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COMMENTS BY TSU TO EXPERT REVIEWERS

Please note that Box 10.2 and 10.3 are to be found at the very end of the document after the bibliography. These two boxes were omitted in the first version of the SRREN SOD.

Please note, that Figures 10.2.8 and 10.2.9 have now axis labels. This labelling has been missed in the first version of the SRREN SOD.

Yellow highlighted – original chapter text to which comments are referenced

Turquoise highlighted – inserted comment text from Authors or TSU i.e. [AUTHORS/TSU: …]

This chapter has been allocated 68 template pages, currently it counts 79 pages (excluding this page and bibliography), so it is 11 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened.

10. Mitigation Potential and Costs

CONTENTS

EXECUTIVE SUMMARY

RE is expected to play an important, and increasing, role in achieving ambitious climate mitigation targets. Although many RE technologies are becoming increasingly market competitive, many innovative technologies in the field of RE still have a long way to go before becoming mature alternatives to non-renewable technologies. Assessing the future role of technologies requires a reflection of different assumptions on key parameter (e.g. cost parameters), an integrative perspective, interactions with other mitigation technologies and the overall energy system has to be considered.

A comprehensive scenario survey (investigation of 165 scenarios representing the most recent integrated modelling literature) shows fundamental differences regarding the role of RE on climate mitigation: for any given GHG mitigation goal, the rate and magnitude of RE deployment is highly variable across the scenarios. The resulting differences, and therefore corresponding uncertainties in terms of the future of the energy system in general and the role of RE in particular, are understandable. Although the scenarios indicate that, all other things being equal, more aggressive mitigation will lead to greater deployment of RE, there are two determining factors that substantially influence this relationship:

(1) the character of the underlying drivers of energy system scale (energy demand) – economic growth and the proclivity to underpin this growth with energy consumption – and

(2) the relative competitiveness of additional options for reducing GHG emissions.

This latter category includes not just the two competing low-carbon energy supply options – fossil energy with CCS and nuclear energy – but also end-use technologies that can reduce energy demand as well as behavioural changes that can lead to reduced demands for energy services.

For any given mitigation goal, RE deployments are at their highest when energy demand is high and when scenario assumptions see RE as more competitive relative to other available supply options. However, different assessments on key parameters and other objectives besides mitigation lead to many scenarios that achieve large RE deployments, even without efforts to mitigate GHG emissions. There are many objectives in energy policies other than climate change mitigation, such as increasing energy security, reducing energy import dependence, making energy more affordable, reducing pollution levels or creating job opportunities, that RE can contribute to and that have served as reasons for establishing incentive schemes to support RE deployment in the recent past in various countries and will continue do so in the future. Additionally, there are many mitigation scenarios with relatively small RE deployments. However, regardless of the various uncertain factors, one fundamental area of consensus among the scenarios stands out: RE expands well beyond its current levels in the vast majority of the mitigation scenarios. By 2050, deployments in many of the scenarios reach 200 EJ/yr or up to 400 EJ/yr, compared to about 62 EJ/yr in 2007.

At a regional level, the scenarios consistently show larger RE deployment levels over time in both Annex 1 and non-Annex 1 countries, particularly in the latter. This result is consistent with the general result that the bulk of mitigation over time must take place in the non-Annex 1 countries given their increasing share of global emissions.

Therefore, the scenarios do generally confirm the intuition about several aspects of RE deployments. Despite the uncertainty in deployment levels, they are highest when mitigation is most aggressive, when the drivers of energy system scale (energy demand) are at their strongest, when demand-side responses to mitigation are smallest, and when RE is most competitive with competing low-carbon options (nuclear energy and fossil energy with CCS) or the application of the latter technologies is limited within the given scenario frame conditions.

The already more mature technologies, such as hydroelectric power, see relatively less expansion and there is less variance in their deployment levels compared to emerging technologies, such as solar power. Deployments of, under the current status, less mature technologies take more time and ultimately exhibit far greater variance across scenarios because of more uncertainty about their technical and economic potentials. Bio-energy deployment is of a dramatically higher scale over the coming 40 years than any of the other RE technologies. By 2050, wind and solar become the second and third most important technologies in terms of deployment levels.

A regional breakdown for the scope of future RE deployment shows growing shares in every world region, but deployment rates still are significantly lower than their technological limits. Therefore, technical potentials are not the limiting factors for the expansion of RE.

A more in depth look on four selected illustrative scenarios (representing the whole range of the investigated 165 scenarios) and, in particular, on the possible contribution of RE in different regions and sectors respective for different applications show a substantial range of results. The total share of RE based electricity production varies significantly from 21% (2020), 22% (2030) and 24% (2050) under Business-as-usual conditions and 38% (2020), 61% (2030) and 95% (2050) pursuing ambitious mitigation targets and limiting access to competing mitigation technologies. The contribution to the heating sector in all scenarios by 2050 lays between 24% following a Business-as-usual pathway and 91% anticipating an advanced market development triggered by specific mitigation targets. However, even if substantial growth rates are combined with these RE deployment paths, they are, in general, lower than what was achieved in the RE industry within the last decade. Furthermore, the resulting RE deployment for most of the RE technologies requires only a smaller part of the given technical potential.

Regarding primary energy demand, the contribution of RE lays between 15% in 2050 under Business-as-usual conditions and, depending on mitigation targets and the settings for competing mitigation technologies, between 34 and 80 % in more mitigation-oriented scenarios. That is combined with a substantial CO_2 reduction potential, which is hard to calculate correctly as it varies substantially by using different CO_2-calculation methods. Under Business-as-usual conditions and using average numbers for CO_2-emission factors, some 6.3 Gt CO_2/a can be avoided by 2050. The most ambitious deployment path for RE is connected with a mitigation potential of 26.5 Gt CO_2/a by 2050, which is equal to approximately 75% reduction of energy-related CO_2-emissions of the analysed baseline scenario.

Cost curves present RE deployments from a different perspective. The concept of abatement, energy and conservation supply curves nowadays is a very often used approach for mitigation strategies setting and prioritizing abatement options. One of the most important strengths of this method is, of course, that the results can be understood easily and that the outcomes of those methods give, on a first glance, a clear orientation as they rank available options in order of cost-effectiveness.

While abatement cost curves are very practical and can provide important strategic overviews, it is pertinent to understand that their use for direct and concrete decision-making has also some limitations. Most of the concerns are, amongst others, related to simplification issues, difficulties with the interpretation of negative costs, the reflection of real actor's choice, uncertainty factors with regard to discount rates as a crucial assumption for the resulting cost data, the missing dynamic system perspective considering relevant interactions with the overall system behaviour (in particular necessary for the determination of the emission factor), and the sometimes not very sufficient documentation status.

The reviews of the existing regional and national literature on RE, as well as mitigation potential literature as a function of costs, show a very broad range of results. In general, it is very difficult to compare data and findings from RE 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 (technologies reviewed, target years, discount rates, energy prices, deployment dynamics, technology learning, etc.). Concerning the analyzed regional/country studies it is worth to mention that they attribute fairly low abatement potentials to RE under USD100/tCO_2 – typically in the single-digit range. The findings translated in terms of the potential role of RE for mitigation pathways from the analyzed studies are somehow quite different from answers given through other methods (even from a scenario-based RE-supply-curve analysis conducted here).

As most of RE technologies are in early stages of their respective innovation chains, which cover research and development, demonstration, deployment and the final step to commercialization, learning by research (triggered by research and development expenditures) and/or learning by doing (resulting from capacity expansion programs) effects might result in considerable lower costs in the future.

Over time, energy generation costs of the most important innovative RE technologies have shown significant declines. In general, cost decreases are well described by empirical experience curves with global learning rates ranging between 10 and 17% (wind onshore), and 15 to 21% (photovoltaic). Differences in observed learning rates, especially national ones and those referring to biomass, can be explained by differences in geographical conditions, investigated types of technologies, as well as temporary imbalances between supply and demand.

In order to realize the learning effects mentioned above and to approach the break-even point, significant upfront investments are needed (deployment costs). On a global scale, following different scenarios (and depending on whether or not competing technologies, such as nuclear and CCS, are admissible), annual investment needs in the order of 100 to 1,000 billion USD are expected in case that ambitious climate protection goals (e.g., the 2°C mean temperature change limit) are pursued. These numbers allow assessing future market volumes and resulting investment opportunities, as well as resulting policy requirements. Due to avoided fossil fuel costs and decreased investment needs for conventional technologies, the additional costs (learning investments) might be considerably lower than the deployment costs. Unfortunately, currently there seems to be no global scenario available calculating the net-effect of RE deployment over time.

RE, which is abundant in many developing as well as developed countries, in that context can be applied as one option to limit the increase in GHG emissions without compromising the development process. The use of RE can also lead to co-benefits, including, for instance, less air pollution and less imports dependency compared to a Business-as-usual path accompanied with positive economic effects. RE deployment can also have positive impacts on trade balances and employment, e.g. in the case of energy biomass production.

Although social and environmental external costs vary heavily amongst different energy sources, and are still connected with a high uncertainty range, they should be considered if the advantages and disadvantages of future paths are being assessed. Typically, the production and use of fossil fuels cause significant external costs dominated often by the costs due to climate change impacts and health effects. In particular, social costs of carbon emissions vary a lot due to differences in methodologies used to assess the impact of the damages far in the future. In most cases, however, RE sources have clearly lower external costs assessed on a life-cycle basis. Thus, the increase of RE in the energy system in many cases reduces the overall external costs of the system. However, also negative cost relevant effects can emerge. According to the results of some economic model studies, a forced increase of RE can raise the price level of energy and slightly slow economic growth in certain situations.

10.1. Introduction

The evolution of future GHG emissions is highly dependent on various factors, particularly on the future demand for energy and a broad availability of mitigation technologies (IPCC 2007).

A large number of different options exist to mitigate anthropogenic GHG emissions. Mitigation measures within the energy system are of special importance, as more than half of global man-made GHG emissions are attributable to the use of fossil fuel energy sources (cf. chapter 1).

The following mitigation options related to energy supply are relevant:

- Using RE (e.g. hydropower, solar, wind, geothermal and biomass) instead of fossil fuel energy sources
- Using nuclear energy instead of fossil energy sources
- Using carbon capture and storage (CCS) technologies
- Improving the efficiency of energy transformation (e.g. through the use of combined heat and power plants) and distribution
- Switching from fossil fuels with high specific CO_2 emissions (especially coal) to fossil fuels with lower specific CO_2 emissions (especially natural gas)

The main mitigation options related to energy demand are as follows:

- Increasing the energy efficiencies of buildings, industry and transport sectors
- Changing consumer behaviours (e.g. using less products and services, in particular those that are energy-intensive)

Furthermore, non-energy-related mitigation potentials exist in some sectors as well. For example, in the agricultural sector crop and grazing land management can be improved to increase soil carbon storage, and rice cultivation techniques as well as livestock and manure management could be altered to reduce CH_4 emissions.

The implementation of mitigation technologies is triggered, amongst others, by cost effects or specific policy incentives (International Energy Agency (IEA), 2008b)

The uncertain future is reflected in the wide, and growing, range of emissions pathways across emission scenarios in the literature (Calvin *et al.*, 2009), as was already well reflected in the most recent IPCC assessment report (IPCC, 2007c). IPCC AR4 focused on the behaviour of the overall energy system and, as such, discussion of single technologies as a matter of course had to be rather short. One of the main questions in that context is the role RE sources are likely to play in the future and how they can particularly contribute to GHG-mitigation pathways.

RE, following the investigated scenarios, is expected to play an important, and increasing, role in achieving ambitious climate mitigation targets. Although some RE technologies are already competitive technologies (e.g. hydropower) and many others are becoming increasingly market competitive, there are still innovative technologies in the field of RE under the given frame conditions that have a long way to go before becoming mature alternatives to non-renewable technologies. Assessing the future role of technologies requires an integrative perspective, and interactions with other technologies, and the overall energy system have to be considered.

Behind this background, this chapter discusses the mitigation potentials and costs of RE technologies taken as a whole and from a systems perspective based on an assessment of the most recent scenario literature available on the subject, as well as, at least for some sections, on inputs (in particular deployment pathways) coming from previous technology chapters (chapters 2-7) in this report. Figure 10.1.1 shows the general logic behind the whole chapter and outlines the main results of the scenario survey which was conducted in this chapter.

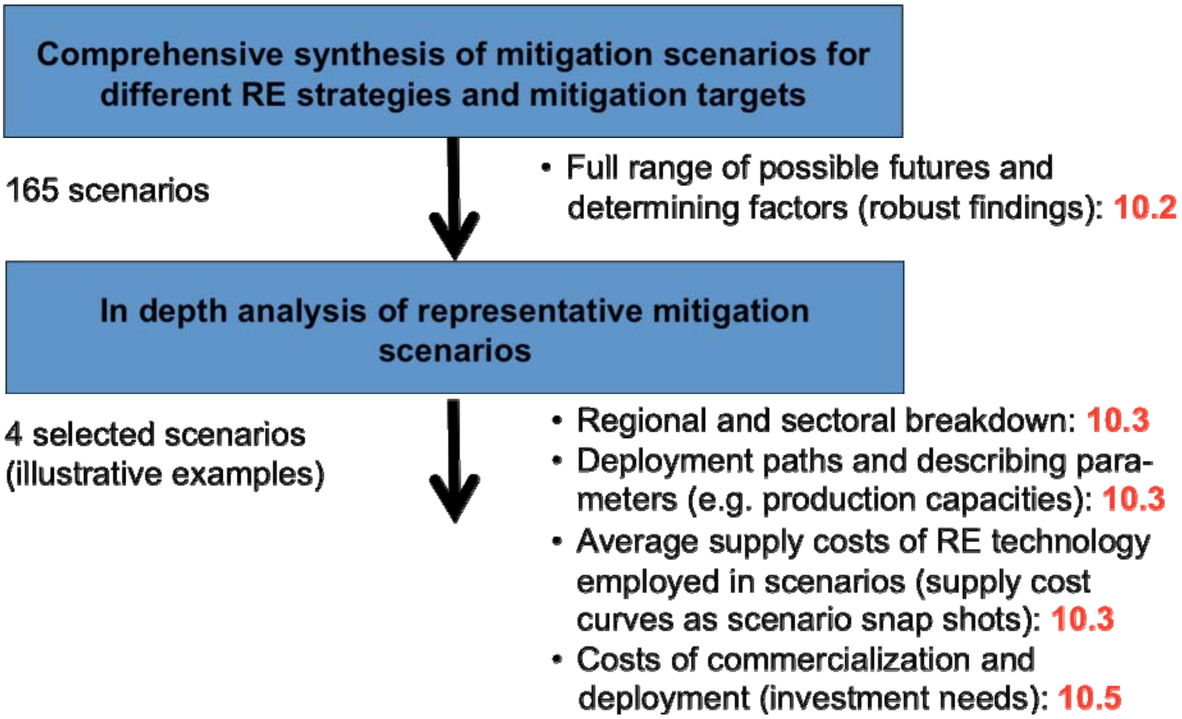

Figure 10.1.1: General logic behind the scenario survey structure conducted in the chapter

In that context, this chapter starts (Section 10.2) by providing context for understanding the role of RE in climate mitigation through the review of a total of 165 medium- to long-term scenarios from large-scale, integrated, energy-economic models as well as from more technology detailed models. The underlying goal of this exercise is, besides others, to gain a better understanding of robust evolutions of RE as a whole and single technologies reflecting different sets of assumptions and systems behaviour.

The section that follows (Section 10.3) complements the review with a more detailed review based on a selected part of the global scenarios, using four scenarios out of the scenario set from the previous section as illustrative representative examples. This section provides a next level of detail for exploring the role of RE in climate change mitigation. As such, while section 10.2, coming from a more statistical perspective, gives a comprehensive overview about the full range of mitigation scenarios and tries to identify the major relevant driving forces and system interactions (e.g. competing technologies) for the resulting RE deployment in the market and the specific role of these technologies in mitigation paths, section 10.3 provides a more detailed view, in particular of the required generation capacity, annual growth rates and the potential costs of RE deployment into the future. Within that context, the section distinguishes between different applications (electricity generation, heating and cooling, transport) and regions. As a link to the technology chapters, the section shows how the potential deployment scenarios and the overall resource potentials from the technology chapters compare with the four chosen scenarios.

In terms of primary energy calculation the direct equivalent methodology is being used here. In that context, Box 10.1 refers to the implications of different primary energy accounting conventions for energy and emission scenarios.

Box 10.1. Implications of different primary energy accounting conventions for energy and emission scenarios

As discussed in Chapter 1, there is no single, unambiguous accounting method for calculating primary energy from non-combustible energy sources: nuclear energy and all renewable energies with the exception of bio-energy. The ***direct equivalent method*** is used throughout this report. The direct equivalent method treats all non-combustible energy sources in an identical way by adopting the secondary energy perspective, which is the focus of chapters 2 to 7. The implications of the direct equivalent method in contrast to the other two most prominent methods – the physical energy content method and the substitution method – are illustrated below based on a selected climate stabilization scenario. The scenario is from Loulou et al. (2009; Teske *et al.*, 2010), and is referred to as 1B3.7MAX in that publication. CO_2-equivalent concentrations of the Kyoto gases reach 550 ppmv by 2100.

Differences from applying the three accounting methods to current energy consumption remain limited (cf. Table 1.x.y). However, substantial differences arise when applying the methods to over long-term scenarios. For the selected scenario, the accounting gap between methods grows substantially over time, reaching 370 EJ by 2100 (see Figure). There are significant differences in the accounting for individual non-combustible sources by 2050, and even the share of total renewable primary energy supply varies between 24% and 37% across the three methods (see Table). The biggest absolute gap for a single source is geothermal energy with about 200 EJ difference between the direct equivalent and the physical energy content method. The gaps for hydro and nuclear energy remain considerable.

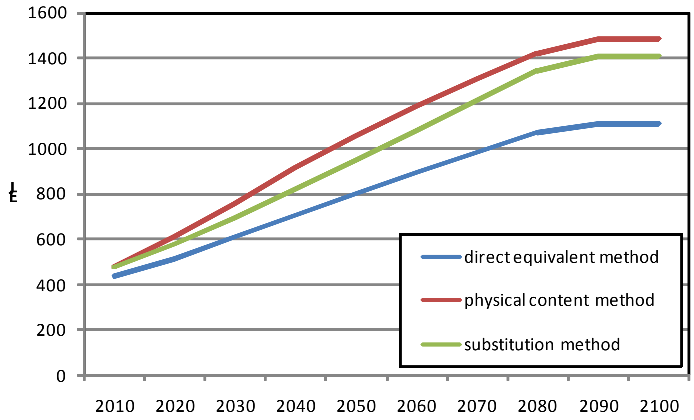

Figure: Primary Energy from non-combulstable energy sources, example scenario [added by TSU]

Table: Primary energy supply [added by TSU]

	Physical content method		Direct equivalent method		Substitution method	
	EJ	%	EJ	%	EJ	%
Fossil fuels	581.56	55.24	581.56	72.47	581.56	61.71
Nuclear	81.10	7.70	26.76	3.34	70.43	7.47
RE	390.08	37.05	194.15	24.19	290.37	30.81
Bioenergy	119.99	11.40	119.99	14.95	119.99	12.73
Solar	23.54	2.24	22.04	2.75	35.32	3.75
Geothermal	217.31	20.64	22.88	2.85	58.12	6.17
Hydro	23.79	2.26	23.79	2.96	62.61	6.64
Ocean	0.00	0.00	0.00	0.00	0.00	0.00
Wind	5.45	0.52	5.45	0.68	14.33	1.52
Total	1052.75	100.00	802.47	100.00	942.36	100.00

The section that follows (Section 10.4) with the discussion about cost curves focuses more in depth on cost aspects. It starts with a general assessment of the strengths and shortcomings of supply curves for RE and GHG abatement, 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 what the different technology chapters have concluded about the individual supply or even resource cost curves for each particular RE technology, including uncertainty. Additionally, and as another perspective on scenario results, the section uses the methodology of supply cost curves to give a sense of how RE technologies are deployed in the chosen four scenarios as a function of costs. The cost curves provide a scenario snapshot for a specific year and a selected region.

The next section (Section 10.5) deals with the costs of RE commercialization and deployment. The idea is to review present RE technology costs, as well as expectations on how these costs might evolve into the future. Learning by research (triggered by R&D expenditures) and learning by doing (fostered by capacity expansion programs) might result in a considerable long-term decline of RE technology costs. The section, therefore, 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 Business-as-usual pathway. In that context, for consistency reasons results from the same four illustrative scenarios are used as in section 10.3.

The following section (Section 10.6) synthesizes and discusses social, environmental costs and benefits of increased deployment of RE in relation to climate change mitigation and sustainable development. It, therefore, continues the discussions of chapter 9, but it is more focused on economic aspects.

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

10.2. Synthesis of mitigation scenarios for different RE strategies

This section reviews 165 recent medium- to long-term scenarios from 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 integrated nature of the scenarios reviewed in the section is particularly valuable for understanding the role of RE in climate change mitigation. In climate stabilization regimes, RE must compete with other options for reducing GHG emissions, including nuclear energy, fossil energy with CCS, energy efficiency and behavioural changes. It is therefore useful to place RE sources into the larger context of the energy system and the economy as a whole, particularly when the goal is to understand the role of RE from a long-term perspective, to 2030, 2050 or even beyond.

The discussion in this section is motivated by four 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, what is the linkage between the costs of mitigation and RE deployments? Finally, what factors, for example, resource availability and characteristics of competing mitigation options, influence the answers to all of the above?

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: quantitative modelling and qualitative narratives (see Morita *et al.*, 2001; Fisher *et al.*, 2007) for a more extensive review). There have also been several attempts to integrate narratives and quantitative modelling approaches (Nakicenovic and Swart, 2000; Morita *et al.*, 2001; Carpenter *et al.*, 2005). The review in this section relies exclusively on scenarios that provide a quantitative description of the future. These scenarios are valuable because of they provide estimates of renewable deployments and other important parameters and because they explicitly and formally represent the interactions between technologies and other factors. It is important to observe, however, that there is enormous variation in the detail and structure of the models used to construct the quantitative scenarios in this review.

Many authors have attempted to categorize these models as either bottom-up and top-down. For several reasons (see Box 10.2), this review will not rely on the top-down/bottom-up taxonomy. The important methodological characteristics of the scenarios reviewed in this section are: (1) they take an integrated view of the energy system so that they can 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; (5) and they have sufficient technology detail to explore RE deployment levels at both regional and global scales. Many also have integrated view beyond the energy system, for example, fully coupled models of the agriculture and land use more generally.

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, 2007c). 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 integrated models, such as those reviewed in this section, is that they capture many of the key interactions with other technologies, 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 varies greatly; some are based on more detailed representation of individual renewable and other energy technologies and aspects of systems integration of RES, while others focus on the implications of RE sources 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.

Several 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 a weakness of the scenarios is that they 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 must therefore gloss over many details that influence the performance and deployment of RE. For example, the representations of limitations on variable electricity generation on the grid are often represented in stylized fashion. The level of sophistication in representing these details varies substantially across models. Integrated global and regional scenarios are therefore most useful for the medium- to long-term outlook, i.e. starting from 2020 onwards. For shorter time horizons, tools such as market outlooks or short-term national analysis 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". Further, many of the scenarios represent sensitivities, particularly along the dimensions of future technology availability and the timing of international action, 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 RE sources in scenarios

10.2.2.1. Overview of the scenarios reviewed in this section

The bulk of the scenarios in this assessment (see Table 10.2.1) come from three coordinated, multi-model studies: the Energy Modeling Forum (EMF) 22 international scenarios (Clarke *et al.*, 2009), the ADAM project (Knopf *et al.*, 2009; Edenhofer *et al.*, 2010) and the RECIPE comparison (Luderer *et al.*, 2009; Edenhofer *et al.*, 2010) that harmonize some scenario dimensions, such as baseline assumptions or climate policies across the participating models. The value of using these scenario sets is that there is consistency within these sets that allows for comparison of how the role of RE might change with the alteration of one or several key factors. The remaining scenarios come from individual publications. Although the 165 scenarios are by no means exhaustive of recent literature, the set is large enough 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 (350-1050 ppm_v atmospheric CO_2 concentration by 2100, see Table 10.2.1), representing both mitigation and no-policy, or baseline, scenarios. The full set of scenarios also covers time horizons 2050 to 2100, and all of the scenarios are global in scope.

Table 10.2.1 Energy-economic and Integrated Assessment models considered in this analysis. Note that the total number of scenarios per model various significantly.

Model	# of scenarios	baseline scenarios	policy scenarios				Comparison project	Citation
			1st best	2nd best technology	2nd best policy	2^{nd} best technology & policy		
AIM/CGE	3	1	1	0	1	0	---	
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, 2008)
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; van Vliet *et al.*, 2009; van Vuuren *et al.*, 2010)
MERGE-ETL	19	4	3	12	0	0	ADAM	(Magne et al., 2010)
MESAP/PlaNet	1	0	0	1	0	0	---	(Krewitt et al., 2009)
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)
WIATEC	3	1	2	0	0	0	---	(Truong, 2010)
WITCH	12	1	4	4	3	0	EMF 22 / RECIPE	(Bosetti et al., 2009; Luderer et al., 2009)
TOTAL	165	27	50	63	20	5	---	

Table 10.2.2 Number of long-term scenarios categorized by CO_2 concentration levels in 2100 and by inclusion of delayed participation in mitigation and limitations on nuclear and CCS deployment. The CO2 concentration categories are defined in the IPCC AR4, WGIII, see (Fisher et al., 2007) with the exception of category IV which is extended here from to 600 ppm_v, because the lowest baseline scenarios reach concentration levels of slightly more than 600 ppm_v by 2100.

	CO_2 concentration by 2100 [ppm_v]	# of scenarios	policy scenarios			
			1st best	2nd-best technology	2nd best policy	2nd best technology and policy
Baselines	>600	27	---	---	---	---
Category III+IV	440-600	97	33	42	17	5
Category I+II	350-440	41	17	21	3	0

The scenarios are valuable in that they represent 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 "2^{nd}-best" scenarios which represent less optimistic views on international action to deal with climate change (2^{nd}-best policy) or address consequences of limited technology portfolios (2^{nd}-best technology). The assumptions regarding 2^{nd}-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 captured 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 and of nuclear energy.

A final distinguishing characteristic of the scenarios is the level of detail on RE deployment levels. RE information for this assessment was 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).

10.2.2.2. Overview of the role of RE in the scenarios

Not surprisingly, there is a strong correlation between fossil and industrial CO_2 emissions and long-term CO_2 concentration goals across the scenarios (Figure 10.2.1). This is consistent with past scenario literature (Fisher *et al.*, 2007). Perceived uncertainty in the nature of key physical processed underlying the global carbon cycle is sufficiently small in relation to other factors to maintain cumulative emissions over the century within relatively tight bounds. Beyond uncertainty in the carbon cycle, the variation in emissions pathways is largely influenced by assumptions regarding factors that influence the allocation of emissions over time. 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.

The relationship between RE deployment and CO_2 concentration goals is far less robust (Figure 10.2.2). On the one hand, the scenarios demonstrate a generally rising trend in renewable deployments as the stringency of the constraint is increased. In other words, larger RE deployments to be associated with more stringent CO_2 concentration goals. At the same time, there is enormous variance among deployment levels for any CO_2 concentration goal. This indicates a lack of consensus among scenario developers as to what might emerge.

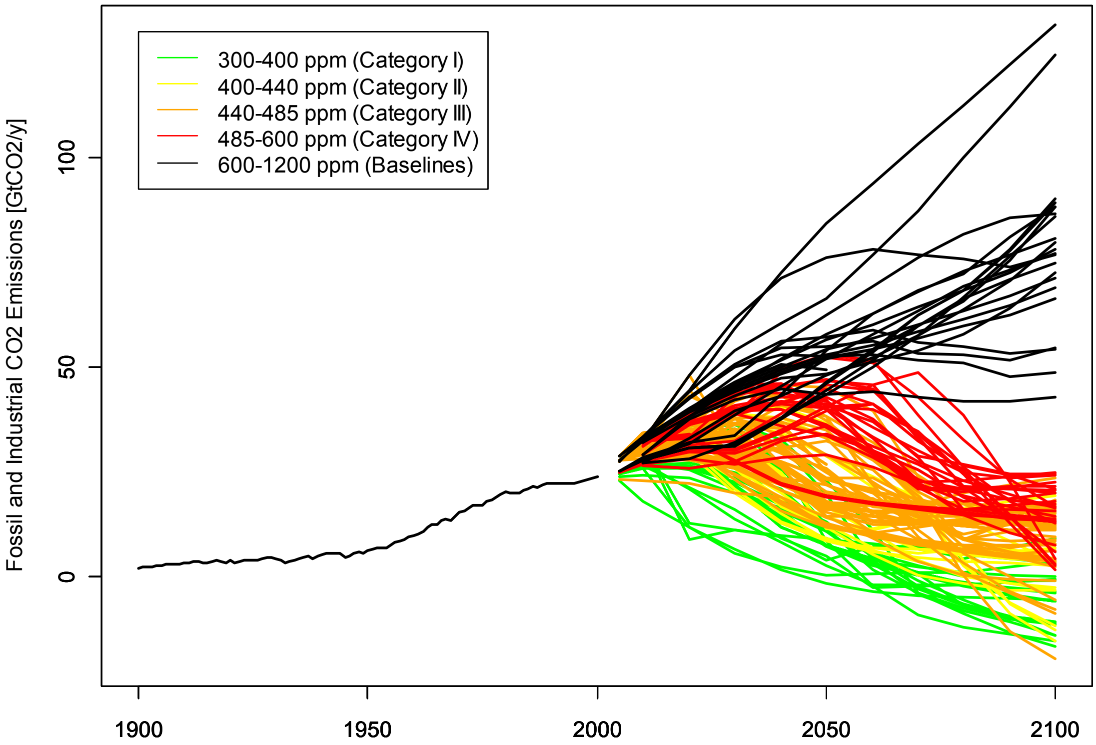

Figure 10.2.1. Historic and projected global fossil and industrial CO2 emissions of the long-term scenarios between 1900 and 2100 (colour coding is based on categories of atmospheric CO2 concentration level in 2100, adapted from (Krey and Clarke, 2010).

Several additional points deserve mention. First, although there is a high range of renewable deployments associated with any CO_2 goal, the highest deployments are associated with the most stringent of the CO_2 concentration goals. Second, the absolute magnitudes of RE sources deployment are dramatically higher than those of today in the vast majority of the scenarios. In 2007, global renewable primary energy supply in direct equivalent stood at 60.8 EJ/yr (IEA, 2009)[1]. In contrast, by 2030 many scenarios indicate a doubling of RE deployment or more compared to today. By 2050, deployments in many of the scenarios reach 200 EJ/yr or up through 400 EJ/yr. This is an extraordinary expansion in energy production from RE. The ranges for 2100 are substantially larger than these, reflecting continued growth throughout the century. Finally, RE deployments are quite large in many of the baseline scenarios. These large deployments result directly from the assumption that energy consumption will continue to grow substantially throughout the century and assumptions regarding the relative competitiveness of, and resource bases for, RE technologies in comparison to those for competing sources such as fossil energy and nuclear power. Both of these factors will be discussed in the coming sections.

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[1] Note that there is a small difference to the value of 62.5 EJ published by the IEA due to the different primary energy accounting methods used. See Box 10.1 and Chapter 1.3.1.2 for additional background on this topic.

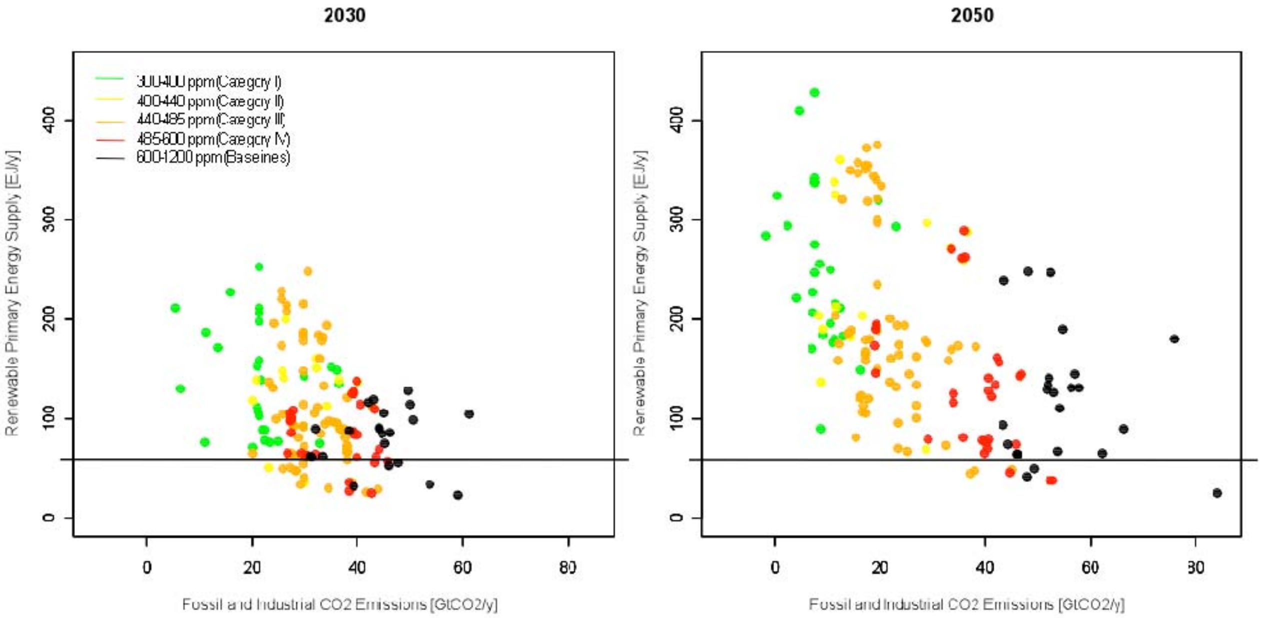

Figure 10.2.2 RE deployments across all scenarios as a function of fossil and industrial CO_2 emissions in 2030, 2050 and 2100 (colour coding is based on categories of atmospheric CO2 concentration level in 2100). The black vertical line shows the renewable primary energy deployment in 2007 which amounts to 60.8 EJ (adapted from Krey and Clarke, 2010).

