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The role of renewable energy in climate stabilization: results from the EMF27 scenarios

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Abstract

This paper uses the EMF27 scenarios to explore the role of renewable energy (RE) in climate change mitigation. Currently RE supply almost 20% of global electricity demand. Almost all EMF27 mitigation scenarios show a strong increase in renewable power production, with a substantial ramp-up of wind and solar power deployment. In many scenarios, renewables are the most important long-term mitigation option for power supply. Wind energy is competitive even without climate policy, whereas the prospects of solar photovoltaics (PV) are highly contingent on the ambitiousness of climate policy. Bioenergy is an important and versatile energy carrier; however—with the exception of low temperature heat—there is less scope for renewables other than biomass for non-electric energy supply.

Despite the important role of wind and solar power in climate change mitigation scenarios with full technology availability, limiting their deployment has a relatively small effect on mitigation costs, if nuclear and carbon capture and storage (CCS) - which can serve as substitutes in low-carbon power supply - are available. Limited bioenergy availability in combination with limited wind and solar power by contrast, results in a more substantial increase in mitigation costs.

While a number of robust insights emerge, the results on renewable energy deployment levels vary considerably across the models. An in-depth analysis of a subset of EMF27 reveals substantial differences in modeling approaches and parameter assumptions. To a certain degree, differences in model results can be attributed to different assumptions about technology costs, resource potentials and systems integration.

1 Introduction

There are multiple technological options for reducing greenhouse gas (GHG) emissions from the energy system. Besides renewable energy sources (RES), nuclear energy and carbon capture and storage (CCS) are important supply-side mitigation options. RES are often praised as the most sustainable source of energy for two reasons. First, RES are, in principle, carbon-free. There are no direct CO_2 emissions associated with the deployment of non-biomass RES. With a few exceptions, e.g. some forms of bioenergy production, life-cycle GHG emissions of RES are much lower than those caused by fossil fuels, even when all the stages of production are accounted for (Sathaye et al. 2011). Second, the defining feature of renewables is that their resource potential does not deplete over time. Moreover, the combined resource potential of all renewables exceeds the current energy demand by at least one order of magnitude (IPCC 2011). Given the constraints on fossil and nuclear fuel availability, and the limited social acceptance of nuclear waste and CO_2 storage, it seems likely that RES will become increasingly important in the long-term, even if climate policies remain weak. On the other hand, future RES deployment may be limited by (a) the competition with other sources of energy, (b) currently high costs, (c) regional heterogeneity of resources (combined with limited transportability) and (d) systems integration challenges. Since there are more options for producing renewable electricity than non-electric energy, the RES contribution to climate change mitigation will also depend on the degree to which end-uses can be electrified, for instance by introducing electric vehicles. A recent IPCC Report provided already a comprehensive overview of the state of scientific knowledge on RES (IPCC 2011) by assessing, inter alia, resource potential, technology development, deployment costs, and potential future deployment levels. A recent meta-assessment of the role of RES in model based climate mitigation scenarios performed for the SRREN (Krey and Clarke 2011) showed a strong expansion of renewable energy (RE) technologies in many scenarios as well as large differences across models.

The EMF27 study (Kriegler et al. 2013) provides a unique framework to further improve our understanding of the role of RES in climate change mitigation. It features a large set of scenarios with harmonized technology assumptions based on a wide ensemble of structurally different, state-of-the art energy-economy-climate and integrated assessment models (IAMs). The goal of this paper is to explore how renewable energy futures depends on climate policy, technology availability and model-specific assumptions. More specifically, we aim to answer the following research questions: (1) What RES deployment levels are consistent with various stabilization levels, and what are the roles of different RES technologies? (2) How can RES contribute to electric and non-electric energy supplies? (3) How does the availability of RES affect the cost and achievability of climate targets, and can ambitious climate targets be achieved through RE and energy efficiency alone? (4) What are the key model assumptions and uncertainties affecting RE deployment levels in mitigation scenarios?

