 14,70 and 280/t CO_2) for the lower limit, best guess and upper limit for SCC, respectively, referring to Downing et al. (2005) and Watkiss and Downing (2008). The study assesses that the range of the estimated SCC values covers three orders of magnitude, which can be explained by the many different choices possible in modelling and approaches to quantifying the damages. As a benchmark lower limit for global decision making, they give a value of about USD_{2005} 17/t CO_2 (£35/t CO_2). They do not give any best guess or upper limit benchmark value, but recommend that further studies should be done on the basis of long-term climate change mitigation stabilization levels.

The price of carbon can also be considered from other standpoints, for example, what price level of CO_2 emissions is needed in order to limit the atmospheric concentration to a given stabilization level. Emission trading gives also a price for carbon that is linked to the total allotted amount of emissions. Another way is to see the SCC as insurance for reducing the risks of climate change (Grubb and Newbery, 2008).

RE sources have usually quite low GHG emissions per each energy unit produced (see Chapter 9.3; WEC, 2004a; IPCC, 2007; Krewitt, 2007), so the impacts through climate change and the external costs they cause are usually low. There can also be exceptions, for example, in some cases of fuels requiring long refining chains like transportation biofuels produced under unfavourable conditions (Hill et al., 2006; Soimakallio et al., 2009) or land clearing for increasing biofuel production (Edwards et al., 2008; Searchinger et al., 2008).

Increasing the use of RE sources often displaces fossil energy sources that have relatively high GHG emissions and external costs (Koljonen et al., 2008). The net impact of an increase in RE supply is therefore positive external benefits if the whole system is considered. The magnitude of these positive impacts will depend in large part on the properties of the original energy system (Kennedy, 2005).

10.6.2.2 Health impacts due to air pollution

Combustion of both renewable fuels and fossil fuels often causes emissions of particulates and gases that have health impacts (Section 9.3.4; Krewitt, 2002; Torfs et al., 2007; Amann, 2008; Smith et al., 2009; Committee on Health, 2010). Exposure to smoke aerosols can be exceptionally large in primitive traditional burning of solid fuels, for example, in cooking of food in developing countries (see Section 9.3; Bailis et al., 2005). Also, emissions to the environment from stacks can reach people living far from the emission sources. The exposure and the number of health impacts depend on the physical and chemical character of the particulates, their concentrations in the air and population density (Krewitt, 2007). The exposure statistically leads to increased morbidity and mortality. The relationships between exposure and health impacts are estimated on the basis of epidemiological studies (e.g., Torfs et al., 2007). The external costs of increased mortality can be assessed using, for example, the concepts of value of life years lost (Preiss, 2009; Ricci, 2010) or value of statistical life (Committee on Health, 2010).

The results depend on many assumptions in the modelling, calculations and epidemiological studies. Krewitt (2002) describes how the estimated external costs of fossil-based electricity production have changed by a factor of ten during the ExternE project period between the years 1992 and 2002. ExternE is a major research programme launched by the European Commission at the beginning of the 1990s to provide a scientific basis for the quantification of energy-related externalities. The cost estimates have been increased by extension of the considered area (more people affected) and by inclusion of the chronic mortality. Furthermore, the cost estimates have been lowered by changing the indicator for costs arising from deaths and by using new exposure-impact models. It can be argued that the results include considerable uncertainty (Torfs et al., 2007).

The typical specific external costs through various impact chains per tonne of emissions have been assessed, for example, in Krewitt and Schlomann (2006), Preiss (2009) and Committee on Health (2010), to be for sulphur dioxide (SO_2) about USD 4,000 to 10,000/t, for nitrous oxides (NO_x) about USD_{2005} 2,000 to 10,000/t, and for particulates PM2.5 about USD 10,000 to 30,000/t. The wide ranges of values give a picture of variability and uncertainty.

When RE is used to replace fossil energy, the total social costs of the total energy system due to health impacts usually decrease (Kennedy, 2005; Bollen et al., 2009), which can be interpreted to lead to social benefits linked to the increase of RE. However, this is not always the case, as discussed in this section, but requires a more detailed analysis.