10.2.2.3. Setting the Scale of RE Deployment: Energy System Growth and Long-Term Climate Goals

The deployment of RE in climate mitigation does not take place in a vacuum; it takes place in the context of a growing demand for energy and competing low-carbon energy sources. This section discusses the influence of energy system growth and Section 10.2.2.4 explores the competition with other low-carbon energy supply sources.

CO_2 mitigation puts downward pressure on total global energy consumption by increasing energy prices, but the effect is generally small enough that there is far less correlation in the scenarios between total primary energy consumption and long-term climate goals (Figure 10.2.3) than there is for CO_2 emissions and long-term climate goals (Figure 10.2.1.). In other words, the effect of mitigation on primary energy consumption is overwhelmed by variation in assumptions about the fundamental drivers of energy consumption. The variation results from the lack of consensus about these drivers; these are forces that simply cannot be understood with any degree of certainty today.

The variation in primary energy consumption increases with the stringency of the concentration goal. Although this assessment has not explored this phenomenon in detail, it is consistent with the following logic. The baseline scenarios are less varied because few scenarios envision primary energy demands decreasing over the coming century without emissions constraints. The emission constrained scenarios are more varied because these scenarios may assume, on the one extreme, abundant low-carbon options (leading to high primary energy demands) or, on the other extreme, approaches to mitigation based on reducing the demand for energy (leading to low primary energy demands).

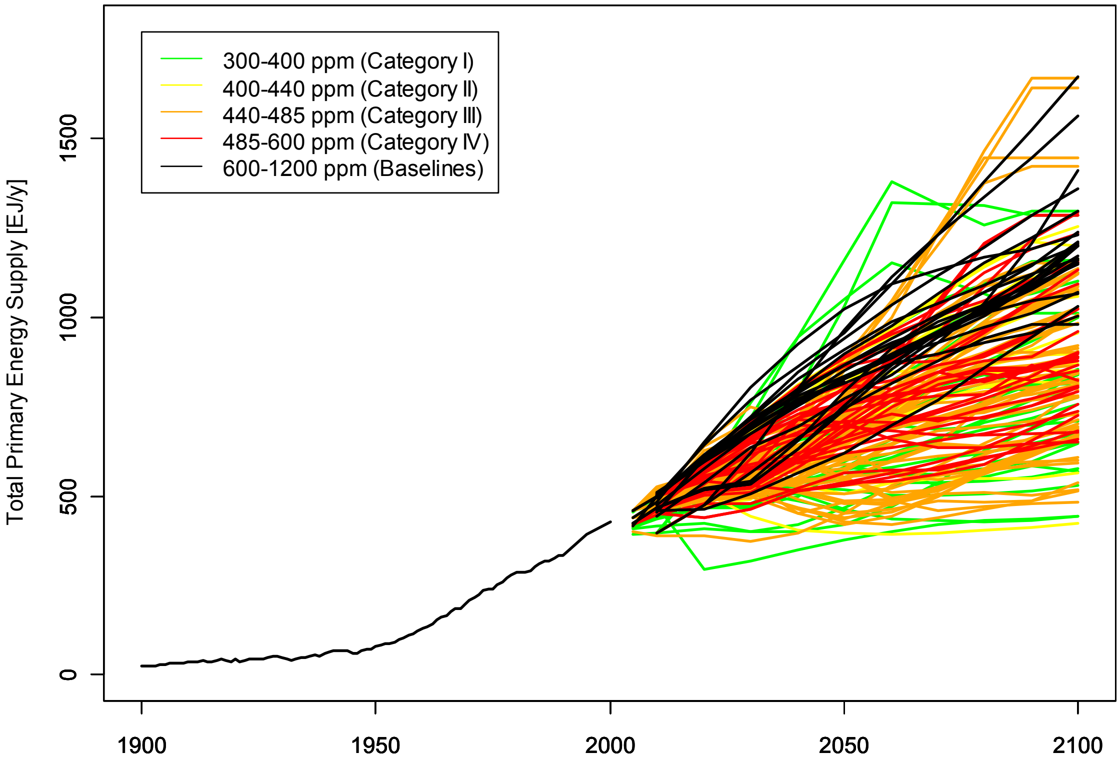

Figure 10.2.3 Historic and projected global primary energy supply (direct equivalent) across both baseline and mitigation scenarios (colour coding is based on categories of atmospheric CO2 concentration level in 2100 (adapted from Krey and Clarke, 2010).

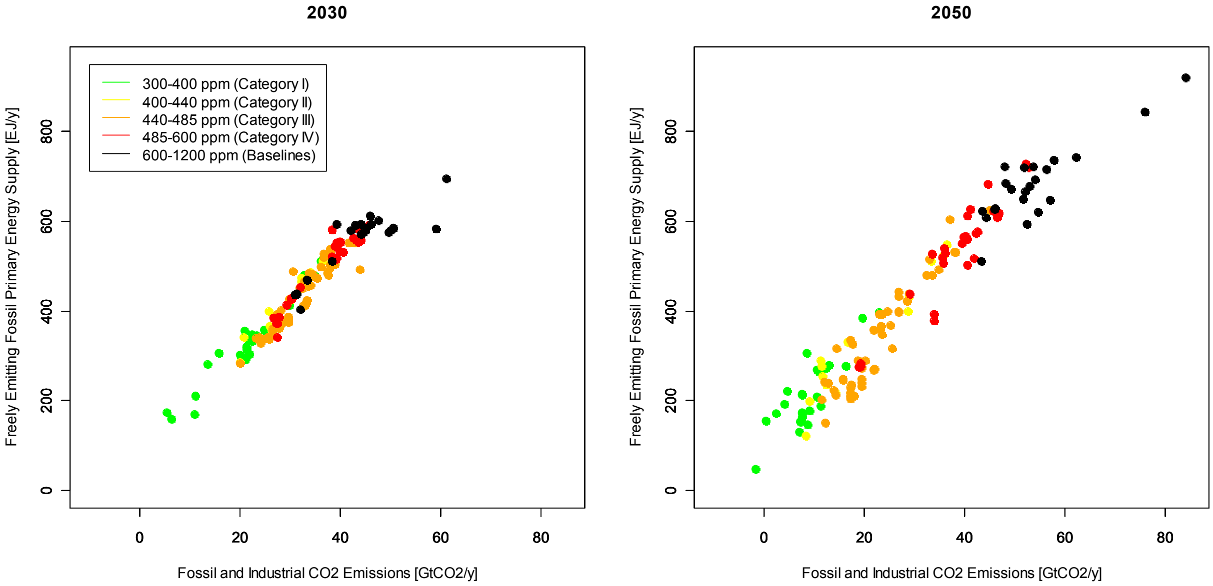

Figure 10.2.4 Freely emitting fossil primary energy consumption in the long-term scenarios by 2030 and 2050 as a function of fossil and industrial CO_2 emissions (colour coding is based on categories of atmospheric CO_2 concentration level in 2100 (adapted from Krey and Clarke, 2010).

In contrast to the variation in total primary energy, the production of freely-emitting fossil energy (fossil sources without CCS) is tightly constrained by the long-term CO_2 concentration goal and the associated CO_2 emissions at any point in time (Figure 10.2.4). 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 flexibility in freely-emitting fossil energy include: the ability to switch between fossil sources with different carbon contents (e.g., per unit of energy natural gas has a lower carbon content than coal); the potential to achieve negative emissions by utilizing bio-energy with CCS or forest sink enhancements; and differences in the time path of emissions reductions over time as a result of differing underlying model structures, assumptions about technology and emissions drivers, and representations of physical systems such as the carbon cycle.

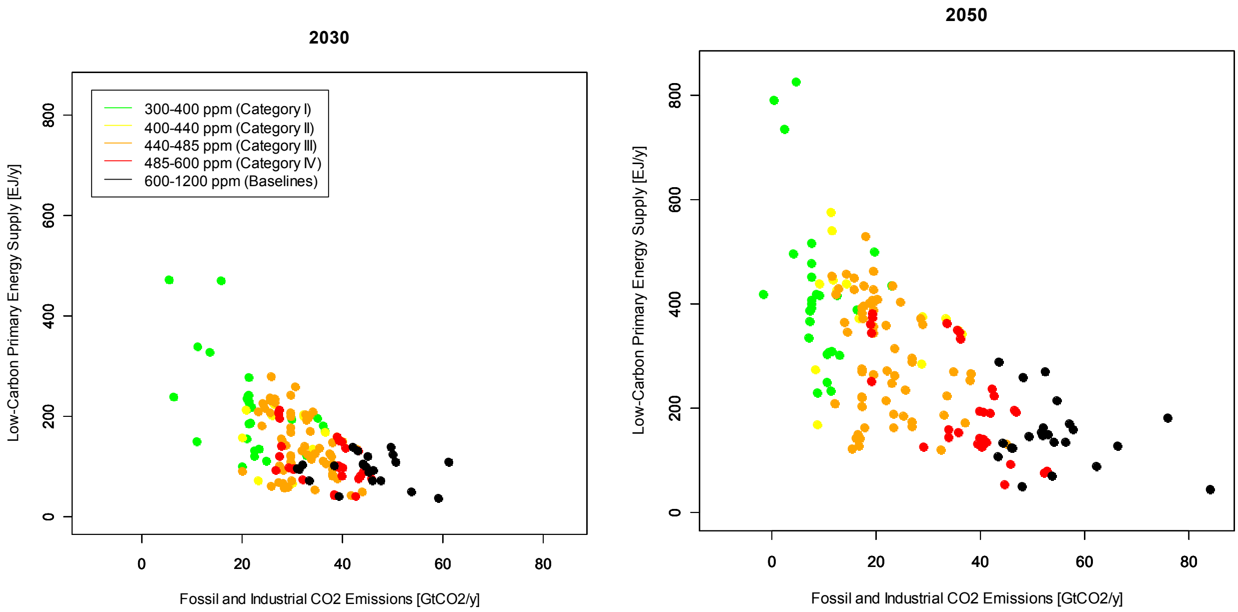

Figure 10.2.5 Global low-carbon primary energy supply in the long-term scenarios by 2030 and 2050 as a function of fossil and industrial CO2 emissions (colour coding is based on categories of atmospheric CO2 concentration level in 2100, (adapted from Krey and Clarke, 2010).

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 the difference between total primary energy demand and the production of freely-emitting fossil energy (see Figure 10.2.5). Total low-carbon energy production is correlated to the long-term concentration goal because freely-emitting fossil is partially offset by increasing production from low-carbon sources (Clarke et al., 2009; O'Neill et al., 2010). Total energy consumption also generally decreases in response to mitigation efforts because of higher fuel prices that make the implementation of additional energy efficiency measures economic[2]. However, as discussed above, 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

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[2] Note that this is not always true. There have been scenarios in which primary energy increases because of large-scale electrification in response to climate policy (see, for example, Loulou, R., M. Labriet, and A. Kanudia, 2009: Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. *Energy Economics*, **31**(Supplement 2), pp. S131-S143.

between the CO_2 concentration goal and low-carbon energy, there is still substantial variability in low-carbon energy for any given CO_2 concentration goal.

The competition between RE, nuclear energy, and fossil energy with CCS adds another layer of variability in the relationship between RE deployment and CO_2 concentration goal (the left panel in Figure 10.2.5). Given the variability in pathways to a long-term goal, the variability in energy consumption, and the competition between three low-carbon supply options, there is a great deal of variability in the relationship between CO_2 concentration goals and RE deployment levels (see Figure 10.2.2). At the same time, there is a clear correlation between CO_2 concentration goals and RE deployment levels; more stringent goals are associated with higher RE deployments on average, and the highest RE deployments are associated with the tightest goal.

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

It was not possible to systematically understand or articulate the competitiveness between RE and other supply options across the scenarios in this assessment as a means to understand the basis for RE market shares. This would require a level of information (e.g., detailed cost information by technology by region, underlying non-climate policy assumptions) from each of the scenarios far beyond what was collected for this study. It is also methodologically difficult, because of the complexity of the energy system in which different supply options compete. For example, the competitiveness of wind power depends on a range of factors beyond turbine costs, including the distribution of wind sites and their quality (i.e., wind class), transmission distances and costs to bring wind energy to the grid, and the technologies (e.g., electricity storage technologies) and management techniques available for managing large levels of intermittent electricity supply technologies on the grid. This sort of complexity does not lend itself to simple descriptions of technology competitiveness and is, indeed, a primary reason that integrated models are required to understand the deployment of RE technologies. (It should be emphasized again that the models in this study do not capture all of the technical or societal issues that might influence RE deployment levels.)

Although such a systematic exploration was not possible, it was possible to highlight the role of technological competition by exploring scenarios with explicit limitations on competitors to RE: energy sources with CCS and nuclear energy. Constrained CCS scenarios simply exclude the option to install CCS either on new or existing power plants or other energy conversion facilities with fossil or bio-energy as an input (e.g., refining). Constrained nuclear energy scenarios take on three forms. Two approaches maintain nuclear deployments at or below today’s levels, allowing current stocks to retire over time and not allowing any new installations, or maintaining 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 scenarios, limiting comparability and, in many cases, providing an intermediate constraint on nuclear energy (see caption of Figure 10.2.6 for details).

All other things being equal, when competing options are not available, RE deployments will be higher (Figure 10.2.6). Two effects simultaneously contribute to the increase of 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 puts downward pressure on total energy consumption because end use options become increasing economically attractive. The relative influence of these two forces varies across models.

It is interesting to note the relatively small influence on RE deployment levels from the absence of only one of the two competing low-carbon options. One possible explanation for this behaviour is that these two options both provide base-load power, and they are often close substitutes in the integrated models. 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, several of which (solar and wind) provide intermittent rather than base-load power.

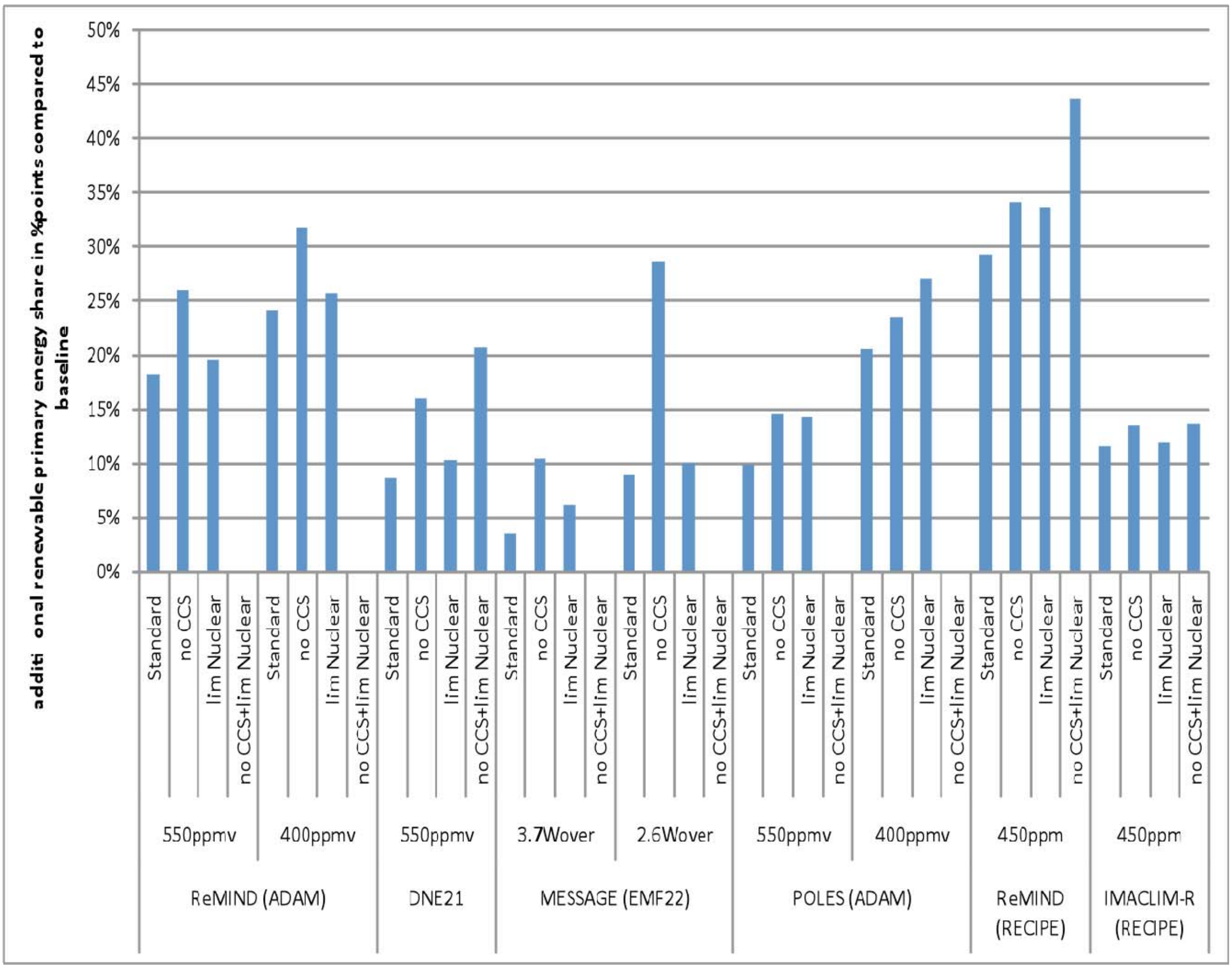

Figure 10.2.6 Increase in renewable primary energy share by 2050 in constrained in the technology scenarios compared to the respective baseline scenarios. The definition of “lim Nuclear” and “no CCS” cases varies across models. DNE21 and POLES model a nuclear phase-out at different speed, MESSAGE limits the deployment to 2010 levels, and ReMIND and IMACLIM-R limit nuclear energy to the contribution in the respective baseline scenarios which still implies a significant expansion compared to current deployment levels. In the “no CCS” cases, all models completely exclude CCS as an option with the exception of ReMIND (ADAM) that constrains cumulative CO_2 storage to 120 $GtCO_2$. POLES (ADAM) allowed higher GHG emissions in the “400 ppm_v no CCS” case compared to the “400 ppm_v standard” case to make the scenario feasible (adapted from Krey and Clarke, 2010).

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 system scale – 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 (**Error! Not a valid bookmark self-reference.**2.7). If only one of these options is limited, then the RE deployment 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.

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, as shown in **Error! Not a valid bookmark self-reference.**2.7, models were able to produce these scenarios. Several studies found that limits on RE deployments kept models from achieving stabilization goals (see, for example, Figure 10.2.12). Other studies have indicated that it is the combination of RE, in the form of bio-energy with CCS that makes low stabilization goals substantially easier (Clarke *et al*., 2009).

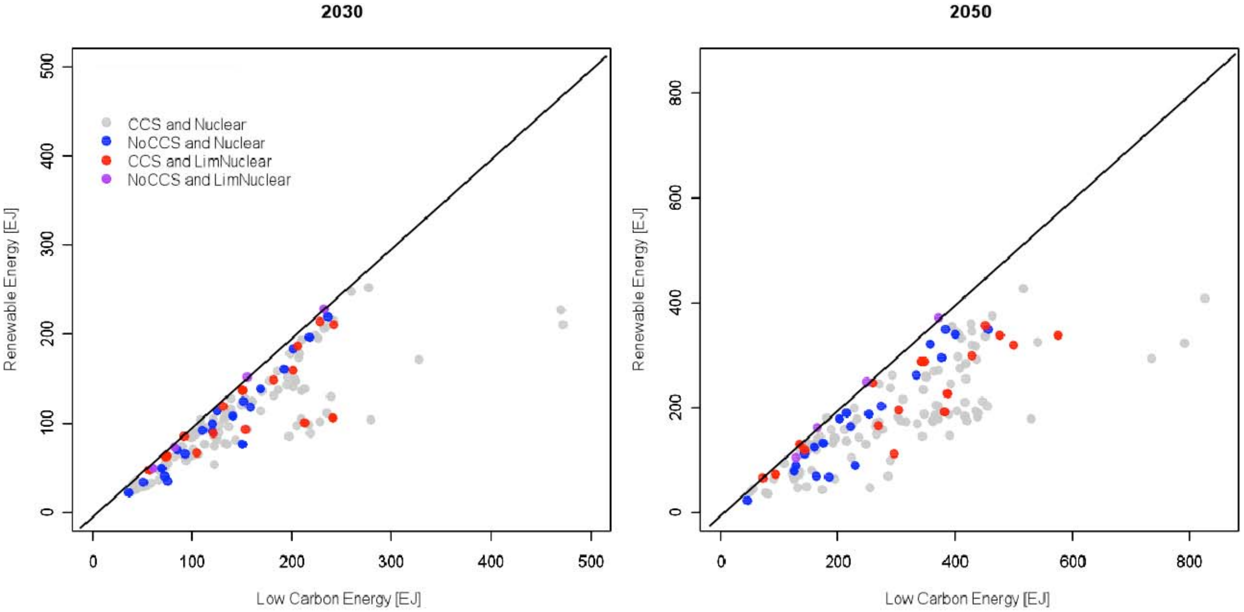

Figure 10.2.7 RE deployment plotted against total low-carbon energy primary energy supply in 2030 and 2050, depending on the availability of the competing low-carbon energy supply options CCS and nuclear energy (adapted from Krey and Clarke, 2010).

10.2.2.5. RES deployment by technology, over time, and by region

There is great variation in the deployment characteristics of individual technologies (Figure 10.2.8 and Figure 10.2.9). Several dimensions of this variation bear mention. First, the absolute scales of deployments vary considerably among technologies. Bio-energy deployment is of a dramatically higher scale over the coming 40 years than any of the other RE technologies, although it should be noted that the figures include traditional biomass which contributes close to 40 EJ in the base year with a modest decline over time in most scenarios. By 2050, wind and solar constitute a second tier of deployment levels. Hydroelectric power and geothermal power deployments fall into a lower tier.

The variation in these deployment levels represents variation in assumptions by the scenario developers regarding the cost, performance, and potential of these different sources. They indicate, for example, that most scenario developers have used assumptions that make solar power, bio-energy, and wind power the most likely large-scale contributors in the 2050 time frame and beyond; there is room for growth in hydroelectric power and geothermal power, but the potential for this growth is limited.

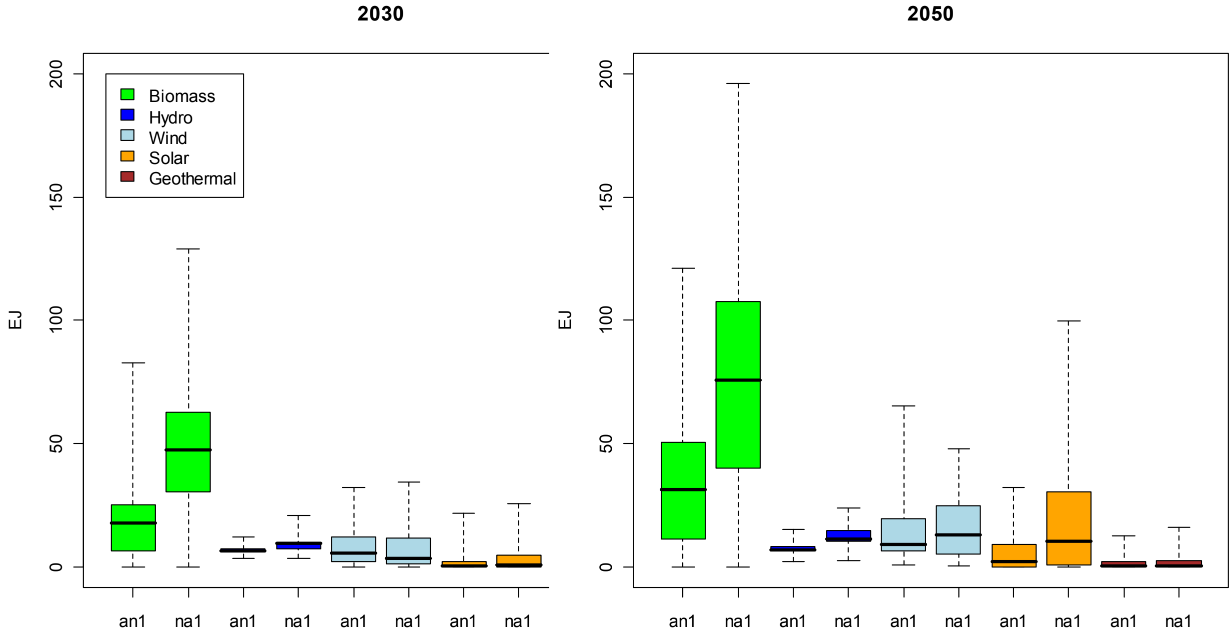

Figure 10.2.8 Renewable primary energy consumption by source in Annex I (an1) and Non-Annex I (na1) countries in the long-term scenarios by 2030 and 2050. [The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios.] (adapted from Krey and Clarke, 2010).

Second, the time-scale of deployment varies across different RE (Figure 10.2.8 and Figure 10.2.9), in large part representing differing assumptions about technological maturity. Hydro, wind and biomass show a significant deployment over the coming one or two decades in absolute terms. These are the most mature of the technologies. (Note that the bio-energy assumed here may include cellulosic approaches, which are an emerging technology.). Solar energy is deployed to a large extent beyond 2030, but at a scale that is surpassing that of the other RE sources apart from biomass, capturing the notion that there is substantial room for technological improvements over the next several decades that will make solar largely competitive and increase the capability to integrate solar power in the electricity system. Indeed, solar energy deployment by 2100 is on the same scale at bio-energy production. Direct biomass use in the end-use sectors is largely stable or even slightly declining across the scenarios. It should be noted that direct use is dominated by traditional, non-commercial fuel use in developing countries (Figure 10.2.8 and Figure 10.2.9) which is typically assumed to decline as economic development progresses. This decrease cannot be compensated by an increase in commercial direct biomass use in the majority of scenarios. In contrast, biomass that is used as a feedstock for liquids production or an input to electricity production – commercial biomass – is increasing over time, reflecting assumptions about growth in the ability to produce bio-energy from advanced feedstocks, such as cellulosic feedstocks.

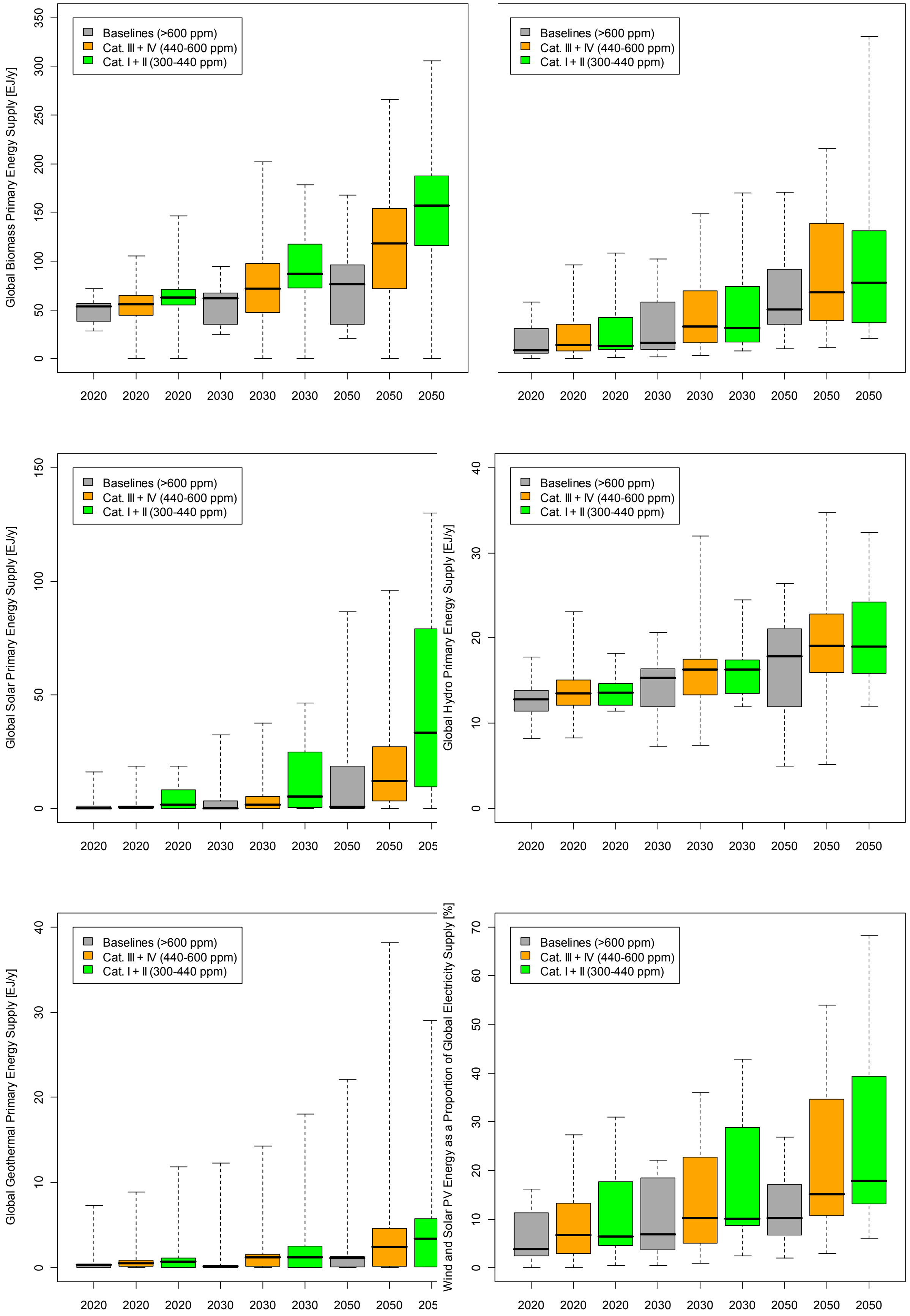
Global Biomass Primary Energy Supply [EJ/y]
0
50
100
150
200
250
300
350
Baselines (>600 ppm)
Cat. III + IV (440-600 ppm)
Cat. I + II (300-440 ppm)
2020
2020
2020
2030
2030
2030
2050
2050
2050
Baselines (>600 ppm)
Cat. III + IV (440-600 ppm)
Cat. I + II (300-440 ppm)
2020
2020
2020
2030
2030
2030
2050
2050
2050
Global Solar Primary Energy Supply [EJ/y]
0
50
100
150
Baselines (>600 ppm)
Cat. III + IV (440-600 ppm)
Cat. I + II (300-440 ppm)
2020
2020
2020
2030
2030
2030
2050
2050
205
Global Hydro Primary Energy Supply [EJ/y]
0
10
20
30
40
Baselines (>600 ppm)
Cat. III + IV (440-600 ppm)
Cat. I + II (300-440 ppm)
2020
2020
2020
2030
2030
2030
2050
2050
2050
Global Geothermal Primary Energy Supply [EJ/y]
0
10
20
30
40
Baselines (>600 ppm)
Cat. III + IV (440-600 ppm)
Cat. I + II (300-440 ppm)
2020
2020
2020
2030
2030
2030
2050
2050
205
Wind and Solar PV Energy as a Proportion of Global Electricity Supply [%]
0
10
20
30
40
50
60
70
Baselines (>600 ppm)
Cat. III + IV (440-600 ppm)
Cat. I + II (300-440 ppm)
2020
2020
2020
2030
2030
2030
2050
2050
2050

Figure 10.2.9 Global primary energy supply of biomass, wind, solar, hydro, geothermal and share of variable RE (wind and solar PV) in global electricity generation in the long-term scenarios by 2020, 2030 and 2050, grouped by different categories of atmospheric CO_2 concentration level in 2100. [The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios.] (adapted from Krey and Clarke, 2010).

Third, the deployment of some RE in the scenarios is driven mostly by climate policy (e.g. solar, geothermal, commercial biomass) whereas the deployment of others is largely independent of climate action (e.g. wind, hydro) (Figure 10.2.9). This is also to a large degree a reflection of assumptions regarding technology maturity. Wind and hydro are already considered largely mature technologies, so the imposition of climate policy would not provide the same increase in competitiveness as it would for emerging technologies such as solar, geothermal, and advanced bio-energy.

Finally, the distribution of RE deployments across countries is highly dependent on the nature of the policy structure. In scenarios that assume a globally efficient climate regime in which emissions reductions are undertaken where and when they will be most cost-effective, non-Annex 1 countries begin to take on a larger share of RE deployment compared to Annex I countries toward mid-century. This is a result of the assumption that these regions will continue to represent an increasingly large share of total global energy consumption (see, for example, Clarke *et al.*, 2009), along with the assumption that RE supplies are large enough to support this growth.

The notion that deployment in the non-Annex 1 will become increasingly important is robust across scenarios; in the long run, meeting the stricter goals will require fully comprehensive global mitigation. At the same time, a more realistic assumption regarding the near- to mid-term is that mitigation efforts may differ substantially across regions. In this real-world context, the distribution of RE deployments in the near-term would be skewed toward those countries taking the most aggressive action. As an example, Figure 10.2.10 shows the change in RE deployment in China in 2020 and 2040 from the Energy Modelling Forum 22 study (Clarke *et al*., 2009). This study explored the implications of delayed participation by non-Annex 1 regions on meeting long-term climate goals. In the delayed accession scenarios, China takes no action on climate prior to 2030. After 2030, China begins mitigation. Not surprisingly, the relative deployment of RE in 2020, when China is not taking on mitigation actions (the left panel in Figure 10.2.10). The effect of delay on RE deployments is ambiguous in 2050, after China has begun mitigation (the right panel in Figure 10.2.10). This ambiguity is due in large part to the fact that China would need to quickly ramp up mitigation efforts by 2050 if action has been delayed but the same long-term climate target is to be met as in the case with immediate action.