The overview paper (Kriegler et al. 2013) provides a full description of the EMF27 scenario design. This paper focuses on the following technology variations:

- ***FullTech:*** Default case with full technological availability
- ***LimSW:*** Share of electricity production from wind and solar limited to 20%, and pessimistic assumptions regarding cost reductions of these energy sources, reflecting technical, economic and

institutional challenges associated with the expansion of variable and uncertain electricity generation.
- ***LimBio:*** Primary energy supply from modern biomass limited to 100 EJ/yr, reflecting sustainability concerns about strong expansion bioenergy production.
- ***Conv:*** Share of electricity production from wind and solar limited to 20%, and primary energy supply from modern biomass limited to 100 EJ/yr (focus on conventional supply-side options).
- ***EERE:*** Unavailability of CCS, nuclear phase-out, and higher autonomous energy intensity improvement (30–45% lower baseline final energy demand in 2100 compared to the other scenarios).

Each of these technology variations consider scenarios where atmospheric GHG concentrations are limited to 450 ppm CO_2e by 2100 (temporary overshooting allowed), stabilize at 550 ppm CO_2e (no overshoot allowed), or no climate policy is implemented (baseline).

2 RE deployment pathways

The EMF27 models differ significantly in their representations of RES. First, they include different RE technologies. Table S2.1 in the supplementary material (SM) provides a detailed overview of the RE technologies represented in the models. While some models describe RE technologies with a high level of detail, e.g., by distinguishing between different solar and wind power technologies (TIAM-WORLD, MESSAGE, POLES, GCAM), other models with a stronger macro-economic focus only represent a few generic types of technology. In general, the models represent a wider variety of renewable options in the electricity sector than in the non-electric sector. Second, the models differ in terms of their methodological approaches and parameter assumptions. Differences related to renewable resource potentials, cost assumptions, and the representation of systems integration are particularly relevant. It is important to keep these differences in mind when comparing scenario results.

We find that (a) there is significant scope for an increasing role of RES even in the absence of climate policies, (b) the contribution of RES to energy supply increases strongly with climate policy stringency, (c) there is greater scope for RES use in power supply than in the supply of non-electric energy, and (d) that RE deployment varies considerably across models (Fig. 1a,b). The remainder of this section reviews the renewable energy deployment levels in the EMF27 scenarios without technology constraints and compares these deployment levels to the potentials provided in the literature. Section 3 analyses how RES contribute to electric and non-electric energy supply in various climate change mitigation scenarios. Section 4 examines the relationship between model assumptions and deployment levels for a subset of EMF27 models.

2.1 Wind power

In 2010, wind turbines produced 1.23 EJ, or 1.6% of global electricity generation (IEA 2012). The resource potential of wind power is large and uncertain, with several studies citing 70–450 EJ/yr (Wiser et al. 2011; Rogner et al. 2012; Turkenburg et al. 2012) as the practical potential and as much as 5700 EJ/yr as the technical potential (GEA).[1] The growth in deployment of wind power in the *Base FullTech* scenario is significant (Fig. 1c), with most models showing an increase of 5–6% per year throughout the century. In most models, climate policy results in an acceleration of wind deployment. Six models represent offshore wind power explicitly, and project that its share in total wind power production will increase with increasing wind deployment (Fig S2.2 in the SM).

2.2 Solar Power

Although deployment of solar power has shown annual growth rates of almost 40% over the last ten years, the current deployment level is still very small, supplying only 0.11EJ/yr of electricity in 2010 (IEA). By contrast, the technical potential for solar power is enormous. (Turkenburg et al. 2012) estimate the global technical potential for photovoltaics (PV) to range from 1,600–50,000 EJ/yr. Similarly, (Arvizu et al. 2011) estimate a technical potential of 1,338–14,778 EJ/yr for PV and a technical potential of 248–10,791 EJ/yr for concentrating solar power (CSP). Solar power production varies significantly across the models, ranging from 0-17 EJ/yr in 2050 in the baseline and 0-53 EJ/yr in the 450 FullTech scenario (Fig. 1d). While in some models solar power becomes competitive even without climate policies due to technological progress and increasing scarcity of fossil fuels, power supply remains largely based on fossils in other models. Most of the models that represent that level of technology detail project that the share of CSP in solar power increases with increasing total solar deployment (Fig S2.2 in the SM). Climate policy increases solar power generation in most of the models, often substantially. With stringent climate policies in place, solar power assumes a dominant share of electricity production in the 2nd half of the century in some models (MESSAGE, REMIND, TIAM-WORLD).