10.6.2.3 Other impacts

RE can have impacts on waters, land use, soil, ecosystems and biodiversity (Section 9.3.4). It can also have a positive influence on energy security and trade balance and rural employment or have impacts on other socioeconomic aspects. Some of these impacts are not in a strict sense external as they are covered by price mechanisms, although they can be of importance from the viewpoints of the society. Most of these impacts have been considered in the technology Chapters 2 to 7 or in Chapter 9 in detail. The external costs due to these impacts are usually lower than the external costs due to GHG emissions or due to health effects caused by pollutant emissions (Krewitt and Schlomann, 2006; Preiss, 2009; Committee on Health, 2010; Ricci, 2010). However, in some cases specific impacts may cause considerable external costs that should be evaluated on the project by project basis. Some information on the magnitudes of the impacts can be found in Section 10.6.3.

10.6.3 Social and environmental costs and benefits by energy sources and regional considerations

Most of the studies covered in this section consider North America (Gallagher et al., 2003; Roth and Ambs, 2004; Kennedy, 2005; Chen et al., 2007; Committee on Health, 2010; Kusiima and Powers, 2010) and Europe (Groscurth et al., 2000; Bergmann et al., 2006; Krewitt and Schlomann, 2006; Ricci, 2009b), whilst some are more general without a specific geographical area.

Some studies consider developing countries. Da Costa et al. (2007) discuss social features of energy production and use in Brazil. Fearnside (1999, 2005) and Oliveira and Rosa (2003) studied large hydropower projects and the technical potential of wastes in Brazil, respectively. Sparovek et al. (2009) investigated the impacts of the extension of sugarcane production in Brazil. Bailis et al. (2005) considered biomass- and petroleum-based domestic energy scenarios in Africa and their impacts on mortality on the basis of particulate emissions. Spalding-Fecher and Matibe (2003) studied total external costs of coal-fired power generation in South Africa. Amann (2008) studied cost-effective reduction of emissions of air pollutants and GHGs in China.

Studies concerning different areas of the globe are still sparse. More investigations, articles and reports are needed to provide information on external costs and their possible variation in the ecosystems and societies of different geographical areas.

To calculate the net impact in terms of social costs of an extension of RE sources, two things have to be done. First, (a) the external costs and benefits can be assessed on the basis of the lifecycle approach for each technology in the conditions typical for that technology so that only the direct impacts of that technology are taken into account (Pingoud et al., 1999; Roth and Ambs, 2004; Krewitt and Schlomann, 2006; Ricci, 2009b). The other thing (b) is to consider the RE technologies as parts of the total energy system and society, when the impacts of a possible increase in the use of the RE technologies can be assessed as causing decreases in the use and external costs of other energy sources. These decreases in external costs can be seen as external benefits of the RE technologies for society (Kennedy, 2005; Loulou et al., 2005; Koljonen et al., 2009).

An assessment of external costs in Central European conditions is presented in Table 10.11 (Krewitt and Schlomann, 2006). It can be seen that the social costs due to climate change and health impacts dominate the results in Table 10.11. The other impacts make a lesser contribution to the final results, keeping in mind that not all impacts are quantifiable. Even if the low-end SCC value of USD 17/t CO_2 assumed in the reference is used in Table 10.11 instead of USD 90/t CO_2, the climate impact still dominates in the total social costs of fossil-based technologies, but for renewable technologies the health impacts would be dominant.

Figure 10.36 shows the large uncertainty ranges of two dominant external cost components, namely climate- and health-related external costs. As one example, a recent extensive study made for the conditions in the USA (Committee on Health, 2010) arrived at almost similar

Table 10.11 | External costs (US cents/kWh (3,600 kJ)) due to electricity production based on RE sources and fossil energy in Central European conditions. Valuation of climate change is based on an SCC value of 90 USD/t CO_2 (Krewitt and Schlomann, 2006). Uncertainty ranges are not reported in the table. For uncertainty estimates, see Figure 10.36.