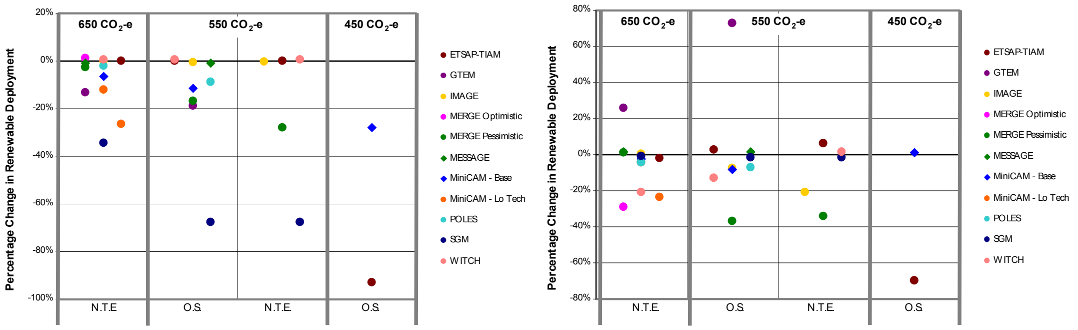

Figure 10.2.10 Change in RE deployment in China across EMF 22 scenarios as a result of delayed accession in 2020 (left panel) and 2040 (right panel) (Clarke *et al*., 2009). In addition to the Kyoto gases CO_2-equivalent concentration level by 2100, the study explored the differences between overshoot (O.S.) and not-to-exceed (N.T.E) in the before 2100.

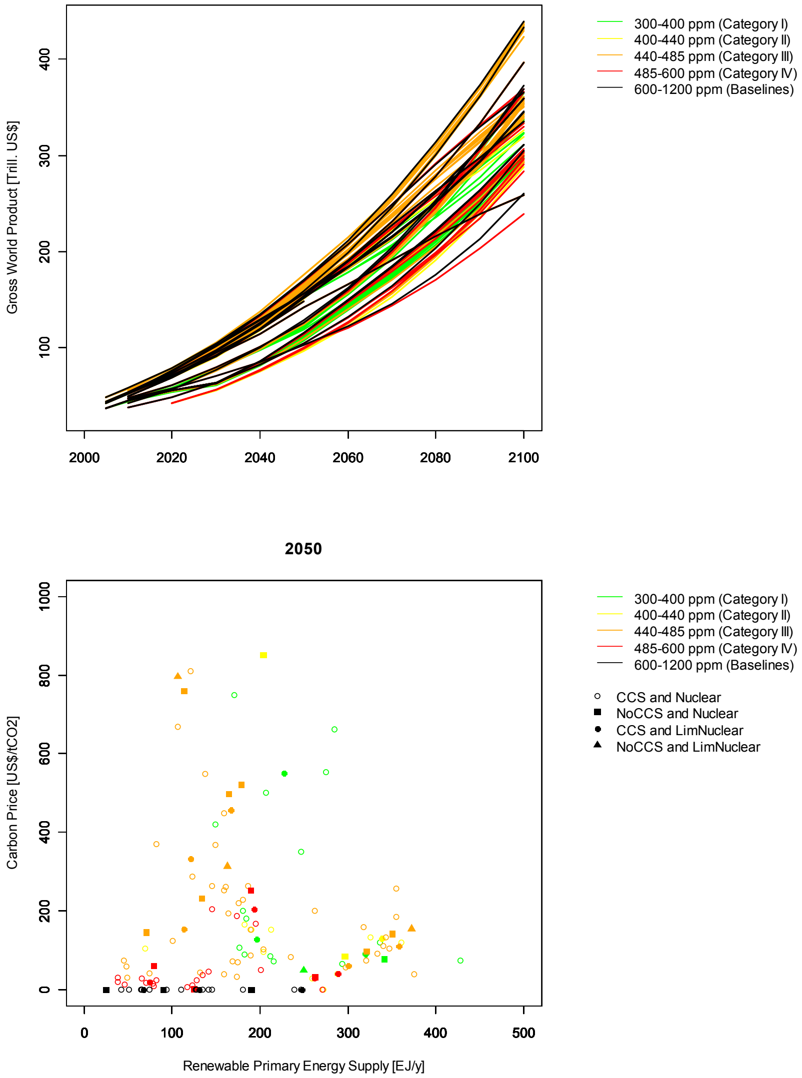

Figure 10.2.11 Carbon prices as a function of RE deployment levels in 2050 and Gross World Product development in the scenarios until 2100. The colour coding is based on categories of atmospheric CO_2 concentration level in 2100. Different symbols in the graph denote the availability of CCS and nuclear energy (adapted from Krey and Clarke, 2010).

10.2.2.6. RE and the Costs of Mitigation

One way that researchers characterize the challenge of mitigation is to quantify its economic consequences. Questions about mitigation costs have often been posted in the context of particular technologies, such as RE technologies. A typical question is how much CO_2 abatement and at what cost can be provided by RE technologies? It was not considered feasible to provide mitigation cost results using the scenarios in this assessment, primarily because assignments of mitigation to particularly technologies is not an output of integrated models; such assignments are the result of post-processing, offline, accounting calculations that rely on analyst judgment about key assumptions. Applying these assumptions to the scenarios would blur the signal from the scenarios themselves. In addition, these analyses are not accounting for the benefits of climate mitigation (e.g. less severe climate change impacts in the long term, reduced need for adaptation), energy security and air pollution (e.g. reduced health expenditures) due to the deployment of RE technologies (see e.g. Nemet and et al., 2010). A more detailed discussion of co-benefits can be found in section 10.6.

There are, however, several related questions that can be explored directly with the outputs from the 165 scenarios. One such question is: what sorts of RE deployment levels will be associated with what sorts of carbon prices? This question was posed and explored in the most recent IPCC assessment report (IPCC, 2007c), which asserted that RE could provide 30-35% of global electricity generation at carbon prices below \$50/tCO_2 . Although higher RE deployments are generally associated with higher CO_2 prices in the scenarios in this assessment (right panel of Figure 10.2.11), there is a great deal of variation in this correlation. Interacting, and to some degree counteracting, forces confuse the relationship. More aggressive mitigation generally calls greater deployment of low-emissions energy sources, including RE, which raises CO_2 prices. On the other hand, to the extent that RE technologies have higher performance, larger supplies, or lower cost, they will both have higher deployments and make mitigation cheaper. These two effects are not disentangled in this section. It is only noted here that the scenarios reviewed here generally do not indicate a clear correlation between RE deployments and carbon prices.

One limitation of CO_2 prices as cost metrics is that they only provide the marginal costs of abatement and not the total cost. Cost measures such as changes in GDP or consumption, or total mitigation costs can provide a broader sense of the cost implications of RE. Although mitigation tends to reduce GDP (Fisher *et al.*, 2007), the other forces that drive GDP exert a larger influence on total GDP than mitigation. This means that RE deployments in response to climate mitigation will not be tightly linked to total global GDP (see left panel of Figure 10.2.11).[3]

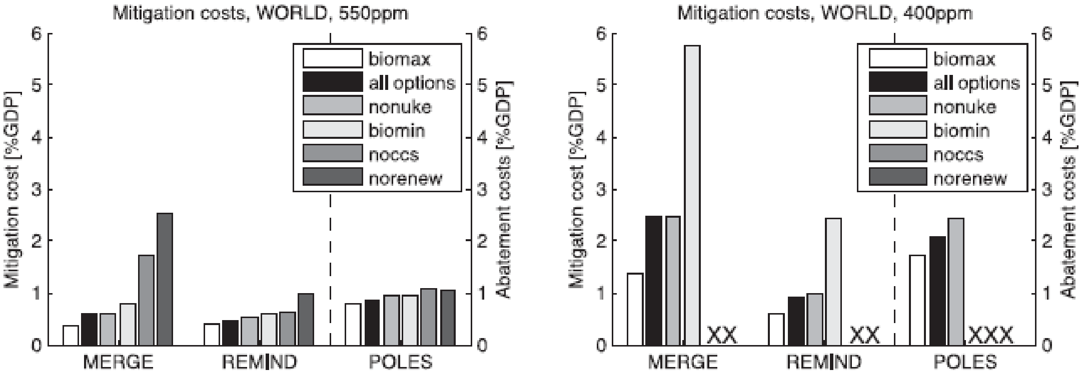

Figure 10.2,12 Mitigation Costs from the ADAM Project under Varying Assumptions Regarding Technology Availability for long-term stabilization targets of 550 and 400 ppm$_v$ CO_2-equiv (Edenhofer et al., 2010). In the legend, “all options” refers to the standard technology portfolio assumptions in the different models, while “biomax” and “biomin” assume double and half the standard biomass potential of 200EJ respectively. “noccs” excludes CCS from the mitigation portfolio and “nonuke” and “norenew” constrain the deployment levels of nuclear and RE to the baseline level which still potentially means a considerable expansion compared to today. The “X” in the right panel indicate non-attainability of the 400 ppm$_v$ CO_2-equiv target in case of limited technology options.

A more appropriate reflection of the relationship between the economic consequences of mitigation and RE deployments is the relationship between deployments and mitigation costs. Several of the analyses that produced scenarios for this study explored the relationship between mitigation costs and the presence or absence of RE and competing low-carbon technologies. Consistent with

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[3] Note that a minority of researchers have argued that climate mitigation could lead to increased economic output (e.g. Barker, T., H. Pun, J. Köhler, R. Warren, and S. Winne, 2006: Decarbonizing the global economy with induced technological change: Scenarios to 2100 using E3MG. *Energy Journal*, **27**(SPEC. ISS. MAR.), pp. 241-258.). The basic argument is that under specific assumptions induced technological change due to a carbon price increase leads to additional investments which trigger higher economic growth.

intuition, these studies demonstrate that the presence of RE technologies reduces the costs of mitigation. This is not surprising; more options should not increase costs. More important is the relative magnitude of the costs in these studies when RE growth is constrained relative to cases in which fossil with CCS and nuclear energy are constrained. 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 on 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 Figure 10.2.12).

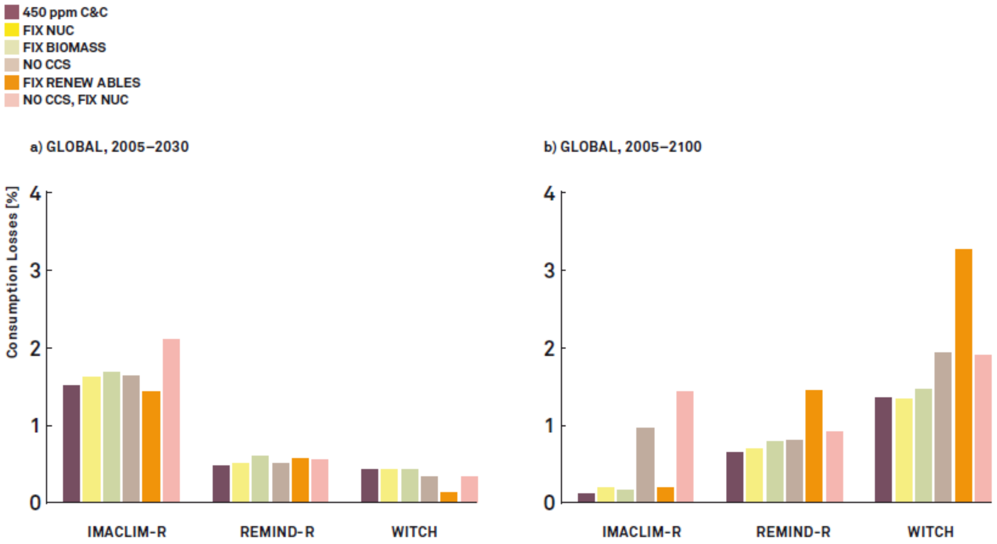

Figure 10.2.13 Mitigation costs from the RECIPE project under varying assumptions regarding technology availability for a long-term stabilization target of 450 ppm_v CO_2 (Luderer et al., 2009). Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to baseline levels (all other technologies) for the periods 2005–2030 (a) and 2005–2100 (b). Option values are calculated as differences of consumption losses of 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 RE sources in scenarios from the technology perspective

The scenarios in this section were produced using models with 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 to 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 resource potential 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 wind energy.

For some resources, availability is highly geographically constrained, for example, ocean energy sources (tidal, OTEC, ocean current, salinity gradient).

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 hydro power the majority of available potential in OECD countries has been exhausted and the largest future expansion is expected in 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, 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 will likely 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 aggressive scenarios. It is also important to recognize that markets and supply chains for some technologies are global (e.g. wind, solar PV) while others (e.g. passive solar and low temperature solar thermal) to date are purely local.

Technology and Economics: Because the maturity of the renewable technologies is highly variable, so is the need for cost and technological advancements. On the one end of the spectrum, hydro power is competitive with conventional thermal power plants, while on the other end of the spectrum, commercial-scale ocean energy demonstration plants do not yet exist. For both ocean and wind energy more remote offshore locations will need technology advancements and cost reductions. Similarly, concentrating solar power (CSP), but also solar PV and enhanced geothermal systems (EGS) will require improvements of the technology itself, but in particular further reductions of electricity generation costs. In the case of bio-energy, further technical advancements are required especially for next-generation bio-fuels and bio-refineries, where analyses indicate that technological progress could allow for competitive 2nd generation bio-fuel production around 2020 if R&D and near-term market support are offered.

Systems Integration and Infrastructure: Systems integration is challenging for the variable electricity generation technologies wind, solar PV and wave energy (see section 8.2.1). Technical (flexible backup capacity, inter-connection, storage) and institutional (market access, tariff structure) solutions will need to be implemented to address transmission constraints and operational integration concerns. For example, in specific locations, hydro power plants with reservoirs and/or pumped storage can help to operate electricity networks with high penetration of variable RE reliably. Substantial new transmission infrastructure may be required under even modest expansion scenarios to connect remote resources, for example, off- but also onshore wind, CSP, conventional hydrothermal power. A greater reliance on offshore wind is likely for regions such as Europe which require the development of offshore transmission infrastructure. Ocean energy faces similar integration challenges of variability and offshore grid connection and thus synergies may exist in the deployment of these technologies (Section 8.2.1.6). To gain greater penetration into conventional energy supply systems, other RE carriers such as heat, biogas, liquid bio-fuels and solid biomass all need integration into existing system infrastructure as outlined in Chapter 8.

10.2.4. Knowledge Gaps

The coverage of different RE sources in the scenario literature varies significantly. Mature technologies such hydro power are thus covered by all models reviewed in this assessment while less mature and deployed technologies, in particular ocean energy, offshore wind, concentrating solar power and partly also geothermal energy are addressed by a much smaller set 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 (preferably gridded) data for some renewable resources (e.g. geothermal, the various ocean energy forms) which is a precondition for constructing resource supply curves that are inputs to energy-economic and integrated assessment models.

10.3. Assessment of representative mitigation scenarios for different RE strategies

While chapter 10.2 coming from a more statistical perspective gave a comprehensive overview about the full range of mitigation scenarios and tried to identify the major relevant driving forces for the resulting market share of RE and the specific role of these technologies in mitigation paths, this chapter focus on regional and sectoral perspectives. For this more in-depth analysis from the given general overview, four scenarios have been chosen representing different illustrative energy and emission pathways (see table 10.3.2). The primary data for this analysis have been provided by the scenario authors and/or institutions.[4]

10.3.1. Technical Potentials from RE sources

Before looking on the role RE is given by different scenarios, it is worth to know about the upper application limit. The overall technical potential for RE – i.e. the total amount of energy that can be produced taking into account the primary resources, the socio-geographical constraints and the technical losses in the conversion process – seems to be huge and several times higher as the current total energy demand (cf. chapter 1).

A meta study from DLR, Wuppertal Institute and Ecofys which has been commissioned by the German Federal Environment Agency provides a comprehensive overview about the technical RE potential by technologies and region (DLR, 2009). The survey analysed 10 of the major studies which estimate global or regional RE potentials. Different types of studies were used, e.g. studies that focused on all or many RE sources like the World Energy Assessment (UNDP/WEC, 2000) and (Hoogwijk *et al.*, 2004), and studies that only focus on one source, for instance Hofman *et al.* (2002) and Fellows (2000)[5]. The study compared for each RE source, assumptions and regional scope of the relevant studies and special attention has been paid to environmental constraints and their influence on the overall potential. The study came out with an own assessment of potential based on a literature research but also on new calculation from the authors. The assessment provides data for the years 2020, 2030 and 2050 – no ranges given. The technical potential given in Table 10.3.1 can be seen as additive in terms of the needed geographical areas for each RE source and sums up to a total potential of 11,941 EJ/yr in 2050.

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[4] All data from the World Energy Outlook 2008 & 2009, Energy Technology Perspectives 2008 has been provided by the IEA, the energy [r]evolution scenario data from Deutsche Luft- und Raumfahrt (DLR) and data for technology based road maps e.g. `Global Wind Energy Outlook, Sawyer 2008` from industry associations such as Global Wind Energy Council.

[5] Overview of main literature sources analyzed: Aringhoff et al. 2004 World regions Solar CSP 2040/2050, Bartle A. 2002 World regions Hydropower 2010/2020, Bjoernsson et al. 1998 World Geothermal 2020,De Vries et al. 2006, DLR 2005, Doornbosch and Steenblik 2007, Elliot D. 2002, Fellows 2000, Fridleifsson 2001Gawell et al. 1999

		Technical Resource Potential					
		Krewitt et al. (2009)*			**Range of Estimates**		***Source for Range of Estimates****
		2020	*2030*	*2050*	*Low*	*High*	
Electric Power (EJ/y)	Solar PV	1126	1351	1689	1338	14766	Krewitt et al. (2009)
	Solar CSP	5156	6187	8043	248	10603	Krewitt et al. (2009)
	Wind On-shore	369	362	379	70	1000	Chapter 7: low estimate from WEC (1994), high estimate from WBGU (2004) and includes off-shore
	Wind Off-shore	26	36	57	15	130	Chapter 7: low estimate from Fellows (2000), high estimate from Leutz et al. (2001)
	Hydropower	48	49	50	45	52	Krewitt et al. (2009)
	Ocean	66	166	331	330	331	Krewitt et al. (2009)
	Geothermal	4,5	18	45	1,4	144	Krewitt et al. (2009)
Heat (EJ/y)	Geothermal	104	312	1040	3,9	12590	Krewitt et al. (2009)
	Solar	113	117	123	na	na	Krewitt et al. (2009)
Primary Energy (EJ/y)	Biomass Energy Crops	43	61	96	49	1550	Krewitt et al. (2009)
	Biomass Residues	59	68	88	30	170	Krewitt et al. (2009)

World Primary Energy Demand in 2007: 503 EJ/y (IEA WEO 2009)

* Technical potential estimates for 2020, 2030, and 2050 are based on a review of studies prepared by Kewitt et al. (2009). Data presented in

** Range of estimates comes from studies reviewed by Krewitt et al. (2009), as revised based on data presented in Chapters 2-7.

[TSU: Text mussing at end of first footnote.]

[TSU: Electricity Power: Ocean: Range Estimates: low: 330 – figure must be wrong]

Table 10.3.1: Technical Potential by technology for different times and applications

In the literature, generally the assessment about the total (global) technical potential for all RE sources varies significantly from 2,130 EJ/yr up to 41,336 EJ/yr[6]. Based on the global primary energy demand in 2007 (International Energy Agency (IEA), 2009) of 503 EJ/yr following the IEA calculation methodology (physical energy content accounting) respective 482 EJ/yr using the direct equivalent methodology which was chosen as basis for SRREN (cf. chapter 1 and Box 10.1 for the discussion about primary energy calculation) the total technical potential of RE sources at the upper limit would exceed the demand by an order of magnitude. However barriers to the growth of RE technologies may rather be posed by economical, political, and infrastructural constraints. That is why the technical potential will never be realised in total.

The complexity to calculate RE potentials is in particular high as these technologies are comparable young connected with a permanent change of performance parameter. While the calculation of the theoretical and geographical potential has only a few dynamic parameters, the technical potential is dependent on a number of uncertainties. A technology breakthrough or significant technology improvements for example could have a serious impact on the potential. This could change the technical potential assessment already within a short time frame. However, considering the various deployment paths of RE sources discussed in this report, it can be concluded that technical potential is not the limiting factor to expansion of RE generation even although RE having not reached the full technological development limits so far.

10.3.2. Regional and sectoral breakdown of RE sources

To exploit the entire technical potential is neither needed nor unproblematic. Implementation of RE sources has to respect sustainability criteria in order to achieve a sound future energy supply. Public acceptance is crucial to the expansion of RE sources. Due to the decentralized character of many RE technologies, energy production will move closer to consumers. Without a public acceptance, a market expansion will be difficult or sometimes even impossible. Especially the use of biomass has been controversial in the past years as competition with other land use, food production, nature conservation needs etc. accrued. Sustainability criteria have a huge influence on the overall market

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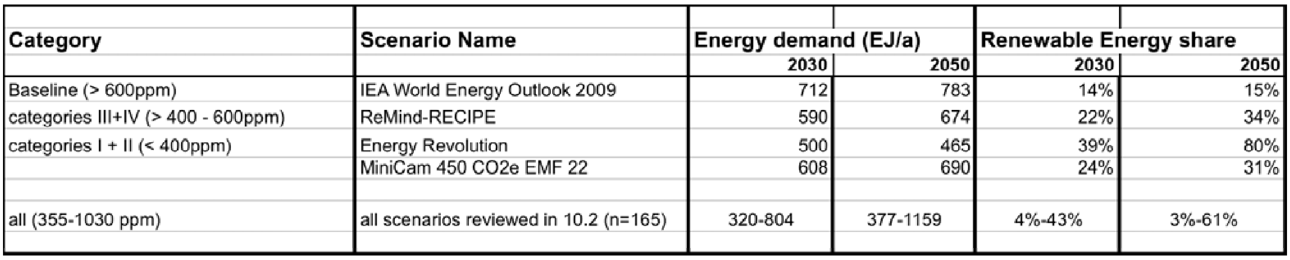
[6] DLR, Wuppertal Institute, Ecofys; Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply; Commissioned by the German Federal Environment Agency FKZ 3707 41 108, March 2009;

potential and whether bio energy can play a crucial role in future energy supply. Much more important especially for policy purposes as the technical potential is the market potential. This term is defined in chapter 1, but often used in different manner. Often the general understanding is that market potential is the total amount of RE that can be implemented in the market taking into account the demand for energy, the competing technologies, and subsidies for any form of energy supply as well as the current and future costs of RE sources, and the barriers. As also opportunities are included, the market potential may in theory be larger than the economic potential, but usually the market potential is lower because of all kind of barriers. Market potential analyses have to take into account the behaviour of private economic agents under their specific frame conditions which are of course partly shaped by public authorities. The energy policy frame work has a profound impact on the expansion of RE sources. An approximation of what can be expected for the future markets can be achieved via using the results of energy scenarios especially those delivering an in depth view on RE technologies from an overall system perspective taking relevant interaction into consideration.

Behind that background the goal of the chapter is, in addition to the more general overview in the previous section, to come out with a range of possible futures based on four representing global energy scenarios (cf. description of storyline in Box 10.3). The selected four scenarios provide substantial information on a number of technical details and represent a wide range of emission categories; from up to 1000 $\mathrm{ppm_v}$ – as a baseline - , via category IV + III (>440 – 660 $\mathrm{ppm_v}$) down to category I + II (<440 $\mathrm{ppm_v}$). Additionally, they stand for different RE deployment paths shown in Table 10.3.2 in comparison to the overall range of RE deployment form the full set of scenarios investigated in the previous scenario survey in section 10.2.



Category	Scenario Name	Energy demand (EJ/a)		Renewable Energy share	
		2030	2050	2030	2050
Baseline (> 600ppm)	IEA World Energy Outlook 2009	712	783	14%	15%
categories III+IV (> 400 - 600ppm)	ReMind-RECIPE	590	674	22%	34%
categories I + II (< 400ppm)	Energy Revolution	500	465	39%	80%
	MiniCam 450 CO2e EMF 22	608	690	24%	31%
all (355-1030 ppm)	all scenarios reviewed in 10.2 (n=165)	320-804	377-1159	4%-43%	3%-61%

Table 10.3.2: Overview: Different demand projections of the analysed scenarios. [TSU: all: RE share: 2050: max=61% contradicts with ER share of 80%]

The possible market penetration for each sector, region and time horizon described in the scenarios depends on a number of assumptions. Especially the assumptions of current and future costs for different RE technologies are crucial for the scenario results. Feedback loops have to be considered as the achievement of cost reduction potentials (= learning curves) correlates with possible annual market growth. While there is information available for the cost development within the power sector, there is very little data available for the heating and cooling sector. This is particularly problematic as renewable heat shows not only a huge technical potential, but is in many cases already cost effective (Aitken, 2003).

10.3.2.1. Renewable Power sector

Global energy scenarios provide the greatest detail for the renewable power sector and the available statistical information about the current renewable market is – compared to the renewable heating sector – very good.

Factors for market development in the renewable power sector

Amongst others, cost assumptions are crucial for the resulting deployment path of technologies. The biggest variations in the cost development assumptions can be found for the younger technologies, such as solar photovoltaic, concentrated solar power plants (CSP) and ocean energy. Among these technologies, in particular the cost projections for solar photovoltaic vary significantly, which leads in the scenarios to very different market development pathways. As illustrative example: for 2020, the highest costs projection was US$ 5960/kW [TSU: needs conversion to US$2005] and the lowest projection at US$ 2400/kW[7]. The upper limit was so far even higher than the current market price (Photon International, 2010). That demonstrates a typical problem of scenario analysis covering a young technology market where technology framework conditions and cost degression effects can heavily be underestimated. However, cost projections for photovoltaic in 2050 had a significant lower range from US$ 830/kW for the low case and US$ 1240/kW for the high case.

Among all RE technologies for power generation, for the already very well established onshore wind energy the least variation in cost projection from around +/- 10% over the entire timeframe could be found. Offshore-wind costs projections vary slightly more, due the different regional circumstance of the water depth and distance to the shore. Besides the investment cost estimates another crucial variable is the capacity factor which has – in combination with the assumed installation cost – a tremendous impact on the specific generation costs. The scenario analysis showed that the ranges are rather small and all scenarios assumed roughly the same capacity factors.

Annual market potential for renewable power

Based on the energy parameters of the analysed scenarios, the required annual production capacity has been either calculated (IEA, ReMind, EMF) or has been provided by the scenario authors. Table 10.3.3 provides an overview about the required annual manufacturing capacities (annual market volume) in order to implement the given RE generation within the analysed scenarios. These calculated manufacturing capacities do not include the additional needs for repowering.

Annual market growth rates in the analysed scenarios are very different, and the expectations about how the current dynamic of the market might continue are various. In some cases, a drastic reduction of the current average market growth rates have been outlined. The photovoltaic industry had an average annual growth rate of 35% between 1998 and 2008 (EPIA, 2008). The wind industry experienced 30% annual growth rate over the same time period (Swayer, 2009). While the advanced technology roadmaps from the photovoltaic, concentrated solar power plants and wind industry indicate these annual growth rates can be maintained over the next decade (Swayer, 2009; EPIA, 2010) and decline later, most of the analysed integrated energy scenarios assume much lower annual growth rates for all renewable power technologies.

Besides the expectations for RE technologies, the specific numbers for the overall electricity demand are decisive for specifying the resulting role of RE sources. High power demand and high market development projections are not necessarily from the same scenario. The ReMind and EMF 22 scenarios assume rather high demand developments, while the first one is connected with a relatively high market share of RE sources and the latter one with a comparable low one. The Energy [R]evolution scenario has the lowest demand projection of all analysed scenario and the highest RE share. In that context the renewable market projections (in absolute numbers) for solar and wind are in the medium and high range, but in lower case for hydro and biomass.

The underlying assumptions for the corresponding manufacturing capacities are quite different. In the IEA WEO 2009, for wind power a lower global manufacturing capacity in 2020 is assumed, than there is currently available. This indicates once more the problem to deal with a very dynamic and in this case policy driven sector within scenario analysis.

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[7] While the average market price in 2009 for solar photovoltaic generators (including installation) in Germany was already at around 3,800 Euro/kW (US$ 5,700/kW)[7] for households, larger photovoltaic parks in the MW-range achieved significant lower prices.

On the other hand the high case projections for wind (ReMind) requires an annual production capacity of 175 GW by 2020 – which would represent a 4-fold increase of production capacity on a global level. Both the Energy [R]evolution and EMF 22 scenario project this production capacity later by 2030, leading to a global wind power share of 12% to 15% under the demand projection of the scenarios. The highest global wind share has the ReMind scenario of 24% by 2020, a share which will be reached under the ER 2010 scenario by 2050.

	Energy Parameter								Market Development							
	Generation [TWh/y]				% of global demand - based on the demand projection of the analysed scenario				Annual Market growth [%/y]				Annual Market Volume [GW/y]			
	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 209	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010
2020	27248	32762	28.736	25819												
2030	34307	40638	34.666	30901												
2050	46542	63.384	61.783	43922												
PV 2020	108	220	115	594	0,4%	0,7%	0,4%	2,3%	17%	27%	18%	42%	5	12	6	36
PV 2030	281	2590	277	1953	0,8%	6,4%	0,8%	6,3%	11%	32%	10%	14%	18	163	17	120
PV 2050	640	20790	822	6846	1,4%	32,8%	1,3%	15,6%	10%	26%	13%	15%	40	651	25	211
CSP2020	38	0	186	689	0,1%		0,7%	2,7%	17%		40%	62%	1		3	12
CSP2030	121	0	553	2734	0,4%		1,5%	8,8%	14%		13%	17%	2		9	45
CSP2050	254	0	1545	9012	0,5%		2,5%	20,5%	9%		12%	14%	4		11	66
Wind																
on+offshore2020	1009	4650	2391	2849	3,7%	14,2%	8,4%	11,0%	12%	33%	23%	26%	26	175	83	101
on+offshore2030	1536	9770	4400	5872	4,5%	24,0%	11,9%	19,0%	5%	9%	7%	8%	60	381	171	229
on+offshore2050	2516	14290	7848	10841	5,4%	22,6%	12,5%	24,7%	6%	4%	7%	7%	93	262	146	202
Geothermal																
for power generation																
2020	117	NA	206	367	0,4%	NA	0,7%	1,4%	6%		12%	20%	1		2	4
2030	168	NA	616	1275	0,5%	NA	1,7%	4,1%	4%		13%	15%	2		9	18
2050	265	NA	1197	2968	0,6%	NA	1,9%	6,8%	5%		8%	10%	4		8	21
heat & power	2															
2020	6	NA	NA	66	0,0%	NA	NA	0,3%	13%		NA	47%	0		NA	1
2030	9	NA	NA	251	0,0%	NA	NA	0,8%	5%		NA	16%	0		NA	5
2050	19	NA	NA	1263	0,0%	NA	NA	2,9%	9%		NA	20%	0		NA	11
bioenergy																
for power generation																
2020	337	2208	506	392	1,2%	6,7%	1,8%	1,5%	8%	33%	13%	10%	3	37	6	4
2030	552	3540	953	481	1,6%	8,7%	2,6%	1,6%	6%	5%	7%	2%	10	59	16	8
2050	994	4217	5847	580	2,1%	6,6%	9,3%	1,3%	7%	2%	22%	2%	13	26	40	4
heat & power																
2020	186	NA	NA	742	0,7%	NA	NA	2,9%	2%	NA	NA	19%	1	NA	NA	13
2030	287	NA	NA	1424	0,8%	NA	NA	4,6%	5%	NA	NA	8%	6	NA	NA	27
2050	483	NA	NA	2991	1,0%	NA	NA	6,8%	6%	NA	NA	9%	8	NA	NA	25
ocean																
2020	3	NA	NA	119	0,0%	NA	NA	0,5%	13%	NA	NA	70%	0	NA	NA	4
2030	11	NA	NA	420	0,0%	NA	NA	1,4%	16%	NA	NA	15%	0	NA	NA	12
2050	25	NA	NA	1943	0,1%	NA	NA	4,4%	10%	NA	NA	19%	1	NA	NA	27
hydro																
2020	4027	4186	3369	4059	14,8%	12,8%	11,9%	0,0%	2%	2%	0%	2%	20	25	0	21
2030	4679	5260	3714	4416	13,6%	13,0%	10,1%	0,0%	2%	3%	1%	1%	135	151	109	127
2050	5963	6570	4402	5108	12,8%	10,4%	7,0%	0,0%	3%	3%	2%	2%	157	172	115	67
total renewables																
for power generation (incl. CHP)																
2020	5831	11264	6773	9876	21,4%	20,7%	23,9%	38,3%	4%	12%	6%	10%	57	249	100	197
2030	7644	21160	10513	18827	22,3%	30,6%	28,5%	60,9%	3%	7%	5%	7%	232	755	331	590
2050	11159	45867	21660	41552	24,0%	72,4%	34,4%	94,6%	4%	9%	8%	9%	319	1112	345	634

Table 10.3.3: Overview: renewable power generation, possible market shares, capacity factors, annual market growth rates and required annual manufacturing capacity. All factors interact with each other and influence the specific generation costs in cent/kWh over time significantly. Source: (Greenpeace and EREC, 2010) (IEA 2009, ReMind ReCIPE 2009, EMF22)

The expected role of CSP as another example is very different within all scenarios and has a wide range from 0.5% of the world's electricity production by 2050 in the IEA WEO 2009 and up to 17% under the ER 2010 scenario. While the ReMind case does not take this technology into account, the EMF 22 projects an electricity share from CSP of 2.5% by 2050. The ER 2010 assumes that annual manufacturing capacity will go up to over 65 GW/y by 2050, while all other scenarios assume an annual production capacity of less than 20 GW/y until 2030.