2.3 Hydropower

Hydro electricity is currently the most significant non-biomass renewable energy source, supplying 12.7 EJ/yr or 16% of the world’s electricity in 2010 (IEA 2012). However, the technical potential for hydropower is limited to 50–60 EJ/yr (Kumar et al. 2011; Rogner et al. 2012; Turkenburg et al. 2012). As a result, growth in the deployment of hydropower is modest in most models, with climate policies resulting in a moderate increase of relative to baseline levels (Fig. 1e).

2.4 Bioenergy

The global consumption of bioenergy, including traditional biomass, was 53 EJ/yr in 2010, which accounts for more than 10% of total primary energy (IEA). However, bioenergy use is currently dominated by traditional fuel use with low final to useful efficiency. The technical potential for

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[1] Wiser et al. (2011) does not use the “practical” and “technical” distinction. Instead, the authors compare potential with “limited constraints” and “more constraints”. They estimate 70-450 EJ/yr with more constraints and 70-3050 EJ/yr with limited constraints.

bioenergy in 2050, as estimated by SRREN, is 50–1000 EJ/yr (Chum et al. 2011). Bioenergy is unique for two reasons: (1) its versatility (it can be used to produce liquids, electricity, hydrogen, gases, or heat) and (2) the possibility to create negative emissions when combined with CCS. The future role of biomass to supply modern forms of energy varies significantly across the models and scenarios in the EMF27 study (Fig. 1f and S2.1). In most models, bioenergy is predominantly used for the generation of liquid fuels and electricity. A limited number of models consider heat or gas produced from bioenergy, and often find substantial deployment potentials. Rose et al. (2013) provide an in-depth discussion of bioenergy use in the EMF27 scenarios.

2.5 Other forms of RE use

In addition to wind and solar power, hydro-power and biomass RES can be harvested in a variety of ways. Geothermal energy can be used to produce electricity. However, in those EMF27 models that represent geothermal power production deployment remains relatively small (7 EJ or lower in *FullTech 450*). Aside from biomass, geothermal and solar energy can provide heat. Deployment is substantial in climate policy cases in the few models that represent these technologies, suggesting that they could be of strategic importance for reducing emissions from the buildings sector. SM2.2 provides a more detailed discussion of geothermal power, geothermal heat and solar heat.