	PV (2000)	PV (2030)	Hydro 300 kW	Wind 1.5 MW Onshore	Wind 2.5 MW Offshore	Geo-thermal	Solar Thermal	Lignite η=40%	Lignite Comb.C η=48%	Coal η=43%	Coal Comp.C η=46%	Natural Gas η=58%
Climate change	0.86	0.48	0.11	0.09	0.08	0.33	0.11	9.3	8.0	7.4	6.9	3.4
Health	0.43	0.25	0.075	0.09	0.04	0.15	0.11	0.63	0.35	0.46	0.33	0.21
Ecosystems	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡
Material damages	0.011	0.008	0.001	0.001	0.001	0.004	0.002	0.019	0.010	0.016	0.01	0.006
Agricultural losses	0.006	0.004	0.001	0.002	0.0005	0.002	0.001	0.013	0.005	0.011	0.006	0.005
Large accidents	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Proliferation	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Energy security	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
Geo-political effects	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
Sum	**~1.3**	**~0.74**	**~0.19**	**~0.18**	**~0.12**	**~0.49**	**~0.22**	**>9.9**	**>8.4**	**>7.9**	**>7.2**	**>3.6**

Notes: 🟢 'green light': no significant impacts or external costs worth mentioning (Krewitt and Schlomann, 2006). 🟡 'yellow': impacts will arise that cannot be neglected and that will cause external costs. Comb.C: combined gas turbine and steam cycles; η: efficiency factor.