Both geothermal and bio-energy power plants – including combined-heat and power technologies – have very diverse technologies in the market and under development as well. However their annual market volume and therefore the required production capacity are low compared to the projections for solar and wind power technologies. The highest projection for the global geothermal power market by 2050 is with 21 GW/y in the ER 2010 on the level of the global wind power market in the year 2007 (19.7 GW/y). The expected yearly growth represents just 0.8% of the global technical potential for geothermal power generation.

The bio-energy share in all analyses is – relative to other technologies – low as well. The ReMind case estimates an annual market volume and a required manufacturing capacity of over 150 GW/a. However, similar to geothermal power generation, bio-energy power generation (excluding CHP) plays in most scenarios a rather low role and achieves an electricity share of maximum 9.3% by 2050 in the EMF 22.

Figure 10.3.1 summarizes the resulting range regarding the electricity generation of RE sources reflecting the selected scenarios distinguishing between the different technologies and compares it with the scenario demand projections for 2050. Solar photovoltaic, concentrated solar power (CSP) and wind power have the largest expected market potential beyond 2020. Hydro power remains on the same high level in almost all scenarios and the range of 10% to 15% by 2030 indicating a high correlation of projections. The total renewable power market potential in the lowest case (IEA WEO 2009) is 9% above the 2008 level with 24% by 2050. The highest renewable electricity shares are 94.6% (ER 2010) and 72% (ReMind) by 2050, while the EMF 22 scenario achieves a global renewable electricity share of 34%.

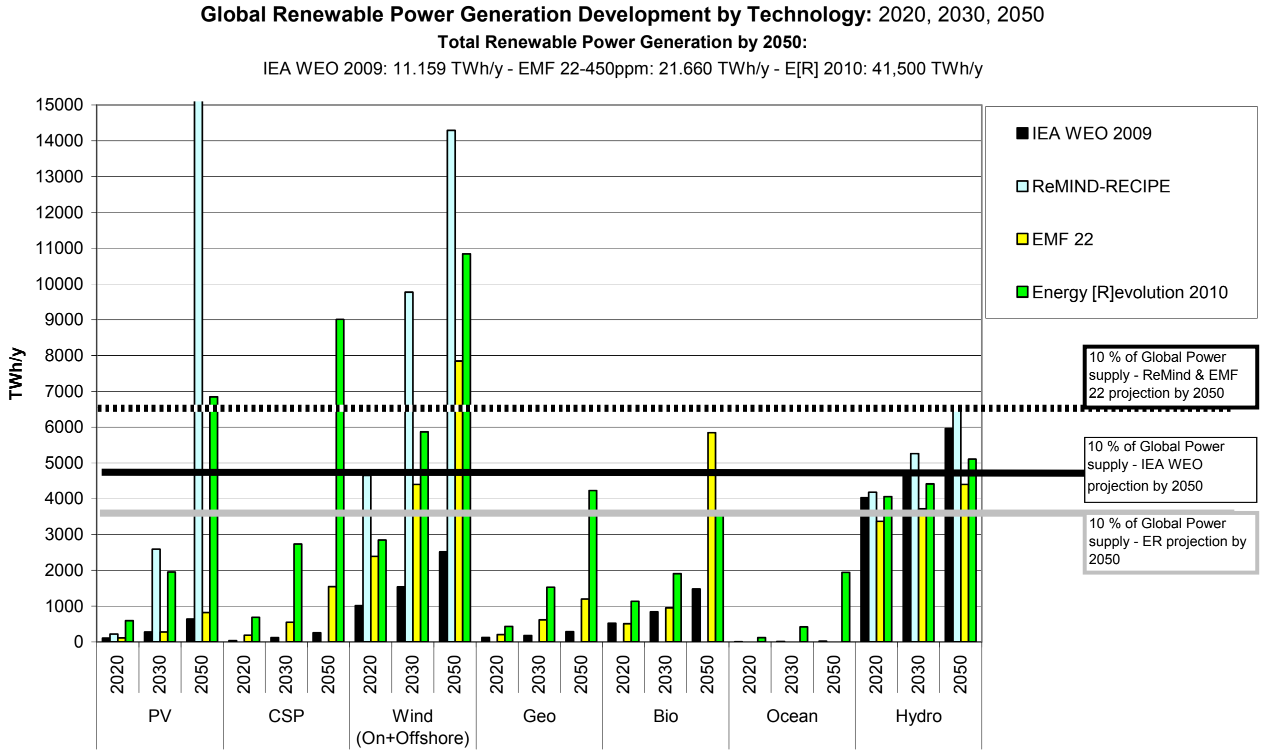

Figure 10.3.1: Global Renewable Power Development Projections by Technology

10.3.2.2. Market potential for the renewable heating and cooling sector

As the heating sector is one of the most dominant demand sectors, renewable heating technologies are already quite important. But, they can be used for cooling as well, which offers a huge new market opportunity for countries with Mediterranean, subtropical or tropical climate. RE for cooling can be applied for instance for air-conditioning and would in that context reduce electricity demand for electric air-conditioning significantly.

Factors for market development in the renewable power sector

None of the analysed scenarios provide detailed information about RE heating or cooling technologies. While the cost reduction potential for geothermal and bio energy share is relatively low as it is already an established technology, the cost reduction potential for solar heating is still significant (ESTIF, 2009). The influence of oil and gas prices, as well as building construction regulations, are huge incentives for the market development of RE heating and cooling technologies. Solar heating as well as some forms of bio-energy heating (e.g. wood pellets) and geothermal (ground heat pumps) have been already competitive in North Europe when oil and gas prices had been high in the first half of 2008. Therefore oil- and gas-price projections in scenarios will have a profound impact on the market potential.

Annual market potential for the RE heating and cooling

The RE heating sector shows much lower growth rate projections than outlined for the power sector. The highest growth rates are assumed for solar heating – especially solar collectors for water heating and space heating followed by geothermal heating. Geothermal heating includes heat-pumps, while geothermal co-generation plants are presented in section 10.3.2.1 under renewable power generation.

Both, the ReMind and EMF 22 scenario provide no information about solar and geothermal heating systems, which might be due to different reporting and/or categorisation. In the most ambitious scenario (ER 2010), solar heating systems show a significant increase. Nevertheless it will last until 2030 until today's bio-energy based heat production level will be reached. To achieve this, the market growth rates for solar collectors must exceed 35% until 2020 and a minimum of 10% afterwards throughout the end of the projection in the year 2050.

A shift from unsustainable traditional use of bio-energy for heating towards modern and more sustainable use of bio-energy heating such as wood pellet ovens are assumed in all scenarios. The more efficient use of biomass would increase the share of biomass heating without the necessity to increase the overall demand on biomass. However, none of the analysed scenarios provide information about the specific breakdown of traditional versus modern bio-energy use. Therefore it is not possible to estimate the real annual market development of the different bio-energy heating systems. Geothermal heating and cooling systems are expected to grow fast in the coming decade (until 2020) as well, and remain on a high level towards 2050.

The market potential 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 power sector, biomass cogeneration could be listed under the power sector or the heating/cooling sector. Geothermal heat pumps use power for their [TSU: was 'there'] operation and therefore increase the demand for electricity. RE heating and cooling is even more dispersed and decentralized than RE power generation, what explains to a certain extend that the statistical data are still quite poor and need further research.

Based on the energy parameters of the analysed scenarios, the required annual market volume has been calculated in order to identify the needed manufacturing capacities and how they relate to current capacities. Table 10.3.4 provides an overview about the annual market volumes but without including the additional needs for repowering. Even with relatively low growth rates in the scenarios manufacturing capacities for all RE heating and cooling technologies must be expanded significantly in order to realize the projected RE heat production in all analysed scenarios. The annual market volume for solar collectors until 2020 must be expanded from less about 35 PJ/y in

2008 to 100 PJ/y in 2020 in the IEA WEO 2009 case and up to 1162 PJ/y in the ER 2010. Due to the diverse technology options for bio- and geothermal energy heating systems and the low level of information in all analysed scenarios, it is not possible to provide here specific market size data by technology.

	Energy Parameter								Market Development							
	Generation [PJ/y]				% of global demand - based on demand projections of the scenarios				Annual Market growth [%/y]				Annual Market Volume [PJ/y]			
	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010	IEA WEO 2009	ReMIND-RECIPE	EMF 22	Energy [R]evolution 2010
2020	157.623	192.000	134.603	151.716												
2030	173.749	193.000	144.593	156.289												
2050	205.190	184.955	150.776	153.913												
Solar Thermal 2020	844	0	NA	6.787	0,5%	0,0%	NA	4,5%	10%	NA	NA	39%	32		NA	409
Solar Thermal 2030	1.629	0	NA	18.963	0,9%	0,0%	NA	12,1%	8%	NA	NA	12%	100		NA	1162
Solar Thermal 2050	3.105	0	NA	51.278	1,5%	0,0%	NA	33,3%	7%	NA	NA	12%	187		NA	1568
Geothermal																
heating																
2010																
2020	631	115	NA	4.488	0,4%	0,1%	NA	3,0%	3%	NA	NA	28%	2		NA	58
2030	918	212	NA	10.865	0,5%	0,1%	NA	7,0%	4%	7%	NA	10%	13		NA	149
2050	1.635	4.568	NA	40.172	0,8%	2,5%	NA	26,1%	7%	41%	NA	16%	22		NA	283
bioenergy																
heating																
2020	36.224	15.760	40.381	41.823	23,0%	50,0%	30,0%	27,6%	not available				28		104	130
2030	38.194	19.645	39.040	46.215	22,0%	60,2%	27,0%	29,6%					678	385	686	811
2050	43.646	20.437	31.663	48.262	21,3%	66,7%	21,0%	31,4%					540	123	186	295
total renewables																
for power generation (incl. CHP)																
2020	37.699	15.875	40.381	53.098	23,9%	8,3%	30%	35,0%	1%	NA	1%	5%	62		104	597
2030	40.741	19.857	39.040	76.043	23,4%	10,3%	27%	48,7%	1%	3%	0%	4%	791		686	2122
2050	48.386	25.005	31.663	139.712	23,6%	13,5%	21%	90,8%	2%	3%	-2%	7%	749		186	2146

Table 10.3.4: Projected renewable heat production, possible market shares, annual growth rates and annual market volumes.

Within the heating sector, solar energy has the highest growth projections of all technologies followed by bio-energy and geothermal heating. Bio-energy has currently the highest share in global heat production, which is mainly due to the traditional use of biomass and in many cases not sustainable[8]. The total share of RE heating systems in all scenarios by 2050 varies significantly between 13.5% (ReMind) and 90% (ER 2010). Both, the IEA WEO 2009 and the EMF 22 project a RE market share of around 20% by 2050.

10.3.2.3. Market potential for RE sources in the transport sector

The quality and quantity of data submitted in the selected scenarios was not comprehensive enough to provide an overview about the estimated market potential in the transport sector. Generally there are two categories of RE used in the scenarios. First of all direct RE applications like bio-fuels or marine wind energy use (first and second generation sails) and secondly indirect RE options like electricity or hydrogen based on RE. In terms of the latter one a competition with stationary sector has to be considered.

10.3.2.4. Global RE primary energy contribution

Figure 10.3.2 provides an overview of the projected primary energy production (using the direct equivalent methodology) by source for the four selected scenarios for 2020, 2030 and 2050 and

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[8] See also Chapter 2.1.1.

compares the numbers as a numerical exercise with different global primary energy demands. Bio-energy has the highest market share in all scenarios, followed by solar energy. This is due to the fact, that bio-energy can be used across all sectors (power, heating & cooling as well as transport) while solar can be used for power generation and heating and cooling. As the residual material potential and available land for bio-energy is limited and competition with nature conservation issues as well as food production must be avoided, the sectoral use for the available bio-energy depends on where it is used most efficiently.

However solar energy can be used for heating and cooling and power generation as well, but solar technology starts from a relatively low level. The relatively low primary energy share for wind and hydro is due to its exclusive use in the power sector.

The total RE share in the primary energy mix by 2050 has a huge variation across all four scenarios. With only 15% by 2050 – about today´s level – the IEA WEO 2009 projects the lowest renewable primary energy share, while the ER2010 covers 80% of the worlds primary energy demand with RE. Both, the ReMind and EMF 22 projection are in the range of one quarter RE by 2030 and one third by 2050. It is worth to mention the resulting primary energy share would be higher in all cases if different accounting methodologies would be used instead of the direct equivalent methodology. The highest share of RE has been achieve with a combination of a high market development for RE and a successfully implemented energy efficiency strategy. While the ER 2010 is based on a RE share of 95% and 91% of global heating and cooling demand, the most difficult sector for RE to supply substantial shares is the transport sector.

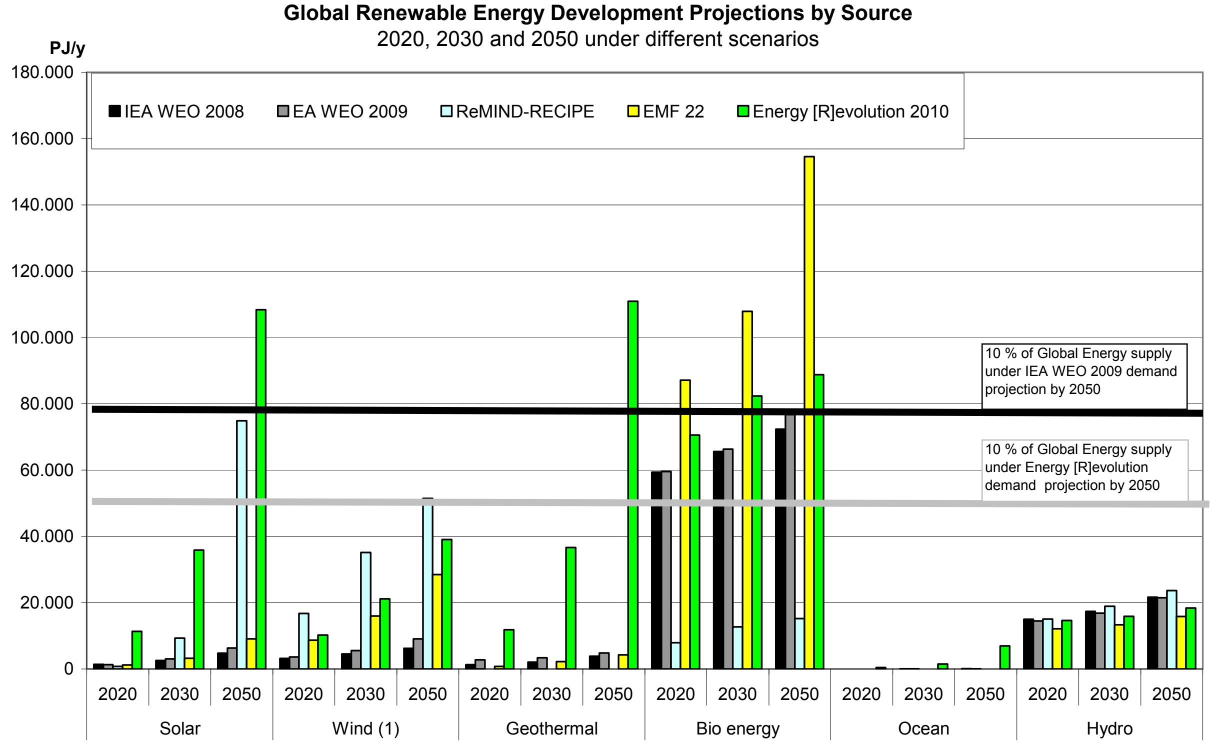

Figure 10.3.3: Global RE development projections by source and global renewable primary energy shares by source

10.3.3. Regional breakdown – technical potential versus market deployment

This section provides an overview about the market penetration paths given in the analysed scenarios versus the technical potential per region as well as an overview about the regional scenario data. The table compares the maximum value of the different scenarios with the technical potential in order to calculate the maximum deployment rate of the technical potential.

The quality of the regional data is not as comprehensive as it is the case for global scenario data. This is partly due to the fact that the number of scenarios providing a regional breakdown is very limited, especially for developing regions.

To give at least an impression about regional aspects, for illustrative purposes Tables 10.3.5 and 10.3.6 show the resulting market shares for the Energy [R]evolution 2010 scenario. Here data are available, furthermore it is amongst the selected scenarios the future path with the highest market projections for RE.

10.3.3.1. RE Power sector by Region

For the power sector the investigation shows that even if significant parts of the technical RE potential has to be deployed in the selected scenarios besides hydro power and geothermal energy the numbers are normally less than 10%. There are a few exemptions. In particular this is the case for wind energy where the deployment rates in China and India are even higher than the technical potential given in table 10.3.1. Obviously the ER 2010 scenario is based on other potential assumptions. Following an analysis by McElroy *et al*. (2009) for instance, it is estimated that China's wind potential could reach 640 GW by 2030, enough to cover the country's current electricity demand three times over.

Electricity: Technical Potential (TP) versus E[R] 2010 deployment in 2050 [EJ/y] - excluding biomass

	solar PV		solar CSP		hydro-power		wind (on + offshore)		ocean energy		geothermal electric		Total	
	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed	Techn. Potential in [EJ/y]	% deployed
Africa	717	0,2%	4.348	0,1%	7	10,6%	29	3,7%	18	2,0%	4	20,0%	5.123	0,2%
China	98	5,6%	60	11,2%	5	100,0%	6	132,6%	7	32,2%	5	71,5%	180	17,0%
India	33	0,6%	106	4,7%	2	39,5%	2	163,5%	4	17,3%	15	13,6%	163	7,5%
Latin America	118	2,9%	299	1,7%	9	8,1%	47	7,5%	44	1,6%	5	43,3%	521	3,0%
Middle East	127	1,7%	1.153	0,5%	1	17,8%	5	24,3%	8	2,9%	1	72,7%	1.295	0,8%
OECD Europe	33	6,9%	4	39,7%	7	25,4%	31	15,6%	25	2,6%	2	89,4%	103	12,6%
OECD North America	84	5,0%	347	1,6%	6	56,9%	166	4,7%	46	2,2%	6	56,6%	655	3,9%
OECD Pacific	225	0,6%	1.513	0,1%	1	58,2%	57	5,8%	30	1,6%	4	11,7%	1.830	0,4%
Rest of Asia	137	2,0%	9	23,3%	6	15,8%	18	19,3%	150	0,6%	6	25,3%	326	3,6%
Transition Economies	116	0,4%	204	0,0%	5	28,4%	75	4,6%	13	1,2%	6	16,0%	418	1,5%
World	1.689	1,6%	8.043	0,5%	50	32,3%	436	9,1%	331	2,3%	45	37,5%	10.595	1,4%

Source RE Potential: DLR, Wuppertal Institute, Ecofys; Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply; Commissioned by the German Federal Environment Agency FKZ 3707 41 108, Marc

[TSU: The text in the footnote on sources is cut off.]

Table 10.3.5: Overview of relation between the market contribution of RE and the corresponding technical potential for different technologies and regions for 2050 and the power sector under the condition of the Energy [R]evolution 2010 scenario

For 2050, the highest deployment rate of the technical RE power potential per region has been found in China (17.0%), followed by OECD Europe (12.6%), India (7.5%), OECD North America (3.9%) and Developing Asia (3.6%). The other remaining regions have rates below 2.0%. On a global level, none of the analysed scenario exceeds a deployment rate of 1% of the total technical potential for renewable power generation.

Regional energy supply cost curves as "snapshots" of selected scenarios discussed in next sections are an alternative way (perspective) to present scenario results. The following curves (see Figures 10.3.4 to 10.3.6) can work as illustrative examples and represent a cross-section of three scenarios

(ReMIND Recipe, Energy Revolution 2008 (abbreviated as ER), and WEO 2008)[9]. They focus on a specific target year and relate the potentials for the deployment of certain renewable electricity technologies in the different regions to their cost levels in discreet steps.

The work 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 determining role of carbon emission factors, energy pricing and fossil fuel policies in the ultimate shape of abatement cost curves, only RE 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 to create the curves as done here also prevents the problem of staticness [TSU: was ‘stactivness’].

Beyond the general issues about cost curves detailed in section 10.4, it is important to note a few points for the interpretation of the curves. First, the ER 2008 and the WEO 2008 scenario data were not as detailed for the costs, thus each technology in a region is represented by a single average cost in these scenarios. Average costs for a technology for a whole region mask the really cost-effective sub-technologies and sites into an average, compromised by the inclusion of less attractive sites or sub-technologies – thus not able to highlight the cheaper (and the more expensive) sites and sub-technologies. Second, it was not possible to deduct the presently existing capacity from the potentials by cost level, thus they include all capacity that can be installed in the target year allowed by the different constraints assumed. Due to the limited space available, but also caused by significant lack of data, curves for only three regions and the electricity sector are shown.

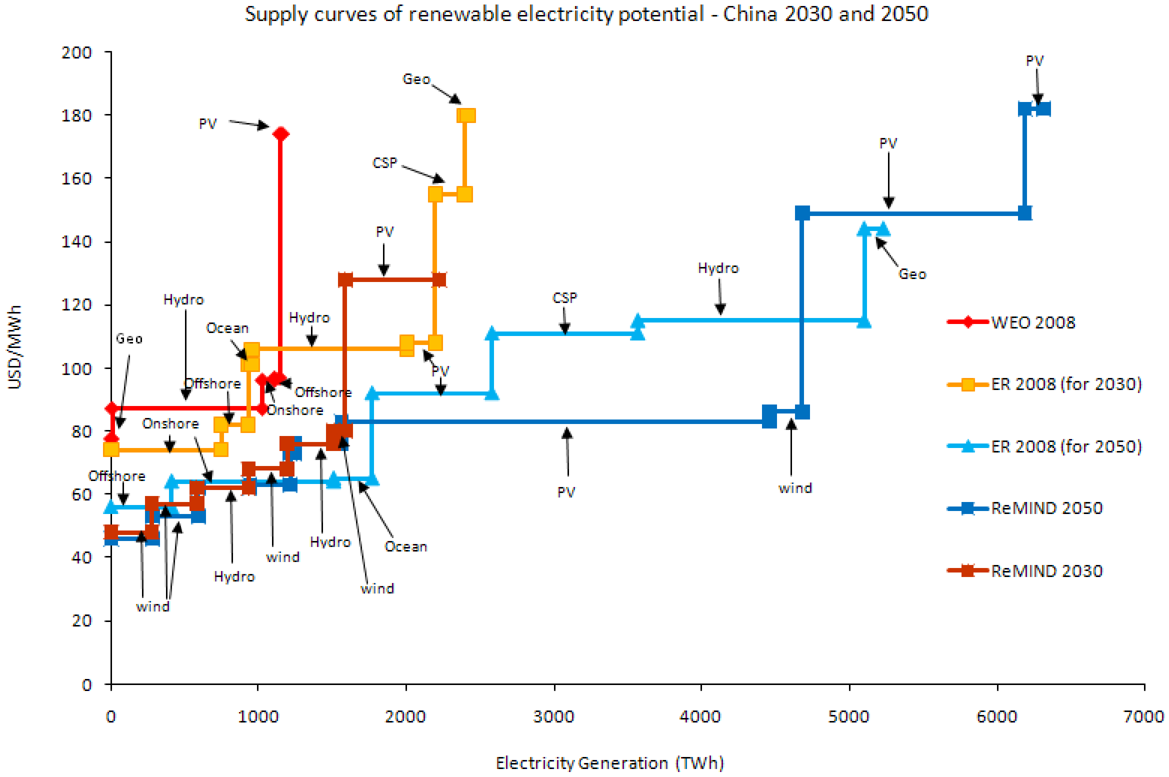

Figure 10.3.4: Renewable electricity supply curves for China for the year 2050.

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[9] For the SOD submission deadline data availability was limited. For the FD it is foreseen to use the same scenarios as been discussed before e.g. Energy Revolution 2010 and WEO 2009 instead of Energy Revolution 2008 and WEO 2008.

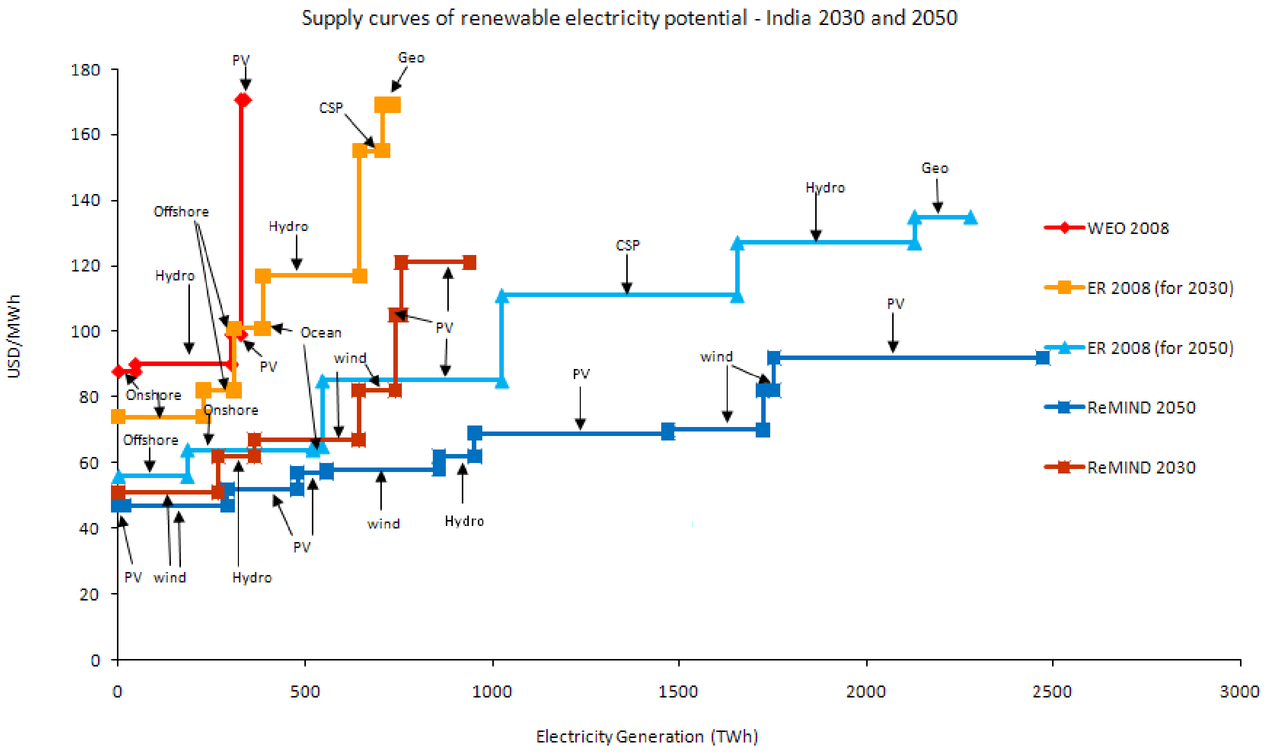

Figure 10.3.5: Renewable electricity supply curves for India for the year 2050.

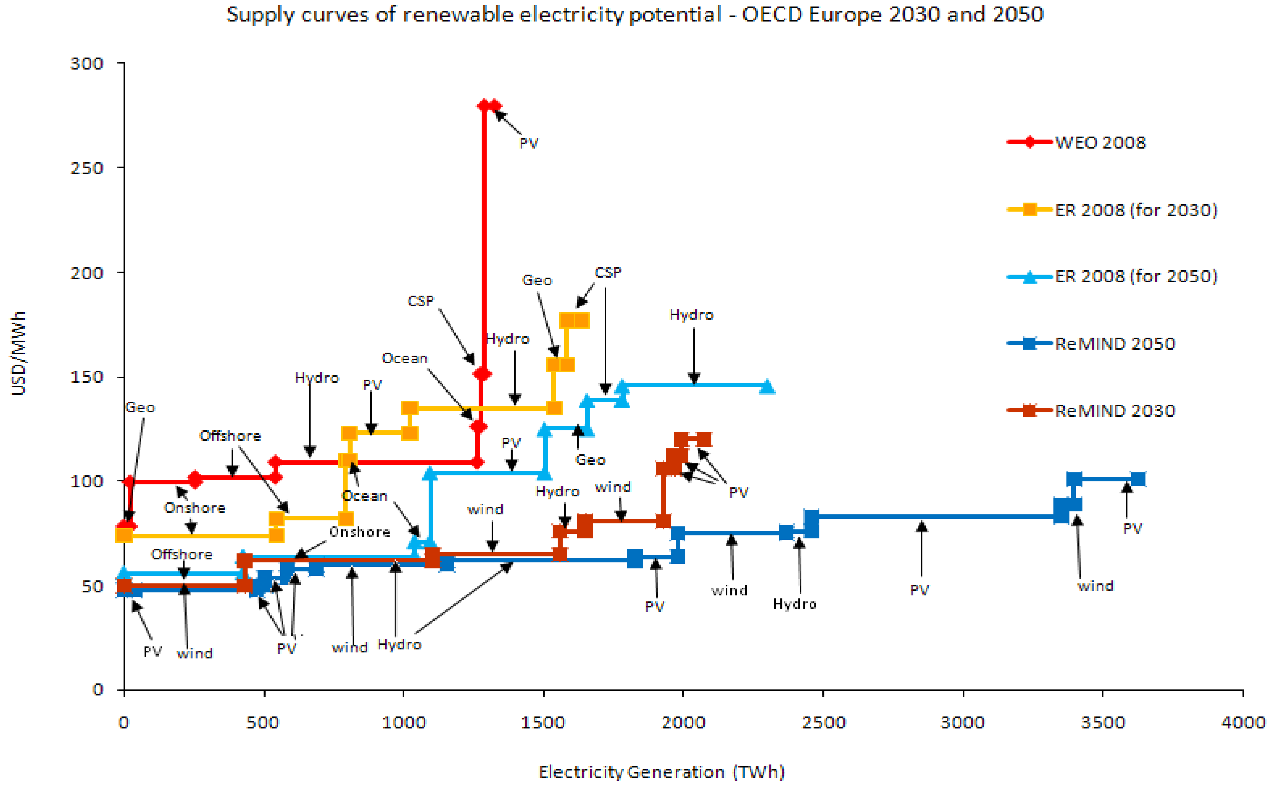

Figure 10.2.6: Renewable electricity supply curves for OECD Europe for the year 2050.

The figures illustrate several important trends. Perhaps the most important message they convey is the importance of a long-term vision when RE is considered. Potentials for deployment are consistently significantly larger for 2050 than for 2030 in all regions and scenarios, often doubling the potential at medium cost levels, except for OECD Europe. Even in this region, there is an important increase in the potential between these two years, but the ReMind scenario sees increase only at the larger cost options (still not very large since their 2050 curve does not go above USD100/MWh), and the ER scenario does not envision a larger than approximatelly 30% increase in the potential at most cost levels. On the other hand an over doubling of the potential in both China and India in both scenarios during this period can be seen.

When comparing the three models, the WEO 2008 projects the highest costs and lowest potentials in all three examined regions, while typically the ReMind scenario envisions the lowest cost levels and highest potentials[10]. While in some regions the curves from different models are close to each other and project similar potentials at similar cost levels, the technologies they consider the most promising are rather different. For instance, the ReMind scenarios see the largest promise in PV and in 2050 the lion's share of its cost-effective potential comes from this technology in all three examined regions. The ER scenario's projected potential consists of a balance of wind (on- and offshore), PV, CSP, hydropower and geothermal. WEO2008's projected potential in 2030 consists mainly of wind and hydro, and considers PV as a very expensive technology in all regions. This is the technology in which the different scenarios differ the most both in terms of costs and potentials. For instance, the ReMind's highest PV cost band for 2050 in OECD Europe is still lower than the average PV cost projected for this year by the ER scenario, and is approximately one-fourth of the average PV cost projected by WEO2008 by 2030, and the 2030 highest cost band is half.

The different scenarios see different roles and costs for CSP. This technology virtually does not play any role in the ReMind scenarios, while the ER 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 potential for geothermal, but they see its costs very differently. The costs of this power source in WEO2008 is approximately half of that in the ER scenarios for the same target year (2030), and even in 2050 the ER cost projections are significantly higher (highest among all technologies for India and China) for this technology than in the WEO2008 scenario in 2030 – although the potentials at this cost are several times higher than projected by the other scenarios, making a noticeable contribution to the total potential in 2050 in India and OECD Europe from among the examined regions. The ReMind scenarios do not consider geothermal power.

10.3.3.2. Primary energy by region, technology and sector

Following the same methodology, Table 10.3.6 compares the resulting primary energy contribution of RE in relation to the technical potential by region and technology. The maximum deployment share out of the overall technical potential for RE [TSU: was 'solar energy'] in 2050 was found in the illustrative scenario for China with a total of 6.7%. The second and third biggest deployment rates were found in scenarios for OECD Europe (5.6%) and India (5.0%). All other regions used less than 2.5% of the available technical potential for solar energy. Wind energy has been exploited to a much larger extend in all regions than solar energy. As indicated in Table 10.3.6, wind potential has been more than fully exploited in the scenario for India and China. This shows one more the complexity of scenario analysis, as the selected scenario here assumes a significant higher technical wind energy potential than the one expressed in Table 10.3.1. Geothermal energy does not play a mayor role in neither of the analysed scenarios. Both on a global and regional level the deployment

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[10] ReMIND assumes that RETs will be deployed at industrial scale at optimal sites and transported over large distances (up to continental scale) to demand centers. It implicitly assumes that bottlenecks, e.g. with respect to grid infrastructure, are avoided by early and anticipatory planning. This results in high capacity factors in ReMIND compared to other scenarios, which in turn has a strong effect on electricity generation costs and deployment levels.

rate of the available technical potential is far below 2.5%. The same is the case for ocean energy as a very young technology form.

Primary Energy: Technical Potential (TP) versus E[R] 2010 deployment in 2050 [EJ/y] - excluding biomass

	Solar		Wind		Geothermal		Hydro		Ocean		Total	
	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	% of TP	Techn. Potential in [EJ/y]	
Africa	5.076	0,2%	29	3,7%	1.015	0,1%	7	70,2%	18	2,0%	6.159	0,19%
China	175	10,7%	6	132,6%	420	1,9%	5	81,7%	7	32,2%	621	6,71%
India	146	5,8%	2	163,5%	144	1,4%	2	39,5%	4	17,3%	306	5,07%
Latin America	428	2,8%	47	7,5%	761	0,5%	9	8,1%	44	1,6%	1.348	1,52%
Middle East	1.298	0,9%	5	24,3%	180	1,0%	1	17,8%	8	2,9%	1.494	0,99%
OECD Europe	61	14,0%	31	15,6%	246	2,3%	7	25,4%	25	2,6%	386	5,61%
OECD North America	455	3,5%	166	4,7%	712	1,1%	6	56,9%	46	2,2%	1.421	2,52%
OECD Pacific	1.741	0,2%	57	5,8%	331	0,5%	1	58,2%	30	1,6%	2.170	0,47%
Rest of Asia	167	4,6%	18	19,3%	528	0,7%	6	15,8%	150	0,6%	878	1,92%
Transition Economies	325	0,8%	75	4,6%	657	0,8%	5	28,4%	1	11,5%	1.087	1,18%
World	9.856	0,9%	436	9,1%	5.000	0,9%	50	32,3%	331	2,3%	15.857	1,24%

Source RE Potential: DLR, Wuppertal Institute, Ecofys; Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply; Commissioned by the German Federal Environment Agency FKZ 3707 41 108, March 2009

Table: 10.3.6: Overview of the relation between the primary energy contribution of RE and the corresponding technical potential for different technologies and regions for 2050 under the condition of the Energy [R]evolution 2010 scenario

The established hydro power market potential on a global level covers roughly one third of the technical potential, in some countries the estimated capacity for 2050 is already very close to the maximum possible capacity for hydro power in these countries.

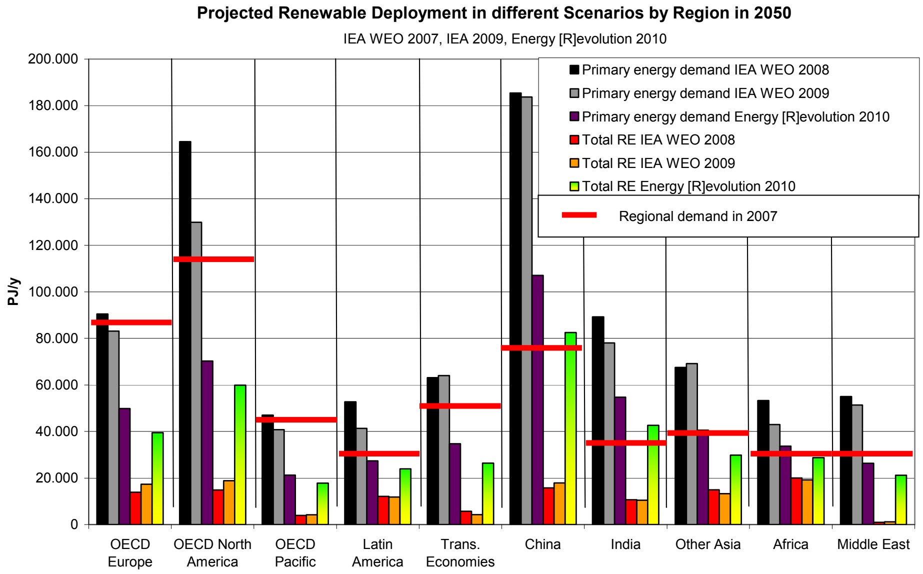

Figure 10.3.7: Regional breakdown from possible RE market potential: baseline (IEA WEO 2009) (>600 ppmv) versus Category II (<440 ppmv) ER 2010 scenario.

While the overall technical potential for RE exceeds current global primary energy by on order of magnitude (see section 10.3.2), even the ER 2010 scenario with the most aggressive growth rates for RE did not exceed 1.2 % (2050) of the given potential on a global level. Considering different regions the highest relation is given with 6.7% for China.

The analysed regional and global scenarios show a wide range of the RE shares in the future. Even if availability of regional data is poor, in order to show the different ranges of deployment rates for RE sources by sector and region, Figure 10.3.7 compares a baseline scenario (>600 ppm$_v$) with a category II (<440 ppm$_v$) scenario (Energy [R]evolution 2010 DLR/EREC/GPI). The data of the baseline scenario for 2040 and 2050 has been developed by the German Aerospace Agency (DLR).

Figure 10.3.7 shows different demand projects under the baseline and the ER 2010 scenarios, as well as total regional renewable market deployment compared to the energy demand in 2007. While the demand in the baseline for all OECD regions remains within the 2007 range, the demand for all other regions are projected to increase by an order of magnitude. The ER 2010, however, projects a drastic demand reduction in OECD regions and slower growth of energy demand in developing countries keeping the overall global demand on 2007 levels. While the RE shares of baseline scenario remain on 2007 levels and there cover only the additional demand, the ER 2010 projects to double or triples the renewable primary energy shares in all regions to well over 50%. The ER 2010 foresees for all OECD regions a RE share of 85% by 2050.

10.3.4. GHG mitigation potential of RE as the whole and as single options

Based on the results of the previous scenario survey and the identified market penetration rates projections for different RE technologies, the corresponding GHG mitigation potential has been calculated. For each sector, for each RE application a factor has to be identified addressing the kind of electricity generation or heat supply being substituted. This can not be done exactly without conducting own scenario analysis or complex power plant dispatching analysis. Therefore the following calculation is necessarily based on simplified assumptions and can only be seen as indicative. In that context RE applications are supposed to fully substitute fossil fuel use. In reality that may not be true as RE can compete for instance with nuclear energy as well. Also within the RE portfolio a competition is possible. To cover the uncertainties even in terms of fossil fuel substitution different factors have been chosen and uncertainty is marked in the following figures by arrow bars.

Behind that background for electricity generation the upper limit has been calculated on the basis of specific carbon emissions of coal fired power plants (0.79 kg CO$_2$ per kWh by 2020 and 0.63 kg CO$_2$ per kWh by 2050). The lower case has been calculated on the basis of specific carbon emissions of natural gas fired power plants (0.498 kg CO$_2$ per kWh by 2020 and 0.475 kg CO$_2$ per kWh by 2050). It is worth to mention that the lower limit is not far away from the specific emissions of the whole power plant mix under baseline conditions. For the power sector with the current global technology mix, the average specific carbon emission for 2007 is 0.539 kg CO$_2$ per kWh (IEA2009). For the future, the IEA 2009 baseline projection expects an increase of the specific emission factors to 0.495 kg CO$_2$ per kWh by 2020 and 0.478 kg CO$_2$ per kWh by 2030. For the heating sector, the average specific global carbon emission is 71 kt CO$_2$/PJ[11] with a chosen uncertainty range of +/- 15% while the upper range assumes a higher coal and oil use for heating and the lower an increased use of gas.

Figure 10.3.8 shows the annual CO$_2$ reduction potential per RE source for all analysed scenarios for 2020. The black line at 6 Gt CO$_2$/y identifies 20% of the global energy related CO$_2$ emissions (Base

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[11]

CO2 intensities heat [kt/PJ]	
District heating plants	95,1
Heat from CHP	187,3
Direct heating	59,1
Total	70,2
Total without CHP	60,8
Total direct only	59,1

year 2008), the grey line below represents 10%. Figure 10.3.9 shows the same sample of results for 2050. The red line here indicates 50% of total energy related CO_2 emissions (Basis 2008 [TSU: was 2007]).

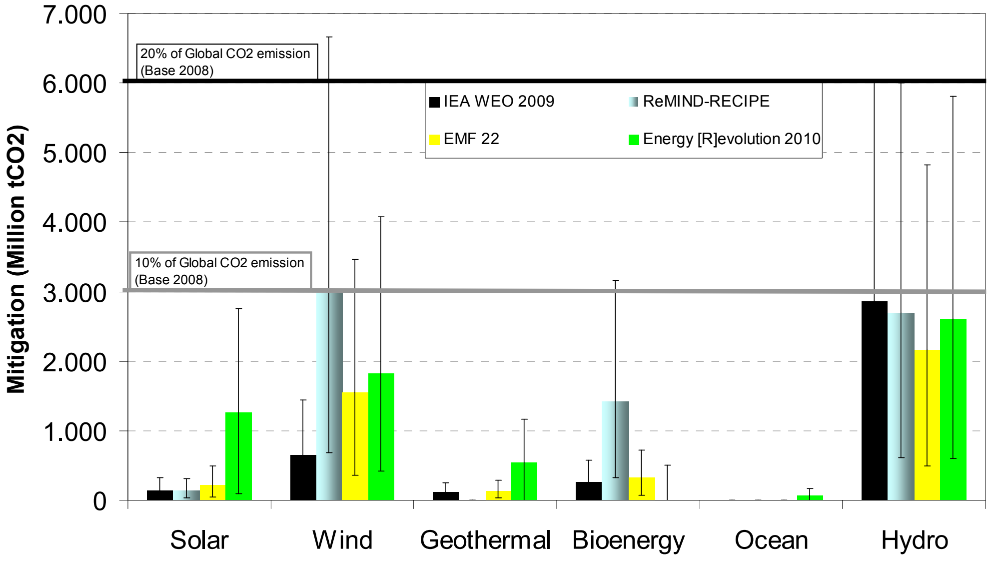

Figure 10.3.8: Annual Global CO2 savings from RE for different scenario based deployment paths for 2020 (NOTE: this is excluding transport and biomass used for direct heating)

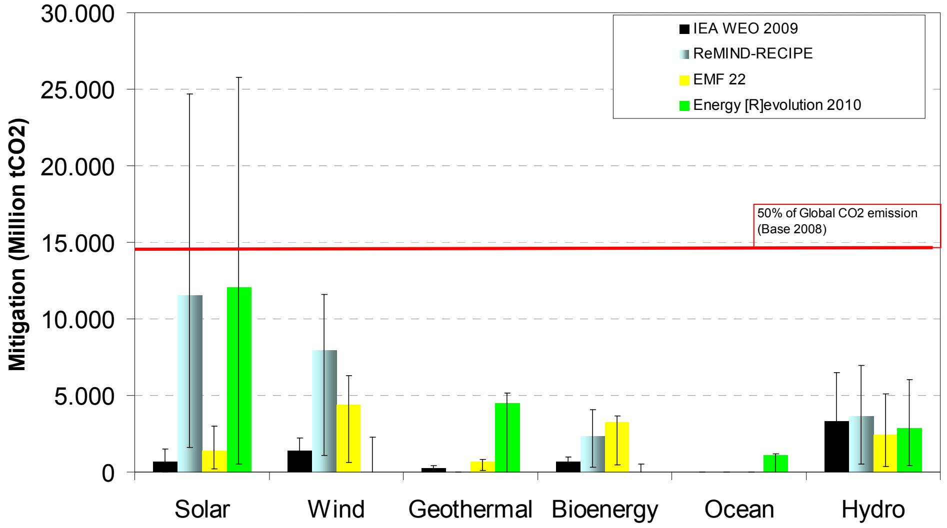

Figure 10.3.9: Annual Global CO2 savings from RE for different scenario based deployment paths for 2050 (NOTE: this is excluding transport and biomass used for direct heating)

Following the given assumptions and the scenario results hydro energy has the highest CO_2 reduction contribution of all scenarios by 2020, followed by wind energy. By 2050, solar has the highest mitigation potential followed by wind and hydro.

In this analysis, bio-energy contributes between 1,169 million tonnes CO2/a in the low case and 6,695 million tonnes CO2/a in the high case by 2050. But one has to keep in mind that, in practice, the uncertainties are significantly higher than for all other technologies. The use of non-renewable bio-fuels or solid biomass would reduce this amount significantly and could even result into higher CO_2 emissions compared to fossil fuels[12] (Crutzen et al., 2007). In addition, all analysed scenario

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[12] Sattler, C., Kachele, H. & Verch, G. 2007. Assessing the intensity of pesticide use in agriculture. Agriculture, Ecosystems and Environment 119: 299-304. and Crutzen, P.J., Mosier, A.R., Smith, K.A. & Winiwarter, W. 2007.

did not identify the share of modern biomass versus modern biomass in the `direct heating category`, therefore the biomass used for direct heating has been excluded from the CO2 reduction emission calculation.

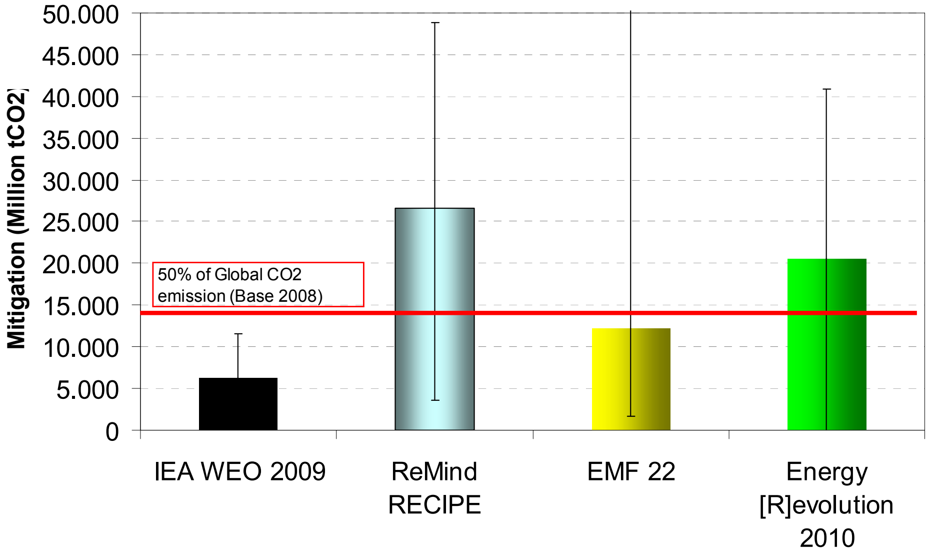


Figure 10.3.10: Annual Global CO2 savings from RE for different scenario based deployment paths for 2050 (NOTE: this is excluding transport and biomass used for direct heating)

Based on the analysed scenarios, the total annual CO_2 reduction potential varies significantly between all analysed scenarios. While the low case abatement potential for RE is the IEA WEO 2009 with 6.3 Gt CO_2/a by 2050, which represents the business-as-usual pathway, the medium case (EMF22) achieves a total of 12.2 Gt CO_2/a by 2050. The highest contribution represented by ReMind (ER 2010) [TSU: correct reference?] is marked by CO_2 savings by 2050 of 26.5 Gt CO_2/ a (20.5 Gt CO_2/a) which is equal to approximately 75% reduction of energy related CO_2-emission of the analysed baseline scenarios. However, the error bars in Figure 10.3.8 indicate that there are very high uncertainties.

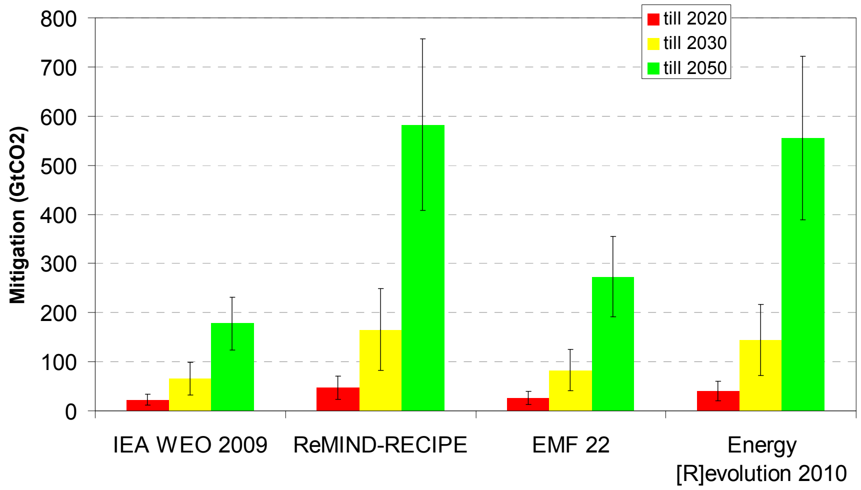


Figure 10.3.11: Global cumulative CO2 savings between 2020 and 2050

N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics Discussions 7: 11191-11205. and Scharlemann, J.P.W. & Laurance, W.F. 2008. How green are biofuels? Science 319: 43-44.

Cumulative CO2 reduction potentials from RE sources until 2020, 2030 and 2050 have been calculated on the basis of the annual average CO_2 savings shown in Figures 10.3.8 and 10.3.9. Based on this, the analysed scenarios would have a cumulated reduction of 178 Gt CO2 under the IEA WEO 2009 baseline conditions, 273 Gt CO2 in the EMF 22 case, 555 Gt CO2 in ER 2010 case and 583 Gt CO2 under the ReMind scenario (see Figure 10.3.11) [added by TSU]. Again, these numbers exclude transport and biomass used for direct heating.

10.3.5. Comparison of the results of the in depth scenario analysis

All analysed scenarios assume an increase of RE sources across all sectors. However, the power sector is in the forefront of all sectors and the sharpest increase of RE capacity is projected. Hydropower is believed to play the dominant role in the RE sector up until 2030 in all four analysed scenarios. Wind is believed in 3 out of 4 scenarios to overtake hydro by 2030. The results for all other technologies are far more diverse. Two scenarios see solar photovoltaic as an important player in the power sector after 2030, with a share of more than 10% by 2050, while the baseline scenario projects photovoltaic remains at marginal levels. In 3 out of 4 scenarios the foreseen role for geothermal energy remains low at levels well below 5% of the global power supply. The heating and cooling sector offers an even more diverse picture, which might be caused not only be uncertainties and distinguished assumptions but partly scenario results are not by 100% comparable because of different accounting methods, e.g. for geothermal heat pumps. In terms of primary energy share, bio-energy plays the most important contribution – especially in the heating sector. Wind and solar are projected to become an important player after 2030.

As already stressed in the comprehensive scenario survey, there are many reasons why the investigated scenarios come to different results. Each of the in-depth analysed scenarios follows a different strategy. Significant differences in the demand projections, a move towards electricity within the transport and/or heating sector or not has a significant impact on the selected technologies and their deployment rates. Besides that, other mitigation technologies, such as CCS and/or nuclear, have an impact on the resulting role of RE sources in the energy mix. Also system aspects play an important role. A high share of relatively inflexible “base load” power plants – such as coal- or lignite power plants - will reduce the technical and economic “space” of variable renewable power generation like solar photovoltaic and wind.

While under the baseline scenario the renewable primary energy production almost doubles to 120 EJ/y by 2050, the category I+II scenario EMF 22 projects tripling to 210 EJ/y. The ER 2010 projects the highest RE primary energy production up to 372 EJ/y – more than 5 times the 2007 level.

10.3.6. Knowledge gaps

Following knowledge gaps can be identified:

- New RE technologies, such as ocean energy, are not represented in most of the current energy scenarios.
- The interaction of the chosen technology pathways with the effects on deployment costs are not well reflected in most scenarios.
- The reporting system, e.g. for geothermal heat pumps, is very different in all scenarios and sometimes not transparent, which makes it difficult to compare the results
- More generally, there is a severe lack of data for the heating and transport sector especially for the sectoral or regional basis.

10.4. Regional Cost Curves for mitigation with RE sources

10.4.1. Introduction

Governments and decision-makers face limited financial and institutional resources and capacities for mitigation, and therefore tools that assist them in strategising how these limited resources are prioritised have become very popular. Among these tools are abatement cost curves – a tool that relates the mitigation potential of a mitigation option to its marginal cost. Recent years have seen a major interest among decision- and policy-makers in abatement cost curves, witnessed by the proliferation in the number of such studies and institutions/companies engaged in preparing such reports (e.g. Next Energy, 2004; Dornburg *et al.*, 2007; McKinsey&Company, 2007; International Energy Agency, 2008; McKinsey&Company, 2008a; McKinsey&Company, 2009c; McKinsey&Company, 2009b) (Creyts et al. 2007) [AUTHORS: Reference missing in bibliography]. However, while abatement curves are very practical and can provide important strategic overviews, it is pertinent to understand 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; (b) review the existing literature on regional abatement cost curves as they pertain to mitigation using RE; and (c) review the literature on (regional) RE technology resource cost curves.

10.4.2. Abatement and energy cost curves: concept, strengths and limitations

10.4.2.1. The concept

The concept of supply curves of carbon abatement, energy, or conserved energy all rest on the same foundation. They are curves consisting typically of discreet steps, each step relating the marginal cost of the abatement measure/energy generation technology or measure to conserve energy to its marginal cost; and rank these steps according to their cost. As a result, a curve is obtained that can be interpreted similarly to the concept of supply curves in traditional economics.

Supply curves of conserved energy were first introduced by Arthur Rosenfeld (see Meier *et al.*, 1983) and became a popular concept in the 1980s (Stoft, 1995) [AUTHORS: Reference missing in bibliography]. The methodology has since been revised and upgraded, and the field of its application field 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 to energy conservation options, and therefore was a practical tool for some decision-making approaches, such as integrated resource planning. Although Stoft (1995) explains why the supply curves used in the studies by Meier et al. cannot be regarded as “true” supply curves, including the fact that markets associated with the different types of options depicted in them, such as energy efficiency and energy supply markets, differ in many aspects; he maintains that they are useful for their purpose.

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

10.4.2.2. Limitations of the supply curve method

The concept of abatement, energy and conservation supply curves have common and specific limitations. Much of criticism in the early and some later literature focuses on the notion of options with negative costs. For instance, the International Energy Agency (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) potentials themselves represent a realm of debates ongoing for decades between different schools of thought (e.g. see Carlsmith *et al.*, 1990; Sutherland, 1991; Koomey, 1998; Gumerman *et al.*, 2001). Those accepting negative cost potentials argue, among others, that certain barriers prevent those investments from taking place on a purely market basis, but policy interventions can remove these barriers and unlock these profitable potentials. Therefore the barriers prevailing in RE markets, detailed in other sections of this report, such as insufficient information, limited access to capital, uncertainty about future fuel prices (for example in the case of fossil fuels or biomass) or misplaced incentives (e.g. fossil fuel subsidies for social or other reasons) 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 EEEC (2007) [AUTHORS: Reference missing in bibliography], criticizing 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 EEEC (2007) and (International Energy Agency (IEA), 2008b) agree that there is the problem of high uncertainty in the use of supply curves for the future. This uncertainty is true both from economic and technological perspectives. Additional uncertainty rising from the methodology is the sensitivity of mitigation curves relative to the baseline assumption of the analysis (Kuik, 2009). Baker *et al.* (2008) have demonstrated that aggregation may also trigger significant uncertainty in MACCs. 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. Optimised, 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 one simply as a result of the differences in emission factors (Fleiter *et al.*, 2009). As a result, a carbon abatement curve for a future date may say more about expected policies on fossil fuels than about the actual measures analysed by the curves, and the ranking of the individual measures is also very sensitive to the developments in carbon intensity of energy supply.

There are some concerns emerging in relation to abatement cost curves that are not yet fully documented in the peer-reviewed literature. For instance, the costs of a RE technology in a future year largely depends on the deployment pathway of the technology in the years preceding – i.e. the policy environment in the previous decades. The abatement cost of a RE option heavily depends also on the prices of fossil fuels which is also very uncertain to predict.

Economic data, such as technological costs or retail rates, are derived from past and current economic trends that may obviously not be valid for the future, as sudden technological leaps, policy interventions, or unforeseeable economic changes may occur – as has often been precedented in the field of 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 the previous 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 does not only stem from the fact that it is difficult to project them for the future, but because it is difficult to decide what discount rate to use, i.e. social vs. market discount rates. A number of studies (see e.g. Nichols, 1994) have discussed that in the case of investments in energy efficiency or RE, individual companies or consumers often use higher discount rates than would be otherwise expected for other types of e.g. financial investments. On the other hand, as Fleiter *et al.* (2009) note, society faces a lower risk in the case of such investments, therefore a lower discount rate could be considered appropriate from that perspective. Kuik *et al*. (2009) demonstrated that depending on the method used to construct them, MACCs 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 the key studies that have produced national or regional cost curves for RE and its application for mitigation. First, we review work that look at RE cost curves, followed by a review of the role of RE in overall abatement cost curves – since designated cost curves for renewable alone are rare.

10.4.3.2. Regional and global RE cost curves

In an attempt to review the existing literature on regional cost curves, a number of studies were identified, as summarized in **Error! Reference source not found.**. 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 total potential identified by the curves, the table also reviews the most important characteristics and assumptions of the models/calculations as well as their key findings.

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 detail their methodology, and most studies use different assumptions (technologies reviewed, target year, discount rate, energy prices, deployment dynamics, technology learning, etc.). Therefore, country- or regional findings in **Error! Reference source not found.** need to be compared with caution, and for the same reasons findings for the same country can be very different in different studies.

Table 10.4.1: Summary of regional/national literature on RE supply curves, with the potentials grouped into cost categories (Baseline refers to the expected projection of the energy type whose potential is described in the “notes” by the target year; most typically the projected TPES for the particular country, unless otherwise noted in the Notes)

Country/region		Cost ($ / MWh)	Total RES (TWh/yr)	% of base-line	Dis-count rate (%)	Notes	Source
Global		< 100	200,000-300,000	>100	10	- Combined potential of Onshore Wind, solar PV and Biomass given land usage constrains and technology scenarios - Sources of uncertainty considered	de Vries et al. (2006), baseline: World Energy Council, 2001 and Hoogwijk, 2004 [AUTHORS: Reference missing in bibliography].
Global (Biomass)		<100	97,200	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	<100	42,000	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 (A1) with stabilizing world population and fast and widespread yield improvements.	RES data: (de Vries *et al.*, 2007) Target year: 2050 Baseline data: (International Energy Agency (IEA), 2003)
		<80	39,000	123			
		<60	23,000	72			
		<40	2,000	6			
	Biomass	<60	59,000	187			
	PV	<100	1,850,000	5,868			
		<80	400,000	1,268			
Global		<70	21,000	600-	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), Reference year: 2004 baseline IEA 1996
		<100	53,000	700			
	Former USSR	<70	2,000	160			
		<100	7,000	550			
	USA	<70	3,000	80			
		<100	13,000	350			
	East Asia	<70	0	0			
		<100	50	3			
	Western Europe	<70	1,000	40			
		<100	2,000	80			
Global		<50	121,805	N/A	10	- Biomass energy from short-rotation crops at abandoned cropland and restland - four IPCC CRES [TSU: should probably read: SRES] 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 $45/MWh (A1 B1 scenarios) and 50 $/MWh (A2 B2 scenarios) in 2050	(Hoogwijk *et al.*, 2009) Target year: 2050
	Former USSR		23,538				
	USA		9,444				
	East Asia		17,666				
	OECD Europe		3,194				

Central and Eastern Europe	<100	3,233	74	N/A	- Biomass only, best scenario with willow being the selected energy crop (highest yield) - Countries: BG, CZ, EST, HU, LV, LT, PL, RO, SK - Baseline data includes Slovenia, however, its share is rather low, therefore resulting distortion is not so high.	RES data: van Dam et al. (2007) Target year: 2030 Baseline data: (Solinski, 2005)
Czech Republic	<100	101	20	4	- Only biomass production - Best case scenario where future yields equal the level of the Netherlands	RES data: (Lewandowski *et al.*, 2006) Target year: 2030 Baseline data: (International Energy Agency (IEA), 2005a)
Germany	<100	160	24	N/A	- Only Wind and PV are included - PV only enters above 200 USD	RES data: Scholz (2008) Baseline data: McKinsey and Company (2007)
	<200	177	27			
	<300	372	56			
India	<200	90	5.6	10	- wind - Grid availability not expected to be a serious concern - baseline refers to 2005 electricity consumption	Pillai et al. (2009) Target year: 2030
	<100	56	3.4		- small hydro - Grid availability not expected to be a serious concern - baseline refers to 2005 electricity consumption	
Netherlands	<100	22	2.1	N/A	- Included: onshore and offshore wind, PV, biomass and hydro; - Interest rate is not available, however, this option is a scenario where sustainable production is calculated. Therefore they use 5% IRR assuming that there are governmental support; - Baseline is TPES forecast for 2020 by IEA;	RES data: Junginger et al. 2004 Reference year: 2020 Baseline data: IEA (2006)
	<200	23	2.2			
	<300	24	2.3			
UK	<100	81	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;	RES data: Enviros (2005) Baseline data: UK SSEFRA (2006)
	<200	119	33			
United States	<100	3,421	15	N/A	- Wind energy only	RES data: Milligan (2007) Baseline data: EIA (2009)
United States (WGA)	<100	177	0.77	N/A	- Only the WGA region - CSP, biomass, and geothermal; - Geothermal reaches maximum capacity under 100 $/MWh; - CSP has a large potential, but full range is between 100 and 200 $/MWh	RES data: Mehos and Kearney (2007), Overend and Milbrandt (2007), Vorum and Tester (2007) Baseline data: EIA (2009)
	<200	1,959	8.5			
	<300	1,971	8.6			
United States (AZ 2025)	<100	0.28	N/A	Biomass and PV: 7.5 Rest: 8	- State of Arizona, United States - RES: wind, biomass, solar, hydro, geothermal Interest rates vary between energy sources	RES data: Black & Veatch Corporation (2007)
	<200	10.5	N/A			
	<300	20	N/A			

The weakness of many regional or technology studies is that they usually do not account for the competition for land and other resources, such as capital among the various energy sources (except for probably the various plant species in the case of biomass). In studies that do take this into account (such as de Vries *et al.*, 2007), potentials substantially decline in case of exclusive land use, with solar PV suffering the worst losses both in technical and economic potentials.

10.4.3.3. Regional and global carbon abatement cost curves

One general trend can be observed based on this limited sample of studies. Abatement 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 potentials.

One factor contributing to this general trend is that RE supply studies typically examine a broader portfolio of RE sources technologies, while the carbon mitigation studies reviewed focus on selected resources/technologies to keep models and calculations at reasonable complexity. For instance, remaining with the UK example, the CBI (2007) [AUTHORS: Reference missing in bibliography] study does not take into consideration other RE sources presented by (Enviros Consulting Ltd., 2005) as low-cost options, such as landfill gas, sewage gas and hydropower.

The highest figure in carbon mitigation potential share by the deployment of RE, as demonstrated by Table 10.4.2, is for Australia: 13.4% under 200 USD/t CO_2e by 2030. This has to be seen in contrast with the much higher shares as a percentage of national 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 – all having high emission factors.

10.4.4. Review of selected technology resource cost curves from the literature

The energy and abatement cost curves discussed above are based on technology specific findings. For selected technologies this section ends with the discussion of illustrative examples of resource cost curves. In this context some studies are highlighted which were already part of the general overview in section 10.4.3. Additionally, this section is linked with the discussion of the energy and cost aspects in the various technology chapters (Chapters 2-7).

Summary of biomass resource cost curves. The analysis of biomass resource cost curves in the literature use typically different land-use scenarios (de Vries *et al.*, 2007; Hoogwijk *et al.*, 2009) (Figure 10.4.1). They take into account geographical potential (crop productivity and land availability) as well as capital and labour input. Hoogwijk et al. (2009) find that biomass can supply about 40-70% of the present primary energy consumption (130-270 EJ/year) by 2050 at costs below USD 2/GJ/year, which is the present lower limit of the cost of coal.