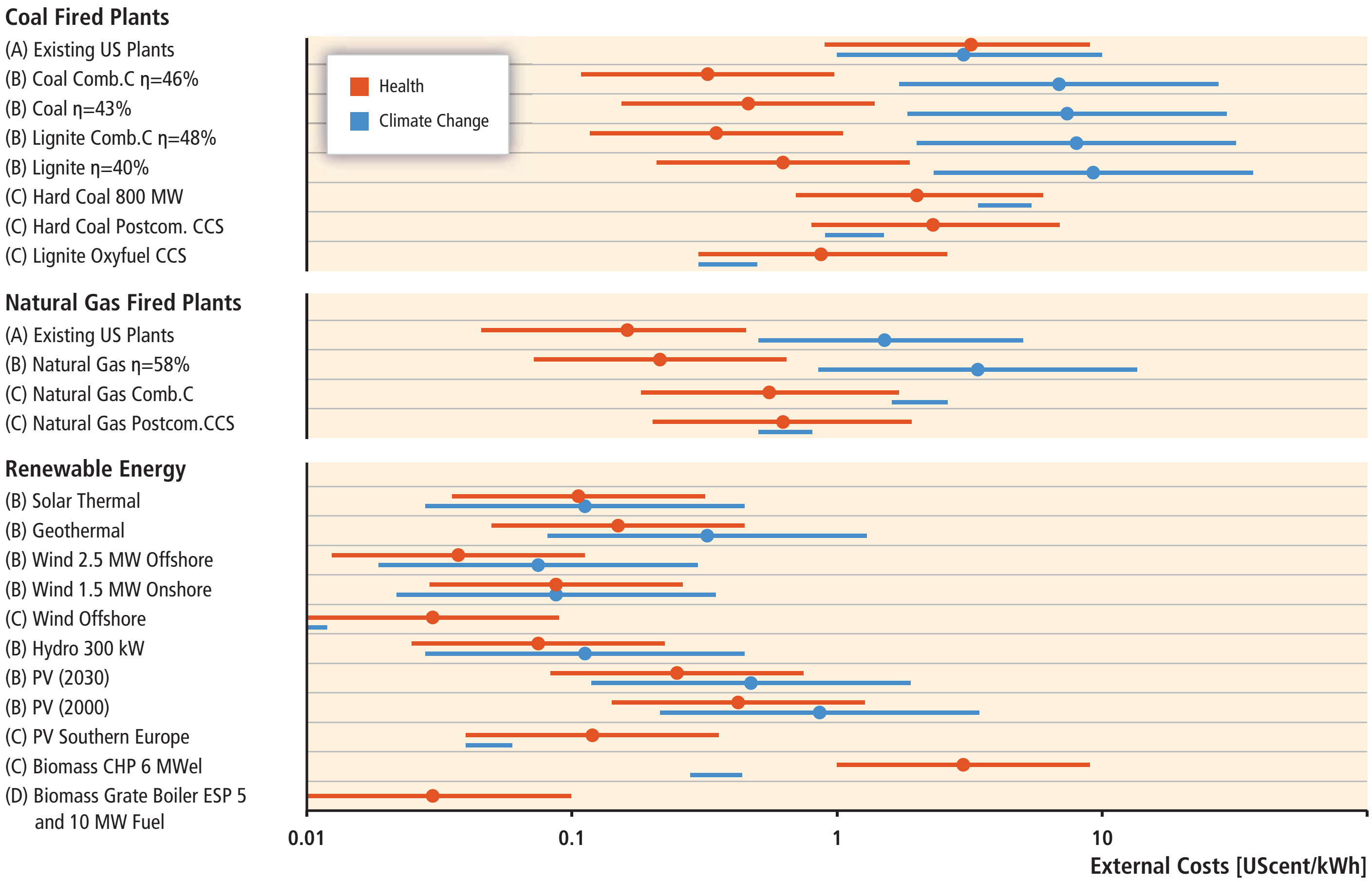


Figure 10.36 | Illustration of external costs due to the life-cycle of electricity production based on RE and fossil energy. The blue lines indicate the range of the external cost due to climate change and the red lines indicate the range of the external costs due to air pollutant health effects. External costs due to climate change mainly dominate in fossil energy if not equipped with carbon capture and storage (CCS). Comb.C: Combined Cycle; Postcom: Post-Combustion; η: efficiency factor. The results are based on four studies having different assumptions: (A) Committee on Health (2010): Existing power plants in the USA, SCC central estimate USD 30/t CO_2, range from USD 10 to 100/t CO_2, assumed value of statistical life USD 6 million; (B) Krewitt and Schlomann (2006): Central European conditions, SCC central estimate USD 90/t CO_2 and range from USD 17 to 350/t CO_2; (C) Results from the NEEDS project (Preiss, 2009; Ricci, 2010): Central European conditions in 2025, value of life year about USD 50,000, SCC range for the considered case is from USD 40 to 65/t CO_2; (D) As biomass case of (C) but particulate emissions reduced by electrostatic precipitators (ESP) (estimated on the basis of Sippula et al. (2009)) and the external costs presented per fuel energy. The uncertainty for the external costs of health impacts is assumed to be a factor of three (based on Preiss (2009); Krewitt and Schlomann (2006); and Krewitt (2002)).

results to those of Krewitt and Schlomann (2006) and Preiss (2009) for natural gas-based electricity production but clearly higher external cost levels for coal-based production due to higher non-climate impacts.

As shown in Figure 10.36, within the portfolio of RE technologies, offshore wind energy seems to cause the smallest external costs. In contrast, small-scale biomass-fired CHP plants cause relatively high external costs due to health effects via particulate emissions (Figure 10.36) based on the specific technology considered in the New Energy Externalities Development for Sustainability (NEEDS) study (Gärtner, 2008; Preiss, 2009). It should be noted that inexpensive technical solutions like electrostatic precipitators or fabric filters can lower particulate emissions considerably in plants of moderate size classes as measured and reported, for example, by Sippula et al. (2009).

External cost estimates for nuclear power are not reported here because the character of external costs and risk from release of radionuclides due to low probability accidents or due to leakages from waste repositories in a distant future are very different, for example, from climate change and air pollution, which are practically unavoidable. Those external impacts related to nuclear power can be, however, considered by discussion and judgment in the society. Also not included here is a quantitative assessment of accident risks, though Chapter 9 covers this issue in some depth, and accident risks in terms of fatalities due to various energy production chains (e.g., coal, oil, gas and hydropower) seem be to clearly higher in non-OECD countries than in OECD countries (Burgherr and Hirschberg, 2008) (see Chapter 9).

Following the results of Figure 10.36, in most cases the environmental damages and related external costs decrease when fossil fuels are replaced by RE. Also the social benefits from the supply of RE usually increase. In some cases, however, there can be trade-offs between RE expansion and some aspects of sustainable development. Therefore, it is important to conduct environmental impact assessments for specific RE projects under consideration in order to be sure that essential requirements for the implementation of the projects are realized. Chapter 9 discusses this topic in more detail.

Figure 10.36 can only summarize a part of the available literature. Some additional studies have, for example, considered the external costs from alternative transportation biofuels and other energy sources for automobiles (Hill et al., 2006, 2009; Committee on Health, 2010). The results suggest that lower external costs per vehicle kilometre than from fossil fuels can be achieved in many cases by using biofuels, but not always. Case-specific studies are needed to assess the impacts of considered feedstock cultivation and harvest, as well as fuel processing and use.

10.6.4 Synergistic strategies for limiting damages and external costs

Many environmental impacts and external costs follow from the use of energy sources and energy technologies that cause GHG emissions, particulate emissions and acidifying emissions—fossil fuel combustion being a prime example. Therefore, it might be beneficial to consider the reduction of emission-related impacts using integrated strategies (Amann, 2008; Bollen et al., 2009).

Bollen et al. (2009) have made global cost-benefit studies using the MERGE model (Manne and Richels, 2005). In their studies, the external costs of health effects due to particulate emissions and impacts of climate change were internalized. According to the study (Figure 10.37), the external benefits were greatest when both external cost types were internalized, although the mitigation costs were high as they work in a shorter time frame. The discounted benefits from the control of particulate emissions are clearly larger than the discounted benefits from the mitigation of climate change. The difference is, according to a sensitivity study, mostly greater by at least a factor of two, but of course depends on the specific assumptions. The countries would therefore benefit from combined strategies quite rapidly due to decreased external costs stemming from the reduced air pollution health impacts.

Amann (2008) reached quite similar conclusions in a case study for China. According to the study, the reduction of GHG emissions in China caused considerable benefits when there is a desire to reduce local air pollution. Also a study (Syri et al., 2002) considering the impacts of the reduction of GHG emissions in Finland stated that particulate emissions are also likely to decrease.

A study by Spalding-Fecher and Matibe (2003) is one of the few for developing countries. They found that, in South Africa, the total external costs of coal-fired power generation are 40 and 20% of industrial and residential charges for electricity. They concluded also that a reduction in GHG emissions lessens air-borne particulates that led to respiratory disorders and other diseases.

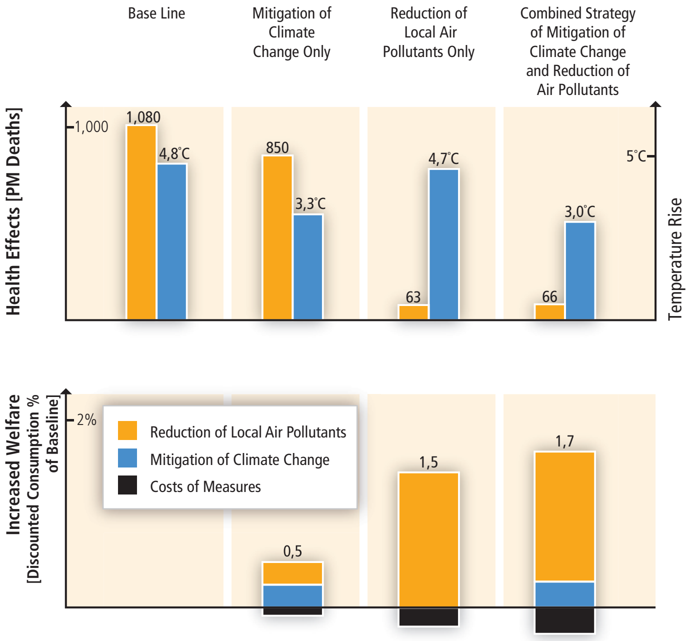


Figure 10.37 | Illustration of changes in costs, benefits and global welfare for three scenarios ('reduction of local air pollutants', 'mitigation of climate change', and 'combined strategy of mitigation of climate change and reduction of local air pollutants'), expressed as percentage consumption change (welfare increase) in comparison to the baseline (lower panel). The global temperature rise (degrees Celsius compared to the pre-industrial level) and number of deaths due to air pollution (millions) are given in the upper panel for each scenario. In the scenario 'mitigation of climate change only', the external costs of climate change have been internalized; in the scenario 'reduction of local air pollutants only', the external costs of local air pollutants have been internalized; and in the scenario of 'combined strategy', both external cost components have been internalized. The 'combined strategy' is most beneficial for society according to the results. In the baseline, the number of particulate matter (PM) deaths due to air pollutants would be around 1,000 million and the temperature rise 4.8°C (Bollen et al., 2009).

10.6.5 Knowledge gaps

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

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

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