Table 10.4.2 summarises the findings and characterises the assumptions in the studies reviewed that construct regional carbon abatement cost curves through the deployment of renewable technologies. They 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 10.4.2: Summary of carbon abatement cost curves literature (cells including grey literature are coloured in grey)

Country/region	Year	Cost (\$/tCO$_2$e)	Mitigation potential (million tonnes CO$_2$)	% of baseline	Discount rate (%)	Notes	Source
Global	2050	<200	46,195	85	N/A	- Key sensitivities: lower potential for wind, hydro or CCS, lower uranium resources raise abatement costs by 2-5%	Syri et al. (2008) [AUTHORS: Reference denoted: 2002]. Baseline model: global ETSAP/TIAM Baseline Scenario: WEO 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 analysed 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	Elzen et al. (2009) [AUTHORS: Reference missing in bibliography] Baseline Scenario: WEO 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	30	N/A	- Storylines do not describe all possible development (eg. 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) [AUTHORS: Reference missing in bibliography] Baseline scenario: IPCC SRES (2000) Baseline Scenario: WEO 2009

Country/region	Year	Cost ($/tCO$_2$e)	Mitigation potential (million tonnes CO$_2$)	% of baseline	Discount rate (%)	Notes	Source
China	2030	<100	2,323	20	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 [AUTHORS: Reference missing in bibliography] Baseline Scenario: IEA 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	55.90	12			
Switzerland	2030	<100	0.9	1.6	2,5	- Base case scenario	(McKinsey&Company, 2009c)
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)
United States	2030	<100	380	3.7	7		Creyts et al. (2007) [AUTHORS: Reference missing in bibliography]
United Kingdom	2020	<100	4.38	0.46	N/A		CBI (2007) [AUTHORS: Reference missing in bibliography]
		<200	8.76	0.93			

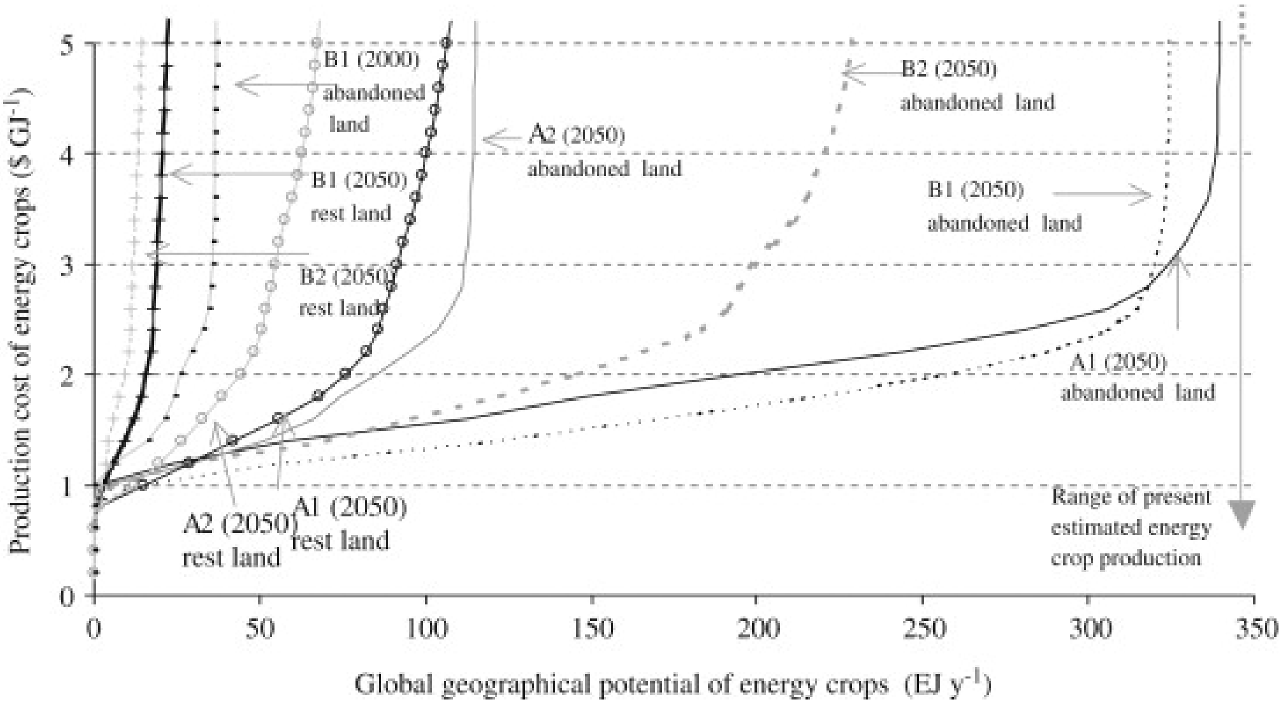


Figure 10.4.1: The global average cost-supply curve for the energy production potential from energy crops for four SRES scenarios for the year 2050 (Hoogwijk et al., 2009).

Regions of low production cost and relatively high 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/year may be generated in 2050 at costs below USD 45/MWh in two scenarios, while below USD 55/MWh in two others. At costs of USD 60/MWh, about 18 to 53 PWh/year of electricity can be produced in 2050. The global curve that sums all regional curves is found to be relatively flat until 300 EJ/year potential, land rental costs and the substitution of capital for labour represent highest sensitivity.

In the study of de Vries *et al.* (2007), another trade-off is addressed: the food vs. energy one. The authors assess four land-use scenarios, each corresponding to different levels of food-trade, technology development and population. Low 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 (Figure 10.4.2).

The price of biomass energy as of 2000 is 50-100 USD/MWh, representing 7 PWh of technical potential in year 2000, while the projected cost ranges between 30-100 USD/MWh, supplying 59 PWh by 2050. Electricity production from biomass is significantly costlier: 100 USD/MWh in 2050, contributing 30–85PWh/year by 2050. Land availability and management factor plays a key part in the evolution of uncertainties.

Summary of PV resource cost curves. De Vries *et al.* (2007) estimate PV electricity generation potential at 4,105 PWh/year in 2050 at the cost of 60-250 USD/MWh. Since the potential for the year 2050 depends primarily on cost reducing innovations: for a cut-off cost level of 100 USD/MWh, a non-zero potential emerges only in scenarios with high economic growth vs. low population growth, or medium economic and population growth (Figure 10.4.3).

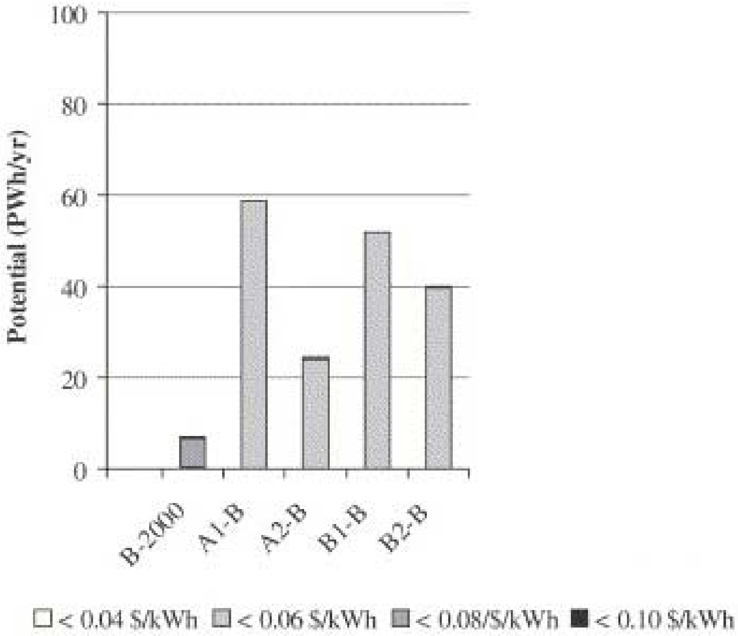


Figure 10.4.2: The global technical potential for electricity from biomass in the year 2000 and in the four scenarios for the year 2050 for four production categories (de Vries *et al*., 2007).

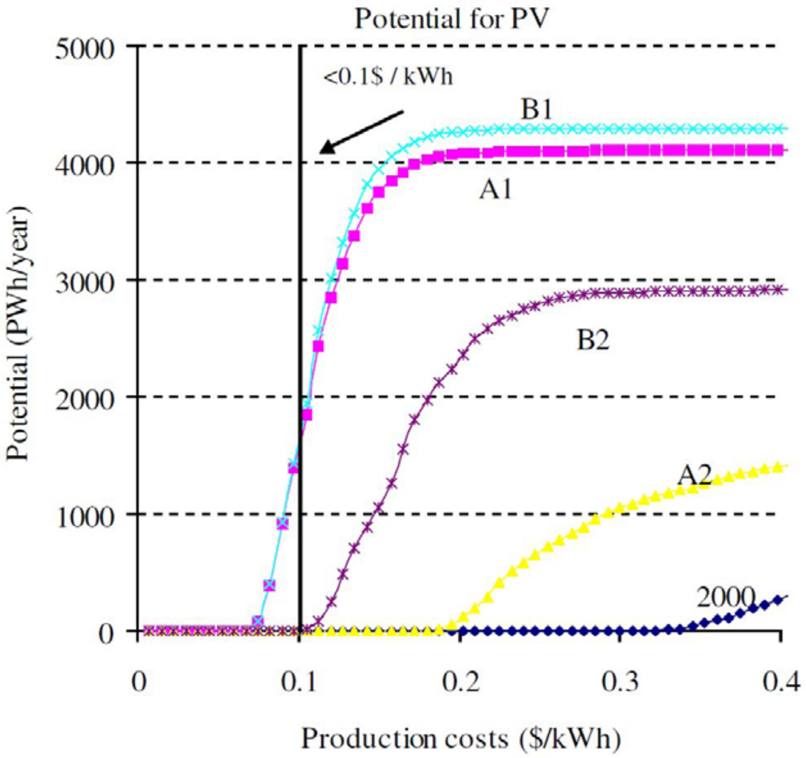


Figure 10.4.3: Resource supply cost curve for PV for four IPCC scenarios in 2050. The figure also shows the 0.1 USD/kWh line used in the paper as cut-off cost in determining the economic potential (de Vries et al., 2007).

Solar PV is extremely sensitive to competition for land, its technical and economic potentials are very sensitive to the cost determinants. If the technological breakthroughs do not take place, a large part of the major potential is unlikely to become economic. Its capital-intensive nature makes it also sensitive for changes in the interest rate, for the same reason. High or low exclusion factors also affect the solar-PV potential, but land does not seem to be the constraint here: even with the high exclusion factor, the potential is over 20 times the 2000 world electricity demand (de Vries *et al*., 2007).

Summary of onshore wind cost curves. Papers assessing wind potential usually base their data on climatic models of wind speeds (de Vries et al., 2007; Hoogwijk et al., 2004; Changliang and Zhanfeng, 2009). Hoogwijk *et al.* (2004) have made explicit assumptions about the average turbine availability, wind farm array efficiency and spacing, and, relatedly, power density; this has not differentiated across grid-cells i.e. one global parameter has been used. The estimated global technical potential for wind in 2000 is 43 PWh/year, which is expected to increase to 61 PWh/year by 2050, but largely confined to three proliferous regions (**Figure** 10.4.4). These are the USA, the Former USSR and Oceania (16 PWh/yr, 8 PWh/yr and 4 PWh/yr, respectively), which is estimated to reach 22 PWh/yr, 11 PWh/yr and 11 PWh/yr for the three regions (Hoogwijk et al., 2004; McElroy et al., 2009). When analysing scenarios taking into consideration socio-economic aspects, it is found that the strongest increase in potential for wind by a stabilizing of population and therefore a decreased need for agricultural land. Compared to current costs (50 – 130 USD/MWh), wind power might even be generated at costs below 40 USD/MWh in scenarios assuming either high economic growth vs. low population growth, or medium economic and population growth.

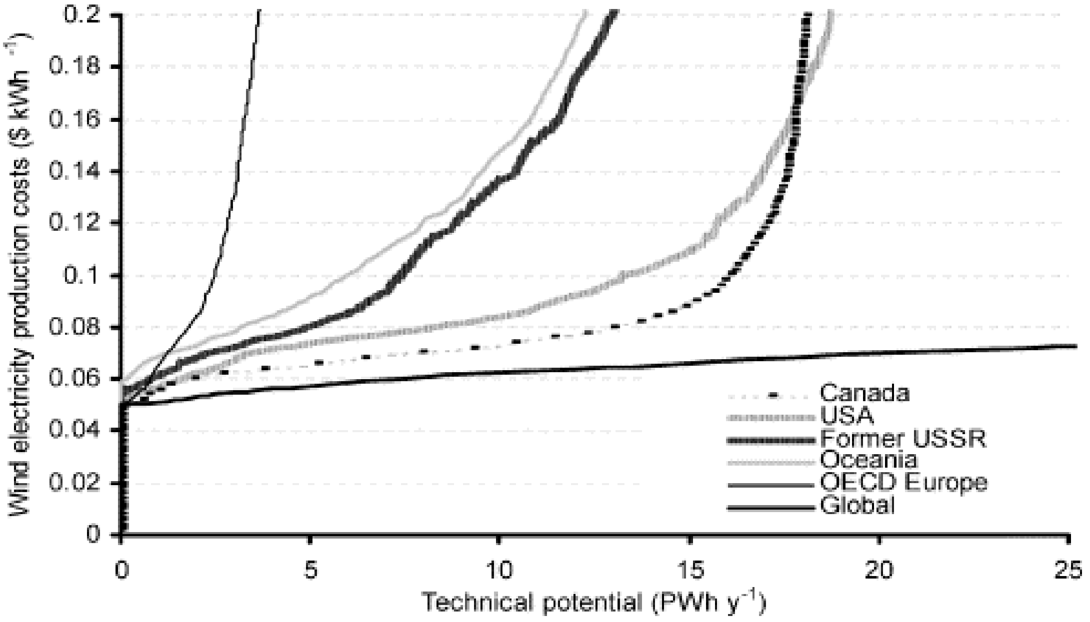
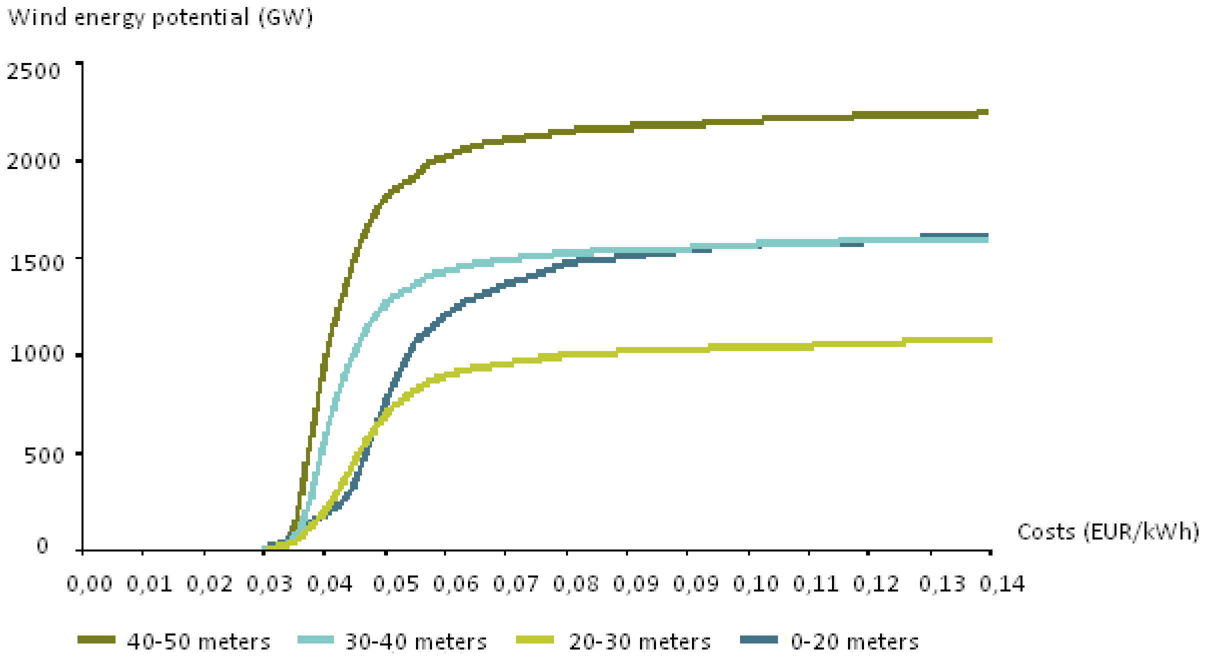


Figure 10.4.4: Regional cost-supply curve for wind energy (USD/kWh vs. PWh/yr) for *D=4* MW km^2. For comparison, the global cumulative curve is also presented (Hoogwijk *et al*., 2004).

The same study demonstrates that competition for land with total exclusion of more than one option can for wind bring down the technical and economic potential with over one third. Nevertheless, none of the wind resource assessments consider grid stability and energy storage issues that are crucial for economic viability of wind installations. Wind remains in all cases an important contributor to the worldwide economic potential at less than 100 USD/MWh, with a potential between 8 and 43PWh/year — or 50–300% of the 2000 world electricity demand (de Vries *et al*., 2007).

Summary of offshore wind cost curves. For offshore wind, the available potential and costs are strongly determined by the distance of the installation from the shore. In a recent study of EEA

(2009), the lower limit of wind speed at hub height has been set to 5.0 m/s to consider the windmill economically viable. At an average production cost of 6.9 eurocents (2005 prices)/kWh in 2030, 5,800 GW of offshore wind power could be developed in Europe. This figure however corresponds to an unrestricted potential (**Figure** 10.4.5).



Source: EEA, 2008

Figure 10.4.5: Potential for offshore wind energy generation at different water depths in 2030 for Europe (EEA, 2009).

Various studies have assessed the technical potential for offshore wind. Nevertheless, only Fellows (2000) presents the assessments on a global level (except Norway and Canada), including cost estimates for the timeframe to 2020. Hoogwijk and Graus (2008) have added values for Canada and corrected the data for the technological development for 2020 to 2050. High potentials are found in OECD Europe, and Latin America, this latter having high shares of low cost potentials unexplored. A capacity of 1,2 PWh/year for OECD Europe and Latin America is found at costs lower than 100 USD/MWh. At costs < 50 USD/MWh, 0,3 PWh/year is available in OECD Europe, while 550 PWh/year in Latin America. Lowest potentials are found in the Middle East, where even at <100USD/MWh only 0,18 PWh/year 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 were found. It is important to emphasise that such studies are comparable only to 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, since these present potentials for deployment taking into account much more constraints than these resource potential/cost studies.

10.4.5. *Gaps in knowledge*

There is a major gap in knowledge for renewable non-electric energy potentials on a regional basis, especially as a function of cost. Additionally, the real benefit of the cost curve method, i.e. to identify the really cost-effective opportunities, in practice cannot be fully utilized with the given datasets. Average costs for a technology for a whole region mask the really cost-effective potentials and sites into an average, compromised by the inclusion of less attractive sites or sub-technologies. Therefore, significant, globally coordinated further research is needed for refining these curves into sub-steps by sites and sub-technologies in order to identify the most attractive opportunities broken out of otherwise less economic technologies (such as more attractive wind sites, higher productivity biomass technologies/plants/sites, etc.).

10.5. Cost of commercialization and deployment (investments, variable costs, market support, RDD&D)

RE sources are expected to play an important role in achieving ambitious climate protection goals, e.g., those consistent with a 2°C limit on global mean temperature change compared to preindustrial times (International Energy Agency (IEA), 2010b). Although some technologies are already competitive, e.g., large hydropower, combustible biomass (under favorable conditions) and larger geothermal projects (>30 MW_e), many innovative technologies in this field are still on the way to becoming mature alternatives to fossil fuel technologies (International Energy Agency (IEA), 2008b). Currently and in the mid-term, the application of these technologies therefore will result in additional *private* costs compared to energy supply from conventional sources.[13] Starting with a review of present technology costs, the remainder of this subchapter will focus on expectations on how these costs might decline in the future, for instance, due to extended R&D efforts, technological learning associated with increased deployment, or spill-over effects (cf., IPCC, 2007d, Chapter 2.7. and Chapter 11.5.1.). In addition, historic R&D expenditures and future investment needs will be discussed.

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 & maintenance costs (OMC), and – if applicable – fuel costs (in the case of biomass), may play an important role as well. The respective cost components were discussed in detail in Chapters 2 to 7. The current section intends to provide a summary of technology costs in terms of specific investment costs (expressed in US$/kW installed capacity) and levelized costs of energy (LCOE, expressed in terms of US$/MWh, see Appendix A II). Both values will be given for the generation of electricity, heat and transport fuel (see Table 10.5.1).

On a global scale, the values of both cost terms are highly uncertain for the various RE technologies. As recent years have shown, the investment costs might be considerably influenced by changes in material (e.g., steel) and engineering costs as well as by technological learning and mass market effects. Levelized costs of energy (LCOE, also called levelized unit costs or levelized generation costs) are defined as 'the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent' (International Energy Agency (IEA), 2005b). LCOE therefore capture the full costs (i.e., investment costs, operation and maintenance costs, fuel costs and decommissioning costs) of an energy conversion installation and allocate these costs over the energy output during its lifetime.

As a result, levelized costs heavily depend on RE resource availability (e.g., due to different full load hours) and, as a consequence, are different at different locations (Heptonstall, 2007; International Energy Agency (IEA), 2010a). Optimal conditions can yield lower costs, and less favorable conditions can yield substantially higher costs compared to those shown in Table 10.5.1. The costs given there are exclusive of subsidies or policy incentives. Concerning LCOE, the actual

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[13] Within this subchapter, the external costs of conventional technologies are not considered. Although the term "private" will be omitted in the remainder of this subchapter, the reader should be aware that all costs discussed here are *private* costs in the sense of subchapter 10.6. Externalities therefore are not taken into account.

global range might be wider than the best guess range given in Table 1, as discount rates, investment cost, operation and maintenance costs, capacity factors and fuel prices are site dependent. Table 10.5.1 contains data which was compiled by the authors of SRREN Chapter 2-7 (this report). Additional information on the derivation of these numbers is given in Appendix 3 (Cost Table).

Technology	Typical characteristics	Typical current investment costs[1] (USD$_{2005}$/kW)	Typical current energy production costs[1] (USD/MWh)	References
POWER GENERATION				
Hydropower				
	Plant size: 10–18 000 MW	1 000–5 500	30–120	IEA, 2008a
	Plant size: 1–10 MW	2 500–7 000	60–140	IEA, 2008a
	Plant size: < 0.1–20 000 MW	1 000–3 000	20–110	IPCC, 2011
Wind				
Onshore wind	Turbine size: 1–3 MW	1 200–1 700	70–140	IEA, 2008a
	Plant size: 5–300 MW	1 200–2 100	50–150	IPCC, 2011
Offshore wind	Turbine size: 1.5–5 MW	2 200–3 000	80–120	IEA, 2008a
	Plant size: 20– 120 MW	3 200–4 600	120–200	IPCC, 2011
Bioenergy[2]				
Biomass combustion for power (solid fuels)	Plant size: 10–100 MW	2 000–3 000	60–190	IEA, 2008a
Biomass co–firing	Plant size: 5–100 MW (existing), > 100 MW (new plant)	120–1 200 + power station costs	20–50	IEA, 2008a
Geothermal power				
Hydrothermal	Plant size: 1–100 MW; Types: binary, single– and double–flash, natural steam	1 700–5 700	30–100	IEA, 2008a
	Plant size: 10–100 MW Type: condensing-flash plant	1 800–3 600	40-130	IPCC, 2011
	Plant size: 2–20 MW Type: binary-cycle plants	2 100–5 200	50–170	IPCC, 2011
Enhanced geothermal system (EGS)	Plant size: 5–50 MW	5 000–15 000	150–300 (projected)	IEA, 2008a
Solar energy				
Solar PV	Power plants: 1–10 MW Rooftop systems: 1–5 kWp	5 000–6 500	200–800[3]	IEA, 2008a; REN21, 2008
	Rooftop (residential) 0.004–0.01 MW	6 400–7 300	400–850	IPCC, 2011
	Rooftop (commercial) 0.02–0.5 MW	5 500–6 800	340–790	IPCC, 2011
	Utility scale (fixed tilt) 0.5–100 MW	3 700–4 500	220–420	IPCC, 2011
	Utility scale (1-axis) 0.5– 100 MW	4100–5000	190–470	IPCC, 2011
Concentrating solar power (CSP)	Plant size: 50–500 MW	4 000–9 000 (trough)	130–230 (trough)[4]	IEA, 2008a
	Plant size: 50–250 MW	6 400–7 300	200–310	IPCC, 2011
Ocean energy				
Tidal and marine currents	Plant size: Several demonstration projects up to 300 kW capacity;	7 000–10 000	150–200	IEA, 2008a
Wave energy[5]		7 700–16 100	210 - 790	IPCC, 2011
Tidal current[5]		8 600–14 300	160-320	IPCC, 2011
OTEC[5]		8 000–10 000	160-200	IPCC, 2011

Technology	Typical characteristics	Typical current investment costs[1] (USD$_{2005}$)	Typical current energy production costs[1,2]	References
HEATING/COOLING				
Biomass heat (excluding CHP)	Size: 5–50 kWth (residential)/ 1–5 MWth (industrial)	120 /kW$_{th}$ (stoves); 380–1 000 /kW$_{th}$ (furnaces)	10–60 USD/MWh	IEA, 2008a; REN21, 2008
Solar hot water/ heating	Size: 2–5 m^2 (household); 20–200 m^2 (medium/ multi–family); 0.5–2 MW$_{th}$ (large/ district heating); Types: evacuated tube, flat–plate	400–1 250 /m^2	20–200 USD/MWh (household); 10–150 USD/MWh (medium); 10–80 USD/MWh (large)	IEA & RETD 2007, REN21, 2008
Geothermal heating/cooling	Plant capacity: 1–10 MWth Types: ground-source heat pumps, direct use, chillers	250–2450 /kW$_{th}$	5–20 USD/MWh	IEA & RETD 2007, REN21, 2008
Geothermal (building heating)	0.1 – 1 MW$_{th}$	1590–3940 /kW$_{th}$	100–240 MWh	IPCC, 2011
Geothermal (district heating)	3.8–35 MW$_{th}$	570–1560 /kW$_{th}$	50–120 MWh	IPCC, 2011
Geothermal (greenhouse)	2–5.5 MW$_{th}$	500–1000 /kW$_{th}$	30–60 MWh	IPCC, 2011
Geothermal (Aquaculture ponds)	5–14 MW$_{th}$	50–100 /kW$_{th}$	30–40 MWh	IPCC, 2011
Geothermal heat pumps (GHP)	0.01–0.35 MW$_{th}$	940–3750 /kW$_{th}$	70–210 MWh	IPCC, 2011
BIOFUELS (1ST GENERATION)				
Ethanol	Feedstocks: sugar cane, sugar beets, corn, cassava, sorghum, wheat (and cellulose in the future)	0.3–0.6 billion per billion litres/ year of production capacity for ethanol	0.25–0.3 USD/litre gasoline equivalent (sugar); 0.4–0.5 USD/litre gasoline equivalent (corn)	REN21, 2008
Biodiesel	Feedstocks: soy, oilseed rape, mustard seed, palm, jatropha, tallow or waste vegetable oils	0.6–0.8 billion per billion litres/ year of production capacity	0.4–0.8 USD/litre diesel equivalent	REN21, 2008

Notes:

1. Using a 10% discount rate. *Current* costs relate to costs either in 2005 or 2006 in case that the reference is made to IEA (2008a), RETD (2007), or REN21 (2008). For cross references to chapers in this report (IPCC, 2011), *current* cost data refer to costs in 2008 (expressed in USD$_{2005}$).

2. Wide ranges due to plant scale, maturity of technology, detailed design variables, type and quality of biomass feedstocks, feedstock availability, regional variations, etc. Costs of delivered biomass feedstock vary by country and region due to factors such as variations in terrain, labour costs and crop yields.

3. Typical costs of 20–40 UScents/kWh for low latitudes with solar insolation of 2,500 kWh/m2/year, 30–50 UScents/kWh for 1,500 kWh/m2/year (typical of Southern Europe), and 50–80 UScents for 1,000 kWh/m2/year (higher latitudes).

4. Costs for (parabolic) trough plants. Costs decrease as plant size increases. Plants with integrated energy storage have higher investment costs but also enjoy higher capacity factors. These factors balance each other out, leading to comparable generation cost ranges for plants with and without energy storage.

5. Highly uncertain projected costs. Underlying assumptions (discount rate and lifetime) are not known (see Chapter 6, IPCC, 2011, this report). Studies older than 2006 showed larger investment cost ranges.

Table 10.5.1: Current specific investment and levelized costs of energy (LCOE).

Source: The table is based on Table 5 in IEA, 2008b (p. 80 – 83) extended by cost data collected for the IPCC SRREN (this report, for details see Appendix 3 (Cost Table).

A comparison of LCOE of RE technologies with those of conventional technologies (nuclear, gas, and coal power plants) shows that RE sources are often not competitive with conventional sources, especially if they both feed into the electricity grid (see Figure 10.5.1). Under favorable conditions, exceptions include biomass, hydro, and geothermal power. If the respective technologies are used in a decentralized mode, their production cost must be compared with the retail consumer power price, which is much higher. In this case, important niche markets already exist that facilitate the market introduction of new technologies. The same holds true for applications in remote areas, where often no grid based electricity is available.

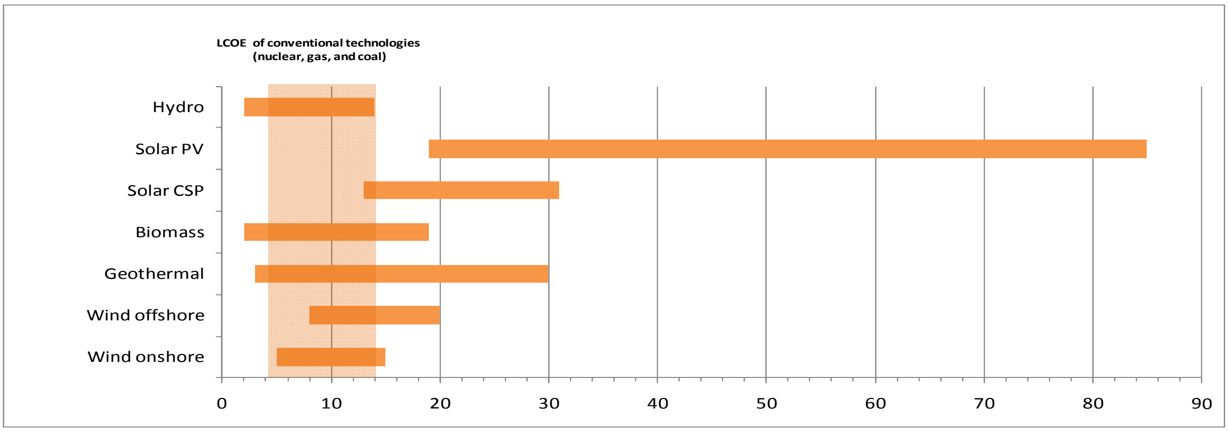


Figure 10.5.1: Cost-competitiveness of selected renewable power technologies. The figure is based on (International Energy Agency (IEA), 2007) and updated by cost data (see Table 10.5.1) collected for the IPCC SRREN (this report). The LCOE are given in US-cent/kWh. LCOE of conventional technologies depict the range valid for North America, Europe, and Asia Pacific (IEA, 2010). For OECD countries a future carbon price of US$ 30/t CO2 is assumed.

As RE technologies are often characterized by high shares of investment costs relative to OMC and fuel costs, the applied discount rate has a prominent influence on the LCOE (see Figure 10.5.2). The attractiveness of RE projects obviously depends on the requested internal rate of return. Projects that are not competitive for utilities might, nevertheless, be interesting from a private investor's point of view.

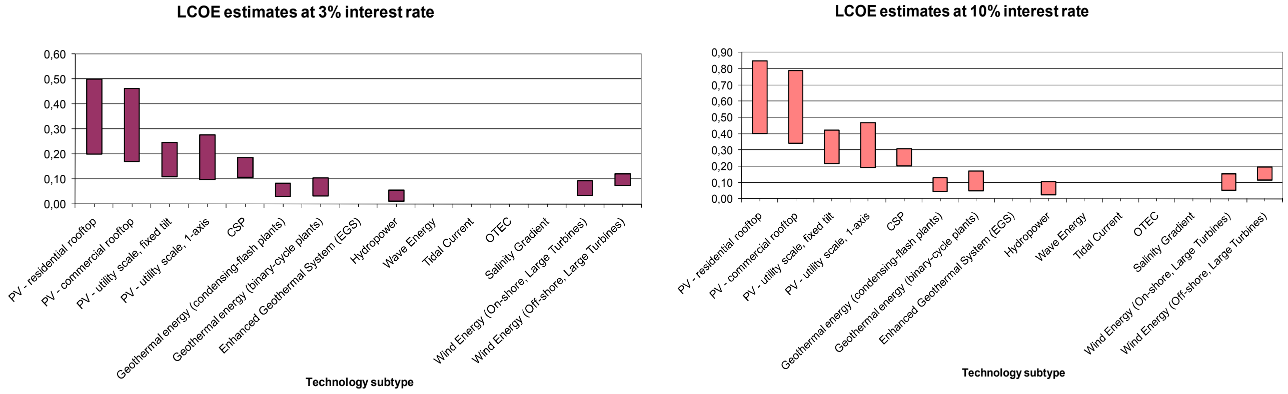


Figure 10.5.2: Cost-competitiveness of selected RE power technologies using different discount rates. The levelized costs of electricity production are given in US$2005/kWh. Source: Chapter 2-7, IPCC SRREN (this report, for details see Appendix 3 (Cost Table)). Note that the scale of the y-axes are different.

10.5.2. Prospects for cost decrease

Most technologies applied in the field of RE (and some other climate protection technologies, e.g., CCS power plants) are innovative technologies. As a consequence, large opportunities often exist to improve the energy efficiency of the technologies, and/or to decrease their production costs. Together, these two effects are expected to decrease the levelized cost of energy of many RE sourcing technologies substantially in the future. According to Junginger *et al.* (2006), the list of the most important mechanisms causing cost reductions comprises:

- *Learning by searching*, i.e. improvements due to Research, Development and Demonstration (RD&D) – especially, but not exclusively in the stage of invention,
- *Learning by doing* (in the strict sense), i.e. improvements of the production process (e.g., increased labor efficiency, work specialization),
- *Learning by using* (i.e. improvements triggered by user experience feedbacks) occur once the technology enters (niche) markets,
- *Learning by interacting (or "spillovers",* (cf. Clarke *et al.*, 2006; IPCC, 2007a), i.e. the reinforcement of the above mentioned mechanism due to an increased interaction of various actors in the diffusion phase,
- *Upsizing of technologies* (e.g. upscaling of wind turbines),
- *Economies of scale* (i.e., mass production) once the stage of large-scale production is reached.

The various mechanisms may occur simultaneously at various stages of the innovation chain. In addition, they may reinforce each other. As a consequence of the aforementioned mechanisms, many technologies applied in the field of RE sources showed a significant cost decrease in the past (see Figure 3). This empirical observation is highlighted by *experience (or "learning") curves,* which describe how costs decline with accumulated experience and corresponding cumulative production or (ever) installed capacity (International Energy Agency (IEA), 2000; International Energy Agency (IEA), 2008a).

For a doubling of the (cumulatively) installed capacity, many technologies showed a more or less constant percentage decrease of the specific investment costs (or of the levelized costs or unit price, depending on the selected cost indicator). The numerical value describing this improvement is called *learning rate (LR)*. It is defined as the percentage cost reduction for each doubling of the cumulative capacity. A summary of observed learning rates is provided in Table 2. Frequently, the *progress ratio (PR)* is used as a substitute for the learning rate. It is defined as PR = 1- LR (e.g., a learning rate of 20% would imply a progress ratio of 80%). Frequently, energy supply costs (e.g. electricity generation costs) and the cumulative energy (ever) supplied by the respective technology (e.g., the cumulative electricity production) are used as substitutes for capital costs and the cumulative installed capacity, respectively (cf. Figure 10.5.3c).

If the learning rate is time-independent, the empirical experience curve can be fitted by a power law. In this case, plotting costs versus cumulative installed capacity in a figure with double logarithmic scales shows the experience curve as a straight line (see Figure 3). As there is no natural law that costs *have* to follow a power law (Junginger *et al.*, 2006), care must be taken if historic experience curves are extrapolated in order to predict future costs (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). In order to avoid implausible results, projections that extrapolate experience cost curves in order to assess future costs therefore should constrain the cost reduction by appropriate *floor costs* (cf. Edenhofer *et al.*, 2006).

Unfortunately, *cost* data are not easily obtained in a competitive market environment. Indicators that are intended to serve as a substitute, e.g., product *prices* do not necessarily reveal the actual improvement achieved. Instead, they might be heavily influenced by an imbalance of supply and demand. This refers to both the final product itself (e.g., if financial support stipulates a high demand) and the cost of product factors, which might be temporarily scarce (e.g., steel prices due to supply bottlenecks). A deviation from price-based experience curves as observed for photovoltaic modules and wind energy converters in the years between 2004 and 2008 (see Figure 3a and 3b), therefore does not necessarily imply that a fundamental cost limit has been reached. Instead, it might simply indicate that producers were able to make extra profits in a situation where, for instance, feed-in tariff systems led to a demand that transgressed the production capabilities of the respective manufacturers.

As these extra profits can be increased by further cost reduction efforts, there is an incentive for producers to proceed in doing so. The fundamental incentive scheme of the feed-in-tariff system therefore is still working in the background even in the high price phases recently observed. However, the actual cost reductions are not passed to consumers in that phase.

According to some researchers (Junginger et al., 2006), the cost reduction achieved in the background might reveal itself after the supply and production bottlenecks are removed or the market power of the prime producer was destroyed in the so-called “shakeout” phase. In this case, the deviation from the long-term experience curve might be largely removed. Short term deviations that can be explained by supply bottlenecks, for instance, or by typical effects of demand or supply driven markets therefore should not immediately lead to a corresponding decrease of the learning rates that are used, for instance, for projections of future energy costs.

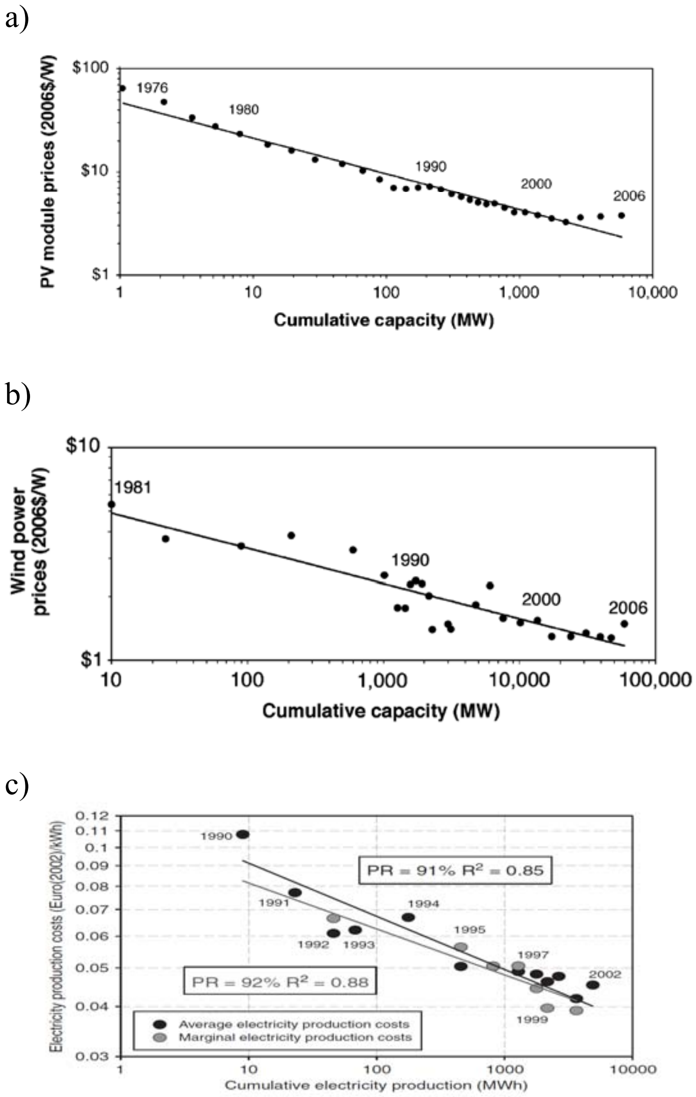


Figure 10.5.3: Illustrative experience curves for a) photovoltaic modules, b) wind turbines and c) Swedish bio-fuelled combined-heat and power plants. Source: Nemet, 2009; Junginger et al., 2006.

A summary of observed learning rates is provided in Table 10.5.2 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 turbines, for instance, might be small, the scale-up results in higher hub-heights and an associated significant increase in full load hours (and consequently in the amount of energy delivered). In order to assess the success of policy support programs learning rates referring to LCOE therefore should be used. Learning rates referring to single countries vary widely. Especially in countries with high market

Table 10.5.2: Observed learning rates for various electricity supply technologies. Source: IEA, 2008a, p. 205, extended and updated by learning rates collected for the IPCC SRREN (this report).

Technology	Source	Country / region	Period	Learning rate (%)	Performance measure	IPCC SRREN cross reference
Onshore wind						
	Neij, 2003	Denmark	1982-1997	8	Price of wind turbine (USD/kW)	
	Durstewitz, 1999	Germany	1990-1998	8	Price of wind turbine (USD/kW)	
	IEA, 2000	USA	1985-1994	32	Electricity production cost (USD/kWh)	
	IEA, 2000	EU	1980-1995	18	Electricity production cost (USD/kWh)	
	Kouvaritakis, et al., 2000	OECD	1981-1995	17	Price of wind turbine (USD/kW)	
	Junginger, et al., 2005a	Spain	1990-2001	15	Turnkey investment costs (EUR/kW)	
	Junginger, et al., 2005a	UK	1992-2001	19	Turnkey investment costs (EUR/kW)	
	Jamasb, 2007	Global	1980-1998	13	Investment costs (USD/kW)	
	Neij, 1997	Denmark	1982-1995	4	Price of wind turbine (USD/kW)	Table 7.6.
	Mackay and Probert, 1998	USA	1981-1996	14	Price of wind turbine (USD/kW)	Table 7.6.
	Neij, 1999	Denmark	1982-1997	8	Price of wind turbine (USD/kW)	Table 7.6.
	Wene, 2000	USA	1985-1994	32	Electricity production cost (USD/kWh)	Table 7.6.
	Wene, 2000	European Union	1980-1995	18	Electricity production cost (EUR/kWh)	Table 7.6.
	Miketa and Schrattenholzer, 2004 *	Global	1971-1997	10	Investment costs (USD/kW)	Table 7.6.
	Klaassen et al., 2005 *	Germany, Denmark, and UK	1986-2000	5	Investment costs (USD/kW)	Table 7.6.
	Kobos et al., 2006 *	Global	1981-1997	14	Investment costs (USD/kW)	Table 7.6.
	Jamasb, 2006 *	Global	1980-1998	13	Investment costs (USD/kW)	Table 7.6.
	Söderholm and Sundqvist, 2007	Germany, Denmark, and UK	1986-2000	5	Turnkey investment costs (EUR/kW)	Table 7.6.
	Söderholm and Sundqvist, 2007 *	Germany, Denmark, and UK	1986-2001	4	Turnkey investment costs (EUR/kW)	Table 7.6.
	Neij, 2008	Denmark	1980-2000	17	Electricity production cost (USD/kWh)	Table 7.6.
	Kahouli-Brahmi, 2009	Global	1979-1997	17	Investment costs (USD/kW)	Table 7.6.
	Kahouli-Brahmi, 2009 *	Global	1979-1997	27	Investment costs (USD/kW)	Table 7.6.
	Nemet, 2009	Global	1981-2004	11	Investment costs (USD/kW)	Table 7.6.
	* Indicates a two-factor learning curve that also includes R&D; all others are one-factor learning curves					
Offshore wind						
	Isles, 2006	8 EU countries	1991-2006	3	Installation cost of wind farms (USD/kW)	
	Jamasb, 2006	Global	1994-2001	1	Investment costs (USD/kW)	
Photovoltaics (PV)						
	Harmon, 2000	Global	1968-1998	20	Price PV module (USD/Wpeak)	
	IEA, 2000	EU	1976-1996	21	Price PV module (USD/Wpeak)	
	Williams, 2002	Global	1976-2002	20	Price PV module (USD/Wpeak)	
	ECN, 2004	EU	1976-2001	20-23	Price PV module (USD/Wpeak)	
	ECN, 2004	Germany	1992-2001	22	Price of balance of system costs	
	van Sark, et al., 2007	Global	1976-2006	21	Price PV module (USD/Wpeak)	
	Kruck, 2007	Germany	1977-2005	13	Price PV module (EUR/Wpeak)	
	Kruck, 2007	Germany	1999-2005	26	Price of balance of system costs	
	Nemet, 2009	Global	1976-2006	15-21	Price PV module (USD/Wpeak)	
Concentrated Solar Power (CSP)						
	Enermodal, 1999	USA	1984-1998	8-15	Plant capital cost (USD/kW)	
	Jamasb, 2006	Global	1985-2001	2	Investment costs (USD/kW)	
Biomass						
	IEA, 2000	EU	1980-1995	15	Electricity production cost (USD/kWh)	
	Goldemberg, et al., 2004	Brazil	1985-2002	29	Prices for ethanol fuel (USD/m^3)	
	Junginger, et al., 2006	Denmark	1984-1991	15	Biogas production costs (EUR/Nm^3)	
	Junginger, et al., 2006	Denmark	1992-2001	0	Biogas production costs (EUR/Nm^3)	
	Junginger, et al., 2005b	Sweden and Finland	1975-2003	15	Forest wood chip prices (EUR/GJ)	
	Van den Wall Bake et al.; 2009	Brazil	1975-2003	32	Sugarcane production costs (USD/t sugarcane)	Table 2.7.4
	Hettinga et al., 2009	USA	1975-2005	45	Corn production costs (USD/t corn)	Table 2.7.4
	Junginger et al., 2006a		1984-1998	12	Biogas plants (€/m^3 biogas/day)	Table 2.7.4
	Van den Wall Bake et al., 2009	Brazil	1975-2003	19	Ethanol from sugarcane (USD/m^3)	Table 2.7.4
	Goldemberg et al., 2004	Brazil	1980-1985	7 / 29	Ethanol from sugarcane (USD/m^3)	Table 2.7.4
	Van den Wall Bake et al., 2009	Brazil	1975-2003	20	Ethanol from sugarcane (USD/m^3)	Table 2.7.4
	Hettinga et al., 2009	USA	1983-2005	18	Ethanol from corn (USD/m^3)	Table 2.7.4
	Junginger et al., 2006a	Sweden	1990-2002	8-9	Biomass CHP power (EUR/kWh)	Table 2.7.4
	Junginger et al., 2006a	Denmark	1984-2001	0-15	Biogas production costs (EUR/Nm^3)	Table 2.7.4

growth rates country specific learning can be low, because learning is a global phenomenon and – compared to the global average – the cumulative capacity installed in these countries is higher (Neij, 2008) ; Schaeffer et al, 2009) [AUTHORS: Reference missing in bibliography].

10.5.3. Deployment cost curves and learning investments

According to the definition used by the IEA (2008b), "*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 operation costs and investment needs of conventional technologies, the *learning* investments are considerably lower. The *learning investments* are defined as the *additional* investment needs of the new technology. They are therefore equal to the deployment costs minus (replaced) cumulative costs of the incumbent technology.

Although not directly discussed in IEA, 2008 – to give the full picture – the cost difference could be extended to take into account variable costs as well (Figure 10.5.4). Because of fuel costs, the latter is evident for conventional technologies, but this contribution should also be taken into account if the RE usage implies considerable variable costs – as in the case of biomass. Once variable costs are taken into account, avoided carbon costs contribute to a further reduction of the *additional* investment needs. Figure 10.5.4 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.

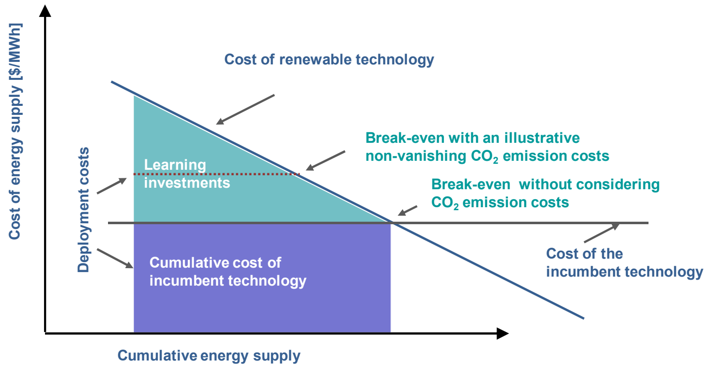


Figure 10.5.4: Schematic representation of experience curves, deployment costs and learning investments (modified version of the diagram depicted in (International Energy Agency (IEA), 2008b).

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 be become negative after some decades. A least cost approach towards a decarbonized economy therefore should not focus solely on the additional costs that are incurred until the break-even point with conventional technologies has been achieved (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 (inter alia the discount rate and the perceived climate policies and associated future carbon prices).

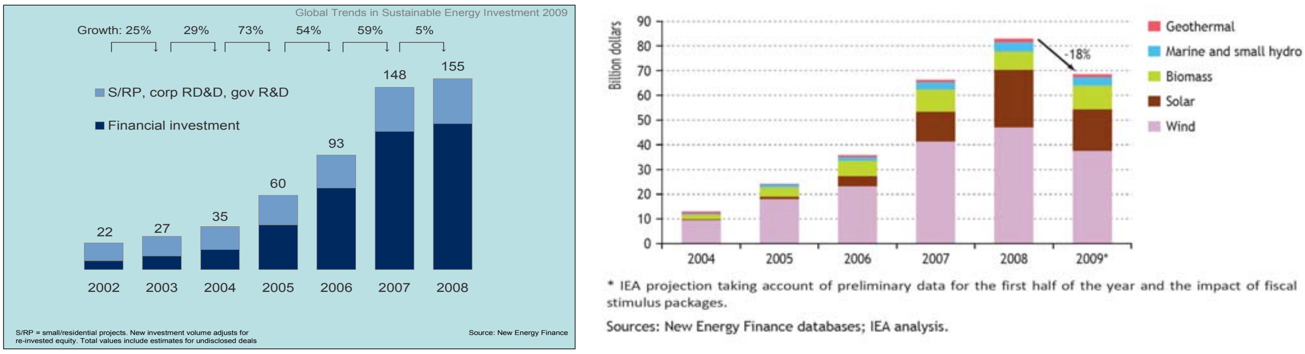
Innovative integrated assessment models – i.e., those which model technological learning in an endogenous way – are capable of assessing the overall mitigation burden associated with a cost optimal application of RE sources within the context of ambitious climate protection goals (Edenhofer *et al.*, 2006). The results obtained from these modeling exercises indicate that – from a macroeconomic perspective – significant upfront investments in innovative RE technologies are often justified if the respective technologies are promising with respect to their renewable resource potential and their learning capability.

The least cost (dynamically efficient) climate protection strategies proposed by these integrated assessment models are not necessarily adopted in reality. Due to the imperfect performance of liberalized energy markets, incentives for private investments in climate-friendly technologies might be artificially low. In fact, several private sector innovation market failures distort private sector investments in technological progress (Jaffe *et al.*, 2005). The main problem in this case is that private investors developing new technologies might not be able to benefit from the huge cost savings that are related with the application of these technologies in a couple of decades. Furthermore, as long as external environmental effects are not completely internalized, the usage of fossil fuels appears to be cheaper than justified.

An optimal strategy therefore has to combine two complementary approaches that address the two market failures mentioned above (externalities due to environmental pollution and the market failures associated with the innovation and diffusion of new technologies). Together these market failures provide a strong rationale (see Chapter 11) for a portfolio of public policies that foster emissions reduction (e.g. by emission trading or carbon taxes) as well as the development and deployment of environmentally beneficial technologies (e.g., by economic incentives like feed-in tariffs or direct subsidies, (Jaffe *et al.*, 2005; Montgomery and Smith, 2007; van Benthem *et al.*, 2008) .

10.5.4. Time-dependent expenditures

The most comprehensive survey on past investments in clean energy technologies is published by the United Nations Environment Programme UNEP in collaboration with New Energy Finance Ltd. on an annual basis (UNEP, 2009). The reported global new investment in sustainable energy projects include: all biomass, geothermal and wind generation projects over 1 MW, all hydroelectric projects between 0.5 and 50 MW, all solar projects over 0.3 MW, all marine energy projects, all bio-fuel projects with a capacity of 1 million liters or more per year, and all energy efficiency projects that involve financial investors.



S/RP = small/residential projects. New investment volume adjusts for re-invested equity. Total values include estimates for undisclosed deals

Source: New Energy Finance

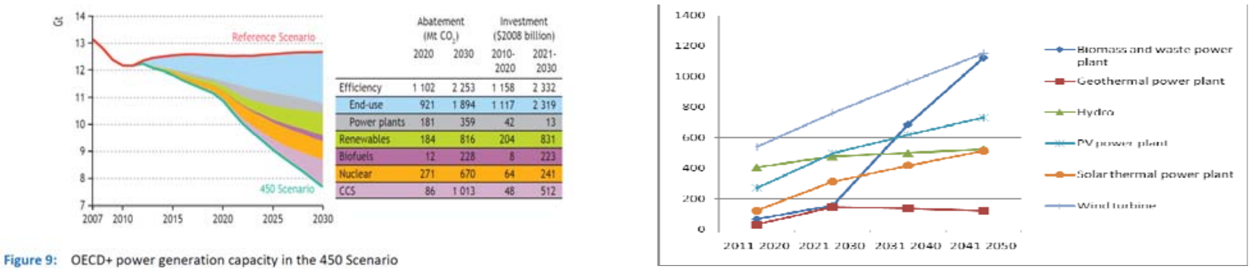
* IEA projection taking account of preliminary data for the first half of the year and the impact of fiscal stimulus packages.

Sources: New Energy Finance databases; IEA analysis.

Figure 10.5.5: a) Global new investment in sustainable energy, 2002-2008, in billion US$ (UNEP, 2009). b) Global investments in new RE-based power generation assets (International Energy Agency (IEA), 2009).

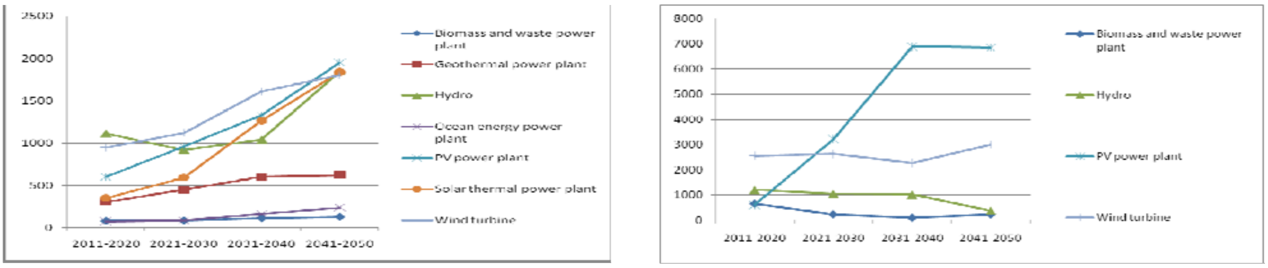
As Figure 10.5.5 clearly shows, the global RE market has shown significant growth over the last decade. Although the absolute share of RE sources in the provision of energy is still small from a global perspective, all RE (including large hydroelectric) attracted more power sector investment (~ 140 billion US$) than fossil-fuelled technologies (~ 110 billion US$) for the first time in 2008 (UNEP, 2009). Due to the financial crises, the growth in 2008 (5%/yr) was small compared to growth rates that exceeded 50%/yr in the years before.

In the following, *future* deployment cost estimates are shown for the different emission mitigation scenarios discussed in Section 10.3. As discussed before, deployment costs indicate how much money will be spent in the sector of RE sources once these scenarios materialize. The given numbers therefore are important for 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.



a) IEA WEO (450 ppmv), PLACE-HOLDER Source: IEA 2009 Copenhagen excerpt

b) MiniCam (450 ppm$_v$ CO_2-equiv., nuclear and carbon capture technologies are permitted). Source: ???



c) Energy [R]evolution (450 ppm$_v$ CO_2-equiv., nuclear and carbon capture technologies are not permitted). Source: (Greenpeace and EREC, 2008).

d) REMIND (450 ppm$_v$ CO_2, nuclear power plants and carbon capture technologies are not permitted). Compared to the other scenarios, the PV share is high as concentrating solar power has not been considered. Source: (Luderer *et al.*, 2009).

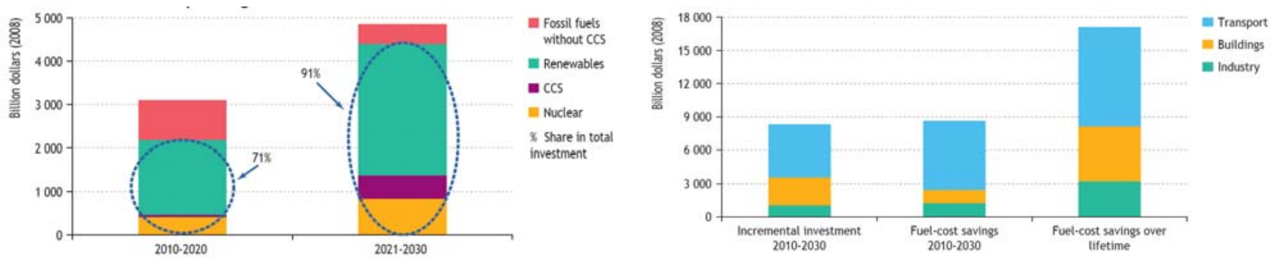
Figure 10.5.6: Illustrative global decadal investments (in billion US $2005) needed in order to achieve ambitious climate protection goals (according to different least costs and 2nd best scenarios).

Figure 10.5.6 depicts the decadal investment needs associated with RE deployment strategies that are broadly compatible with a goal to constrain global mean temperature change to less than 2 °C compared to preindustrial levels. In order to achieve this goal, CO_2 concentrations are stabilized at 450 ppm$_v$. From an investor's perspective, and depending on the technology, the given numbers indicate a future global market volume on the order of several 100 billion US$ per year.

Specific investment costs of RE sources are typically higher than those of conventional energy supply technologies. In order to assess the *additional* costs arising from using RE sources, two effects must be taken into account: Due to the so-called non-vanishing capacity credit, investing in RE sources reduces investment needs for conventional technologies (see Chapter 8). In addition, fossil fuel costs (and OMC) will be reduced as well. As a consequence, deployment costs do not indicate the actual mitigation *burden* societies face if these scenarios materialize. In calculating this burden, replaced conventional investments and avoided variable costs must be considered as well. As the latter are dependent on the development of fossil fuel prices, the overall net cost balance could be positive from a mid-term or long-term perspective (for a national study, see Winkler *et al.*, 2009).

Only a few scenarios considered in Section 10.2 provide data on the total avoided investments in conventional plants, and the overall avoided fuel costs. However, no global scenario exercise currently attributes the *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, up to now (and in contrast to emissions wedges that are quite usual nowadays), it is not standard to calculate the associated “avoided fuel cost wedges”.

Due to the lack of the aforementioned *technology specific* assessments, illustrative results of a specific scenario (IEA, 2009) will be presented here (see Figure 10.5.7b). Note that these results do not only take into account investments into RE sources. In addition, other low carbon technologies (energy efficiency improvements, nuclear energy, carbon capture and storage) are considered as well (cf. Figure 10.5.7a). Nevertheless, the results highlight the importance of comparing investment needs on the one hand and associated avoided (investment and operation) costs of the substituted technologies on the other.



Notes: The changes in power-generation investment and fuel costs are included in the electricity prices charged to the sectors shown in this graph. Costs are not discounted.

Figure 10.5.7: a) Total global investment in RE, nuclear, CCS and fossil fuels for power generation in the 450 Scenario. b) Incremental investment needs and fuel-cost savings[14] for industry, buildings and transport in the WEO 2009 450 ppm$_v$ scenario relative to the WEO 2009 reference scenario. Source: IEA, 2009 (Fig. 7.5, p. 264 and Fig. 7.15 p. 288).

Relative to the reference scenario, the global undiscounted fuel-cost savings that are associated with achieving the ambitious 450 ppm$_v$ goal amount to over 8,600 billion US$ (in the period of 2010 to 2030). Over the lifetime of the investments, the undiscounted fuel-cost savings even exceed 17 000 billion US$. The associated net savings over the lifetime are 3 600 billion US$ for a discount rate of 3% and 450 billion US$ for 10%, respectively (IEA, 2009). From a global macro-economic perspective, avoided fuel costs reduce consumer bills. As the profits of the producers are reduced as well, the “real” reduction of the burden of introducing RE sources is obviously lower than fuel cost savings might imply.

10.5.5. Market support and RDD&D

Whereas the list in 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) [AUTHORS: In Bibliograpy Jamasb 2006 – need to check which is correct] distinguishes:

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[14] Note that fuel cost saving reduce consumer expenditures. As the revenues of producer are reduced as well, fuel cost savings are not identical with “economy-wide” savings.

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

Figures 10.5.8a and 10.5.8b depict the historic 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.

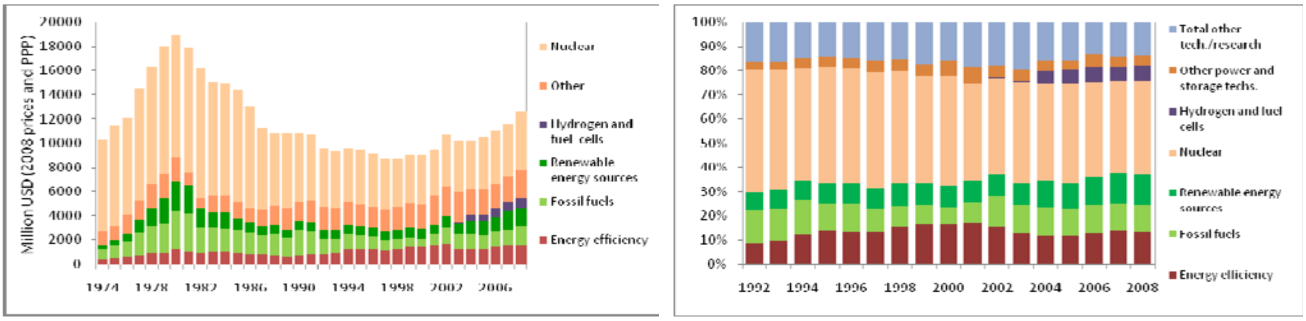

Figure 10.5.8: a) Government budgets on energy RD&D of IEA countries and b) technology shares of government energy RD&D expenditures in IEA countries (cf. (International Energy Agency (IEA), 2008b), p. 172-173, updated with data from http://wds.iea.org/WDS/ReportFolders/ReportFolders.aspx, accessed 29/09/2009).

Whereas RD&D funding is appropriate for infant technologies, market entry support and market push programs (e.g., via norms, feed-in tariff, renewable quota schemes, tax credits, bonus and malus systems) are the appropriate tools in the deployment and commercialization phase (Foxon, 2005; González, 2008). A detailed description of these programs can be found in Chapter 11.

On a global scale, comprehensive assessments on the total expenditures spent by market support programs (e.g., feed-in tariffs, direct subsidies, or tax credits) and on the additional costs that are associated with programs stipulating RE energies by other means (e.g., norms and quotas) are not available. However, the historic and future investment needs discussed in Section 10.5.4. can be used to assess at least the order of magnitude.

10.5.6. Knowledge gaps

Experience curves nowadays are used to initiate decisions that involve billions of dollars of public funding. 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). In addition, a better understanding of the processes that result in cost reductions would be extremely valuable (cf. van den Wall-Bake *et al.*, 2009). Furthermore, there is a severe lack of information which is necessary to decide whether short-term deviations from the experience curve can be attributed to supply bottlenecks, or whether they already indicate that the cost limit (in the sense of floor costs) is reached.

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, (cf. Awerbuch, 2006; Gross and Heptonstall, 2008). Although some assessments of externalities have taken place at a national level (cf., Chapter 9 and Chapter 10.6), a comprehensive global investigation and an associated costs benefit analysis is highly recommended.

In addition, as Chapter 8 shows, there is a severe lack of reliable and comprehensive assessments of the additional costs arising from integrating RE sources into existing and future energy systems (cf., Gross and Heptonstall, 2008).

10.6. Social, environmental costs and benefits [TSU: Heading lacks "(investments, variable costs, market support, RDD&D)"]

10.6.1. Background and objective

Energy production typically causes direct and indirect costs and benefits for the energy producer and for society. Energy producers for instance incur private costs, such as plant investment and operating costs, and receive private benefits, such as income from sold energy. Private costs and benefits are defined as costs or benefits accounted by the agents responsible for the activity. The operations of energy producers often cause external impacts, which may be beneficial or detrimental but which are not covered by the energy producers. The costs and benefits due to external impacts are called external costs or external benefits, correspondingly (for the definition, see Glossary). The external costs are usually indirect and they arise, for example, from pollutant emissions. The reduction of detrimental impacts caused by pollutant emissions can be seen as an external benefit when RE replaces some more detrimental energy sources. Additionally external benefits might occur if energy production and consumptions results in positive effects for the society (e.g. job creation in the energy sector). The social costs are assumed to include here both private costs and external costs (Ricci, 2009a; Ricci, 2009b), although other definitions have also been used in the past (e.g. Hohmeyer, 1992). Figure 10.6.1 below shows a possible illustrative representation of the different definitions of costs and benefits.

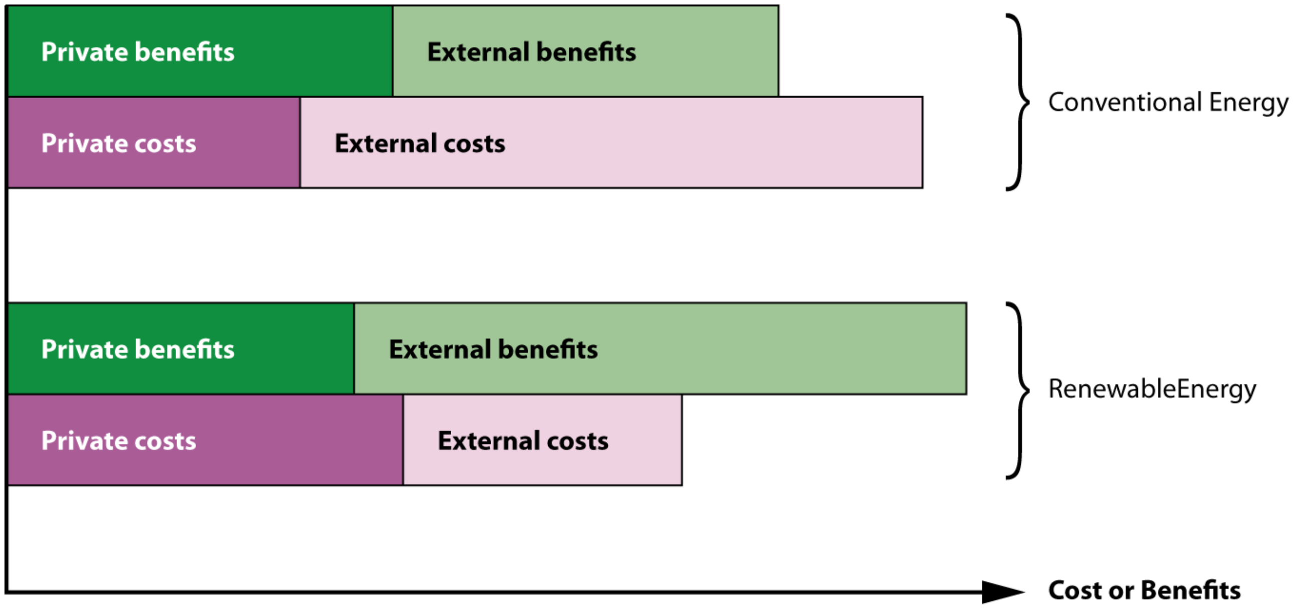

Figure 10.6.1: Simple illustrative representation of cost and benefits in the context of conventional and RE sources. [TSU: No Source]

In conventional 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. Energy derived from RE technologies on the other hand 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 conventional energy production (Owen, 2006).

Typical factors causing external costs include the atmospheric emissions of fossil-fuel-based energy production. The emissions can, among other things, consist of GHGs, acidifying emissions and particulate emissions. These types of emissions can often but not always be lowered if RE is used to replace fossil fuels (Weisser, 2007)[15]. Increasing the share of RE often contributes positively to access to energy[16], energy security and the trade balance and it limits the negative effects from fluctuating prices of fossil-based energy (Berry and Jaccard, 2001; Bolinger *et al.*, 2006; Chen *et al.*, 2007). Further, increasing RE may also contribute to external benefits, e.g. by creating jobs especially in rural areas (e.g. in the fuel supply chain of bioenergy). However, various types of RE have their own private and external costs and benefits, depending on the energy source and the technology utilised.

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 monetarisation of the impacts in general is very difficult. Especially the long time spans associated with climate change and its impacts are difficult to consider in cost-benefit analyses (Weitzman, 2007; Dietz and Stern, 2008). Further, many environmental impacts are so far not very well understood or very complex and new for people and decision-makers, and their consideration and monetary valuation is difficult. This might limit the use of cost-benefit analysis and require other approaches, such as public discussion process and direct setting of environmental targets and cost-benefit or cost-effectiveness analyses under these targets. (Krewitt, 2002; Soderholm and Sundqvist, 2003; Grubb and Newbery, 2007).

The production and use of energy can be considered from the viewpoint of sustainable development. (see Chapter 9) Sustainable development is often divided into three aspects, namely environmental, economic and social sustainability. RE often has synergistic effects with the aspects of sustainable development. However, this is not necessarily always the case. For example, biomass, if extended widely, can be controversial as an energy source because of competition on land use. The land used to produce energy crops is not available for other purposes, e.g. food production and conservation of biodiversity (Haberl *et al.*, 2007) although other references indicate that both food and fuel demand can be met in many cases at some reasonable level (Sparovek *et al.*, 2009). On the other hand, managed areas not favourable for food production may be used for some energy crops with social and environmental benefits. Futhermore, the use of biomass can result in non-negligible or even relatively high GHG emissions (through various means, like production of fertilizers, energy use for harvest and processing, N_2O-emissions from agricultural land and land use changes). If used in a non-suitable manner the land clearing for biofuel production can cause in some cases considerable emissions (“biofuel carbon debt”) the compensation of which with biofuel use replacing fossil fuel can take long time spans (Adler *et al.*, 2007; Fargione *et al.*, 2008; Searchinger *et al.*, 2008). However, it is necessary to analyze case by case, avoiding the misjudgement of general biomass production based on hypothetical case.

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[15] One has to keep in mind that in particular biomass applications can also cause particulate emissions.

[16] There are still about 1 to 2 billion people without access to energy services (IEA), the renewable energy sources due to their distributed character can at least to some extent help to alleviate this problem.

When the response to climate change is considered, RE can be linked to the changing climate in regard to both climate change mitigation and adaptation (IPCC, 2007a; IPCC, 2007b). On the other hand, climate change can have a great impact on RE production potentials and on costs. Examples include biomass, wind and hydropower. The potential of biomass depends on climate changes affecting biomass growing conditions like temperature and soil humidity, the potential of wind power depends on wind conditions, and the potential of hydro on precipitation conditions, specially in the case of run-of-river (Venäläinen *et al.*, 2004; Bates *et al.*, 2008; de Lucena *et al.*, 2009).

The greatest challenges for energy systems are guaranteeing the sufficient supply of energy at fair price and the reduction of the environmental impacts and social costs, including the mitigation of climate change. RE can markedly contribute to the response to these challenges. The understanding of these possible contributions is crucial for transformation in cost terms.

Behind that background, the objective of this Section is to make a synthesis and discuss external costs and benefits of increased RE use in relation to climate change mitigation and sustainable development. The results are presented by technology at global and regional levels. Therefore the section defines the cost categories considered and identifies quantitative estimates or qualitative assessments for costs by category type, by RE type, and as far as possible also by geographical area. (regional information is still very sparse).

This section has links to the other chapters of SRREN, such as Chapter 1 (Introduction to Renewable Energy and Climate Change) and to Chapter 9 (Renewable Energy in the Context of Sustainable Development). Parts of this section (10.6) consider the same topics, but from the viewpoints of social costs and benefits.

10.6.2. Review of studies on external costs and benefits

Energy extraction, conversion and use cause significant environmental impacts and social costs. Many environmental impacts can be lowered by reducing emissions with advanced emission control technologies (Amann, 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, too and of course should be considered if a comprehensive cost assessment is requested.

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

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

The assessment of external costs is often, however, very difficult and inaccurate. As a result, the cost-benefit analysis of some measure or policy, where the benefit arises from decreases in some environmental or external impacts, is often very contentious. On the other hand, the difference between benefits and costs can be made clear even though the concrete numbers of the cost and benefit terms are uncertain. The benefits and costs can often be distributed unevenly among stakeholders, both at present and over time. Discounting of impacts over long time-horizons is at least to some extent problematic. Also, there are usually no compensation mechanisms which could balance costs and benefits between different stakeholders. (Soderholm and Sundqvist, 2003)

10.6.2.1. Climate change

Carbon dioxide is the most important anthropogenic GHG. The growth of its concentration in the atmosphere causes the greatest share of radiative forcing (Butler, 2008). The damage due to changing climate is often described by linking carbon dioxide emissions with the social costs of their impacts, sc. social costs of carbon (SCC), which is expressed as social costs per tonne of carbon or carbon dioxide released. A number of studies have been published on this subject and on the use of SCC in decision-making. Recent studies have been made e.g. by (Anthoff, 2007; Grubb and Newbery, 2007; 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 which are very different from the ecosystems and the society found at the polluter's location. It is for this reason that, for example, the methods used by the Stern review (2006) for damage cost accounting on a global scale are criticised but they can also be seen as a choice for producing reasonable estimates for results. Besides the question about discount rate which is quite relevant considering the long term impacts of GHG emissions there is considerable uncertainty in areas such as climate sensitivity, damages due to climate change, valuation of damages and equity weighting (Watkiss and Downing, 2008).

A German study dealing with external costs uses the values of US$ 17, 90 and 350 per metric tonne of CO_2 (14, 70 and 280 €/tCO_2) for the lower limit, best guess and upper limit for SCC, respectively, referring to (Downing *et al.*, 2005; Watkiss and Downing, 2008) assess that the range of the estimated social costs of carbon values covers three orders of magnitude, which can be explained by the many different choices possible in modelling and approaches in quantifying the damages. As a benchmark lower limit for global decision-making, they give a value of about US$ 17/tCO_2 (£35/tC). They do not give any best guess or upper limit benchmark value, but recommend that further studies should be done on the basis of long-term climate change mitigation targets.

The price of carbon can also be considered from other standpoints, e.g. what price level of carbon dioxide is needed in order to limit the atmospheric concentration to a given target level, say 450 ppm_v. Emission trading gives also a price for carbon which is linked to the total allotted amount of emission. Another way is to see the social costs of carbon as an insurance for reducing the risks of climate change (Grubb and Newbery, 2007).

RE sources have usually quite low GHG emissions per produced energy unit (WEC, 2004; IPCC, 2007a; Krewitt, 2007), so the impacts through climate change and the external costs they cause are usually low. On the other hand, there can also be exceptions, e.g. in the case of fuels requiring long refining chains like transportation bio-fuels produced under unfavourable conditions (Hill *et al.*, 2006; Soimakallio *et al.*, 2009b). Land use change for increasing bio-fuel production can, in some circumstances, release carbon from soil and vegetation and in practice increase net emissions for decades or even longer time spans (Edwards *et al.*, 2008; Searchinger *et al.*, 2008), but there is not yet much empirical information on that. In some cases the organic matter at the bottom of hydro power reservoirs can cause methane emissions, which can be significant (Rosa *et al.*, 2004; dos Santos *et al.*, 2006). However in many cases no significant GHG emissions are emitted (see section 5.6 of this special report).

Increasing the use of RE sources often displaces fossil energy sources which have relatively high greenhouse gas emissions and external costs (Koljonen *et al.*, 2008). This can be seen to cause negative external costs, or positive external benefits if the whole system is considered. In other words, the positive impacts of the increase of the RE depend largely on the properties of the original energy system (Kennedy, 2005).

10.6.2.2. Health impacts due to air pollution

Combustion of both renewable fuels and fossil fuels often cause emissions of particulates and gases which have health impacts (Krewitt, 2002; Torfs *et al.*, 2007; Amann, 2008; Smith *et al.*, 2009; Committee on Health *et al.*, 2010). Exposure to smoke aerosols can be exceptionally large in traditional burning, e.g. in cooking of food in developing countries (Bailis *et al.*, 2005). Also, emissions to the environment from stacks can reach people living far from the emission sources. The exposure and the number of health impacts depend on the physical and chemical character of the particulates, their concentrations in the air, and population density (Krewitt, 2007). The exposure leads statistically to increased morbidity and mortality. The relationships between exposure and health impacts are estimated on the basis of epidemiological studies (e.g. Torfs *et al.*, 2007). The impact of increased mortality is assessed using the concept of value of life year lost. The monetary valuation can be done e.g. by using the willingness-to-pay approach.

The results depend on many assumptions in the modelling, calculations and epidemiological studies. Krewitt (2002) describes how the estimated external costs of fossil-based electricity production have changed by a factor of ten during the ExternE project period between the years 1992 and 2002. 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. On the other hand, the cost estimates have been lowered by changing the indicator for costs arising from deaths and by using new exposure-impact models. It can be argued that the results include considerable uncertainty (Torfs *et al.*, 2007).

The specific costs per tonne of emissions have been assessed in reference (Krewitt and Schlomann, 2006) to be for SO_2 about US$ 3,800 per tonne (3000€/t), for NO_x about $ 3,800 (3,000€/t), for Non-Methane VOC about $ 250 (200€/t) and for particulates PM_{10} about $ 15,000 (12,000€/t). The NMVOC emissions contribute to the formation of ground-level ozone, which has detrimental effects on health. Sulphur dioxide and nitrogen oxide emissions form sulphate and nitrate aerosols which also have detrimental health impacts.

When RE is used to replace fossil energy, the total social costs of the total energy system due to health impacts usually decrease, which can be interpreted to lead to social benefits linked to the increase of RE. However, this is not always the case as discussed in this subchapter but requires a more detailed analysis.

10.6.2.3. Impacts on waters

Thermal condensing power plants usually need water, e.g. from a river. This causes thermal loading of the river on a local scale. If the thermal load is too big, cooling towers, although more expensive than the use of river water, can be used so that the heat is discharged to the atmosphere. In terms of RE sources cooling water demand is relevant in particular for biomass combustion plants or concentrated solar thermal power plants. However, the unit size of bio-energy plants is usually small which may limit the thermal loading peaks.

Hydropower plants, especially if the water must be stored or regulated, can have detrimental impacts on fishing and other water-based livelihoods. The detrimental impacts can be lowered and mitigated (see section 5.6 of this special report) by compensating measures such as fish passes and plantations (Larinier, 1998).

The environmental and social impacts of hydropower projects vary considerably from case to case, leading to variable external costs and benefits. Environmental Impact Assessment (EIA) requirements defined in many national legislations of countries can be used as a tool for assessing the impacts on environment and society of a planned hydropower station (Wood, 2003; UNEP, 2007). The International Hydropower Association's Hydropower Sustainability Assessment Protocol and its current cross-sectional review is the leading initiative at the international level.

10.6.2.4. Impacts on land use, soil, ecosystems and biodiversity

Reservoir hydropower can have an impact on land use depending on the geographic location. In contrast, run-of-river schemes have less social and environmental impacts. Reservoirs are useful not only for hydropower projects but also for the management of fresh water systems for both potable water supply and irrigation. Thus hydropower schemes using reservoirs can have a multipurpose role. A run-of-river hydropower plant draws the energy for electricity production mainly from the available flow of the river. Such hydropower plants generally include some short-term storage, allowing for adaptations to demand and supply. The reservoirs can in some cases cover settlements, agricultural land and land used for other livelihoods as can be glimpsed from Section 5.6 of this Special Report.

The use of bio-energy can be increased by utilising residues from agriculture and forestry as well as by energy plantations. A large increase in bio-energy use, however, requires an increase in the land area designated to energy crops, resulting besides given options for using set-aside lands in competition with other activities like food, fodder and fibre production as well as with land use for biodiversity conservation and settlement. (Haberl *et al.*, 2007).

On the other hand, many residues from agriculture or forestry or even energy crop plantations, such as straw and slash, can be used to maintain or improve the quality of the soil. In contrast, excessive harvesting of forest residues for example can lower the nutrient and carbon content of the soil (Korhonen *et al.*, 2001; Palosuo, 2008).

Sulphur dioxide and nitrogen oxide emissions from energy production can also cause acidification and eutrophication of ecosystems. Air pollutants such as nitrogen dioxides and NMVOC emissions (which may result from the use of some RE options) can have impacts on the productivity of agriculture and on materials used in man-made structures. The external costs of these impacts are considerably lower than the costs of health impacts, according to Krewitt and Schlomann (2006).

10.6.2.5. Other socio-economic impacts

Benefits of energy sources include the facilitation of many services like illumination, heating and cooling of room space, food storage and cooking, the possibility to use information and communication technologies, and benefits in industries and other sources of livelihood. A secure access to energy is crucial for the functioning of modern societies and for a high standard of living. The world population is increasing (United Nations Population Division, 2008). By 2050 it is expected to be about 9 billion. There will likely be strong growth in demand for energy primarily in the developing economies.

The depletion of the limited energy reserves of fossil fuels (WEC, 2007; Similä, 2009) and bottlenecks in the energy infrastructure as well as a high centralization of resources can cause wide fluctuations in the price of energy and also risks in the availability of energy. Therefore, many countries are striving to improve energy security and promote the use of domestic energy sources. These challenges can often be responded to by increasing the share of RE (Koljonen *et al.*, 2009; Similä, 2009).

Generally, long-term measures to increase energy security focus on diversification, reducing dependence on any one source of imported energy, increasing the number of suppliers, exploiting indigenous fossil fuel or RE resources, and reducing overall demand through energy conservation. RE sources, as part of a cleaner energy mix, are growing in importance. Furthermore, RE sources cover a wide spectrum of energy sources, e.g. wind, solar, hydropower, geothermal, biomass, and ocean energy that contribute to security of energy supply.

Increasing the production and use of RE creates jobs in R&D and manufacturing (Monni *et al.*, 2002; Bundesministerium fuer Umwelt Naturschutz und Reaktorsicherheit (BMU), 2006). The supply of bioenergy fuels has also important role in the creation of jobs. The supply of local and domestic energy also has an impact on the economy of the area and even the country and its trade balance (Berry and Jaccard, 2001; Bergmann *et al.*, 2006; Lehr *et al.*, 2008). Moreover there is not only a possible employment effect due to the production process of RE sources, but a general possibility that access to energy and in particular RE enables the creation of new jobs especially in rural areas (e.g. business opportunities in small scale commercial applications).

On the other hand, the number of new jobs associated with some RE technologies can be quite small after the construction period. And the changes in energy system can result in loss of jobs in the fossil sector and in loss of jobs in the overall economy due to the effects of higher energy prices on other parts of the economy (Soimakallio *et al.*, 2009a). However, the net impact on jobs is often positive under a variety of circumstances, especially if export of technologies is accounted (Lehr *et al.*, 2008).

The biggest impacts of RE sources on the built environment (on landscape aspects) might be caused by wind power, hydro dams and large biomass plantations which may even have an impact on property prices in the neighbourhood. The production units for RE are mostly small and quite discrete, except for wind turbines and possibly some constructions needed for big hydropower plants (in the future maybe as well for centralized photovoltaics plants and solar thermal plants). Older wind power plants may also cause some noise in their vicinity. On the other hand, wind power can offer some positive image values (Moller, 2006). Biomass plantations might not be as visible from far away as wind mills are, but they require a large amount of land and are often in the form of monocultures, and can lead to negative impacts on biodiversity if not properly planned.

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 *et al.*, 2010; Kusiima and Powers, 2010) and Europe (Groscurth *et al.*, 2000; Bergmann *et al.*, 2006; Krewitt and Schlomann, 2006; Ricci, 2009b), while some are more general without a specific geographical area.

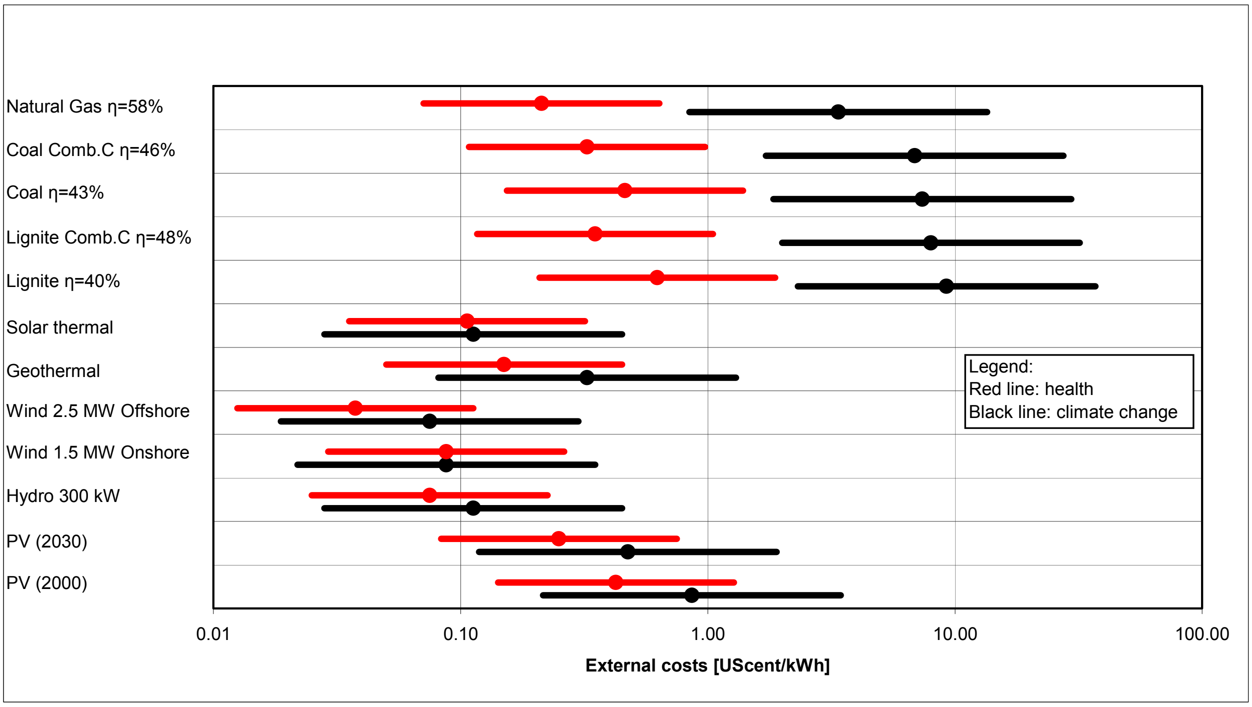
Some studies consider developing countries, especially Brazil. Da Costa *et al.* (2007) discuss social features of energy production and use in Brazil. Fearnside (1999; 2005) and Oliveira & Rosa (2003) study big hydropower projects and the energy potential of wastes in Brazil, respectively. Sparovek *et al*. (2009) investigate the impacts of the extension of sugar cane production in Brazil. Bailis *et al.* (2005) consider biomass- and petroleum-based domestic energy scenarios in Africa and their impacts on mortality on the basis of particulate emissions. Spalding-Fecher and Matibe (2003) study total external costs of coal-fired power generation in South Africa. Amann (2008) study cost-effective emission reduction of air pollutants and greenhouse gas emissions in China.

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

Table 10.6.1: External costs (US cents/kWh) due to electricity production based on renewable energy sources and fossil energy. Valuation of climate change is based on an SCC value of 90 $/tCO_2$. (Krewitt and Schlomann, 2006).

	PV (2000)	PV (2030)	Hydro 300 kW	Wind 1,5 MW Onshore	Wind 2,5 MW Offshore	Geothermal	Solar thermal	Lignite η=40%	Lignite Comb.C η=48%	Coal η=43%	Coal Comp.C η=46%	Natural Gas η=58%
Climate change	0.86	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	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
Geopolitical effects	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
	~1.3	~0.74	~0.19	~0.18	~0.12	~0.49	~0.22	>9.9	>8.4	>7.9	>7.2	>3.6

🟢 ”green light”: no important impacts
🟡 ”yellow”: some impacts arise
🔴 ”red light”: important impacts in conflict with sustainability
Comb.C: combined gas turbine and steam cycles



Comb.C: Combined gas turbine and steam cycles

Figure 10.6.2: Illustration of external costs due to electricity production based on RE and fossil energy. Note the logarithmic scale of the figure! The black lines in dictate the external cost due to climate change and the red lines indicate the external costs due to health effects. External costs due to climate change dominate in fossil energy. Valuation of external costs due to climate change is based on the SCC value of 90 $/tCO_2$ and its lower limit of 17 and upper limit of 350 $/tCO_2$. The uncertainty for the external costs of health impacts is assumed to be a factor of three (Based on Krewitt & Schlomann 2006; Krewitt 2002. Typical household consumer price of electricity varied in 2008 e.g. in EU countries from 7 (Bulgaria) to 19 (Ireland) US cents per kilowatt-hour (Eurostat 2009).

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 life-cycle approach for each technology in the conditions typical for that technology so that only the direct impacts of that technology are taken into account (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 of external costs can be seen as external benefits of the RE technologies for the society (Kennedy, 2005; Loulou *et al.*, 2005; Koljonen *et al.*, 2009).

An assessment of external costs in Central European conditions is presented in Table 10.6.1 (Krewitt & Schlomannn, 2006) and in Figure 10.6.2. It can be seen that the social costs due to climate change and health impacts dominate in the results in Table 10.6.1. The other impacts make a lesser contribution to the final results having in mind that not all impacts are quantifiable. Even if a lower value of social costs of carbon of \$17/tCO_2 is used in Table 10.6.1 instead of \$90 /tCO_2, the climate impact still dominates in the total social costs of fossil-based technologies, but for renewable technologies the health impacts would be dominant. Figure 10.6-2 show the large uncertainty ranges of two dominant external cost components of Table 10.6.1, namely climate related and health related external costs. A recent extensive study made for the conditions in USA (Committee on Health *et al.*, 2010) arrives at almost similar results than Krewitt & Schlomann (2006) for natural gas based electricity production but clearly higher external cost level for coal based production due to higher non-climate impacts. Other external costs due to energy security and geopolitical concerns are not covered by the study but depend e.g. on geographic area and available domestic resources.

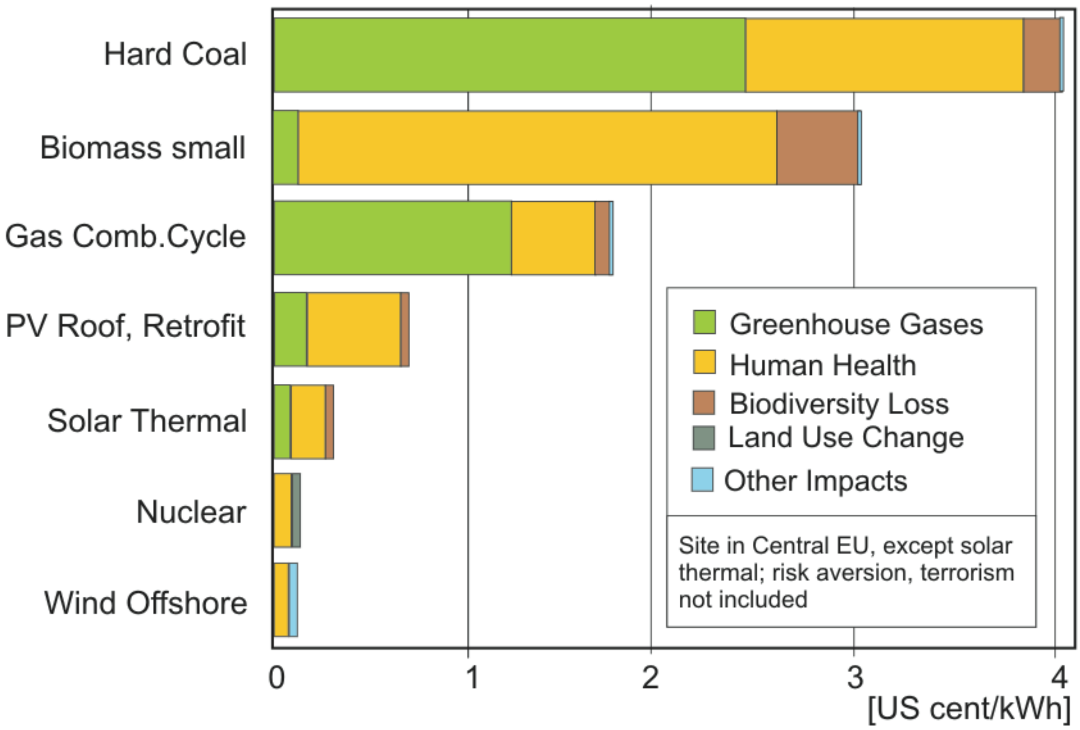


Figure 10.6.3: Quantifiable external costs for some electricity generating technologies. Estimation of external impacts and their valuation include considerable uncertainties and variability(Ricci, 2009a; Ricci, 2009b).

Results of an other study in Figure 10.6.3 show somewhat lower external costs for different technologies (Ricci, 2009a; Ricci, 2009b) than shown in Table 10.6.1. However, the results are within the uncertainty ranges given in Figure 10.6.4. Small scale biomass fired CHP plant

considered in the study causes relatively high external costs due to health effects via particulate emissions, however, inexpensive technical solutions can lower particulate emissions considerably in plants of moderate size classes. Nuclear energy and offshore wind energy cause smallest external cost in this study. The nuclear alternative does not include external cost impacts due to proliferation nor due to risks due to terrorism. Inclusion of these impacts could raise the external cost level of nuclear power.
As only costs of individual technologies are shown in Table 10.6.1 and Figures 10.6.2 and 10.6.3, benefits can be derived when assuming that one technology replaces another one. RE sources and the technologies using them have mostly lower external costs per produced energy than fossil-based technologies. However, case-specific considerations are needed as there can also be exceptions.

When the share of RE sources is increased in the energy system and when the use of fossil energy is decreasing, the external costs of the energy system per unit of energy usually decrease and the external benefits increase.

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 carry out Environmental Impacts Assessment (EIA) studies on RE projects in consideration in order to be sure that sufficient requirements for the implementation of the projects are met.

10.6.4. Synergistic strategies for limiting damages and social costs

Many environmental impacts and external costs follow from the use of energy sources and energy technologies that cause greenhouse gas emissions, particulate emissions and acidifying emissions – fossil fuel combustion being a prime example. Therefore, it is quite natural to consider the reduction of the impacts due to emissions with combined strategies (Amann, 2008)(Bollen et al., 2009) [AUTHORS: Reference missing in bibliography, only Bollen 2007 in bibliography].

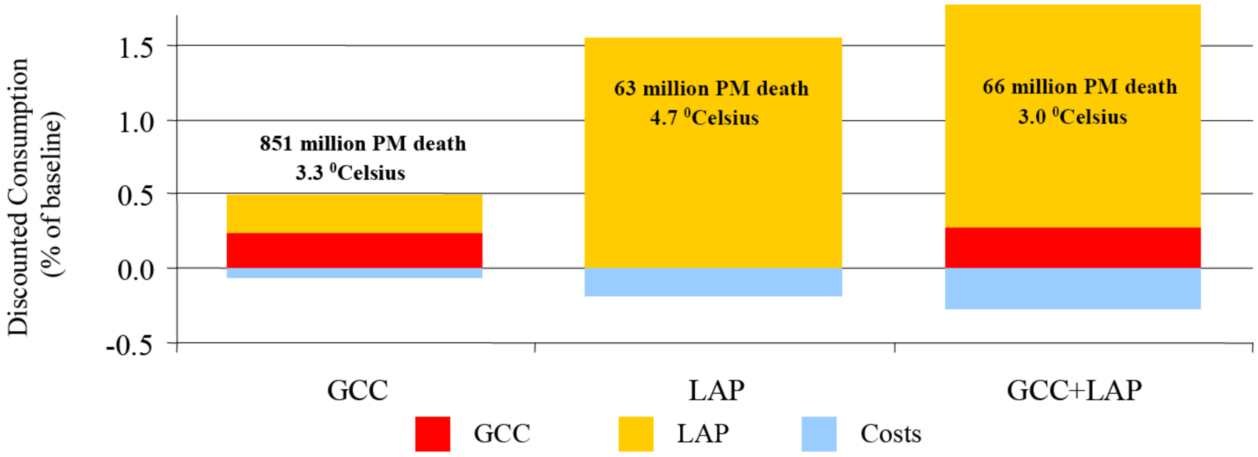


Figure 10.6.4: Changes in costs, benefits and global welfare for three scenarios (GCC, LAP, GCC+LAP), expressed as percentage consumption change (welfare increase) in comparison to the baseline. In the scenario GCC the social costs of Global Climate Change (GCC) have been internalised, in the scenario LAP the social costs of Local Air Pollutants (LAP) have been internalised, and in the scenario GCC+LAP both social cost components have been internalised. For each scenario the number of deaths due to particulate matter (PM) emissions and temperature rise due to greenhouse gas emissions is shown in the Figure. In the baseline the number of particulate matter (PM) deaths due to air pollutants would be 1000 million and the temperature rise 4.8 C.

Bollen et al. (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 internalised. According to the study (Figure 10.6.4), the external benefits were greatest when both external cost types were internalised, although the mitigation costs were high as they work in a shorter time frame. The discounted benefits from the control of particulate emissions are clearly larger than the discounted benefits from the mitigation of climate change. The difference is, according to a sensitivity study, mostly greater by at least a factor of two, but of course depends on the specific assumptions (in particular on the discount rate chosen). The countries would therefore benefit from combined strategies quite rapidly due to reduced external costs stemming from the reduced air pollution health impacts.

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

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

10.6.5. Knowledge gaps

There are considerable uncertainties in the assessment and valuation of external impacts of energy sources. The assessment of physical, biological and health damages includes considerable uncertainty estimates based typically on calculational models, the results of which are often difficult to validate. The damages or changes have seldom market values which could be used in cost estimation but indirect information or other approaches must be used for damage valuation. Further, many of the damages will take place far in the future which complicates the considerations. All these factors contribute to the uncertainty of external costs.

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Box 10.2. Moving Beyond Top-Down vs. Bottom-Up?

In previous IPCC reports (e.g. Herzog et al., 2005; Barker et al., 2007)) quantitative scenario modelling approaches were broadly separated into two groups: top-down and bottom-up. 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 aspects from 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: they are 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). On the other hand, the interpretation of both terms depends on the aggregation level that is typically addressed by the respective scientific community. In the energy-economic modelling community, macro-economic approaches are traditionally classified as top-down models and energy-engineering models as bottom-up. However, in engineering sciences, even the more detailed energy-engineering models that represent individual technologies such as power plants, but essentially treat them as “black boxes”, are characterized as top-down models as opposed to a component-based view which is considered to be bottom-up.

Box 10.3 Storylines of the four illustrative scenarios

IEA WEO 2009: This scenario is a typical baseline scenario or Business-as-usual approach. As such, it calculates the possible energy pathway without any substantial change in government policy (IEA WEO 2009, p 44) and under the assumption of a moderate fossil fuel cost raise. The WEO 2009 baseline does not include specific GHG emissions targets. 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 which was provides by the German Aerospace Agency (DLR) by extrapolating the key macroeconomic and energy indicators of WEO 2009 forward to 2050 (Publication filed in June 2010 to Energy Policy).

ReMind-Recipe: This scenario describes a mitigation path aiming at a stabilization of atmospheric CO_2 concentrations at 450 ppm. 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 (optimal timing of emission reductions) and what-flexibility (cost-optimal technology choice). Another crucial assumption is perfect foresight: Investment decisions fully account for future changes of prices and technology developments. Due to its idealized assumptions, it can be regarded as a benchmark scenario of future developments under perfect institutional settings. ReMIND accounts for a variety of renewable energy sources (wind, solar, biomass, hydro, geothermal) and conversion technologies. Wind power and solar photovoltaic are parameterized as learning technologies. RETs can be deployed at industrial scale at optimal sites and transported within world regions (up to continental scale) to demand centers, whereby the model implicitly assumes that bottlenecks, e.g. with respect to grid infrastructure, are avoided by early and anticipatory planning. (according to Luderer *et al.*, 2009)

EMF 22: The MiniCAM EMF 22 scenario was developed as part of Energy Modelling Forum study 22, looking at possible approaches to long-term climate goals. The scenario was generated using the MiniCAM integrated assessment model, the precursor to the GCAM integrated assessment model. The scenario is an overshoot scenario that reaches 450 ppmv CO_2-e (Kyoto gases) by 2100, after peaking at 525 ppmv CO_2-e (Kyoto gases) in 2050, and assuming full international participation in emissions reductions. 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 people in 2100; a transition in economic production, and the preponderance of associated CO_2 emissions, from the developed regions to the developing regions; and the availability of a wide range of energy supply options, including major renewable energies, nuclear power, and both fossil energy and bioenergy equipped with carbon capture and storage (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. (according to Clarke *et al.*, 2009)

Energy [R]evolution 2010: The ER 2010 (Greenpeace and EREC, 2010; Teske *et al.*, 2010) is based on the socio-economic assumptions of the IEA WEO 2009, but projects increase fossil fuel costs and a price for carbon from 2010 onwards. The scenario has a key target to reduce worldwide carbon dioxide emissions down to a level of around 3.5 Gt per year by 2050. To achieve its targets, the scenario is characterised 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 of the renewable energy industry have been taken into account. To accelerate the market penetration of RE, various additional measures have been assumed. For instance a speedier introduction of electric vehicles, combined with the implementation of smart grids and faster expansion of super grids shall allow a higher share of fluctuating renewable power generation (photovoltaic and wind) to be employed.