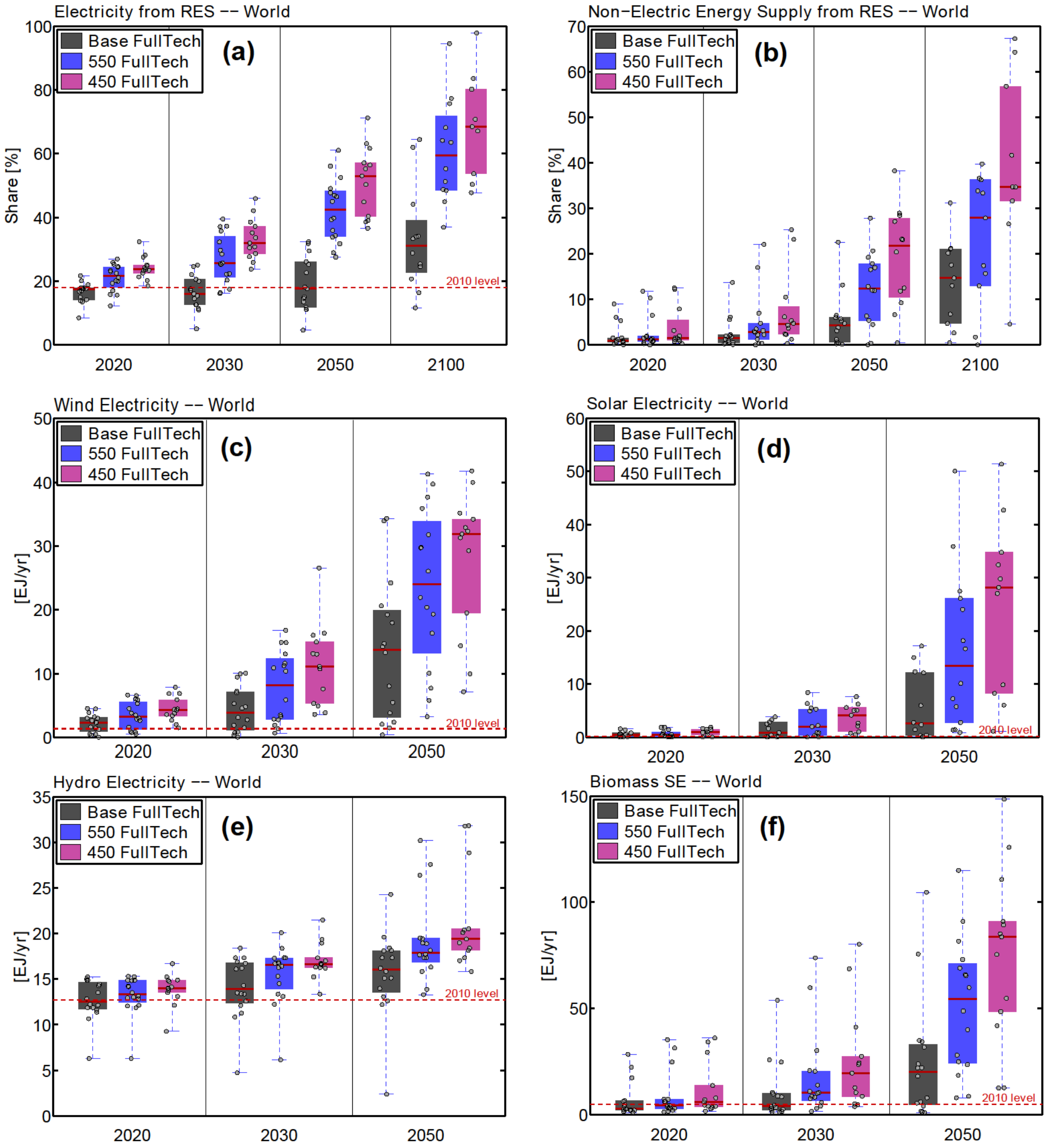


Figure 1. Secondary energy supply from various RE technology groups in the *Base, 550* and *450 FullTech* scenarios. Red dashed lines indicate 2010 deployment levels based on IEA (2012). Boxes represent 25th-75th percentiles, the red line the median, whiskers the full range of results.

3 The relevance of RES for mitigation

This section considers the energy system from a broader perspective in order to examine the relevance of RES for mitigation. The EMF27 scenarios allow us to study how RE deployment levels change with alternative technology assumptions, and how they substitute with alternative energy supply technologies and climate mitigation options. We focus on the 550 ppm climate target because more models report results for technology-constrained scenarios for this stabilization level. By exploring RE deployment for electric and non-electric energy, we analyze in which areas what types of RES contribute most.

3.1 The role of RES in energy supply

The analysis of electricity supplies indicate that renewables can play an important or even dominant role in electricity generation if climate policies are in place. For the *550 FullTech* scenario, the inter-quartile range of RE shares in electricity production is 35-48% in 2050, and 48-68% in 2100 (Fig. 1a). Section 4.3 discusses the treatment of systems integration challenges in such scenarios with high shares of variable and uncertain power generation. Models with high overall RE deployment in the power supply, such as REMIND, MESSAGE, TIAM-WORLD and AIM-Enduse tend to have particularly large shares of solar and wind power, while the contribution of hydropower is more comparable across models (Fig 2a). This is not surprising since the limitations on resource potential are less constraining for solar and wind power than for hydropower. In the scenarios where bioenergy is used for electricity generation, it is mostly deployed with CCS in order to produce net negative emissions. Other models feature limited bioenergy use in the electricity sector. This is often driven by the high value of bioenergy for biofuel production.

Fig. 2b shows the conversion pathways for non-electric secondary energy sources. In contrast to electricity, non-electric energy remains dominated by fossil fuels even if climate policies are in place. Biomass is the most important supply-side mitigation option for non-electric energy. It is primarily used to produce liquid biofuel as a substitute for oil. In models that consider liquid biofuel production with and without CCS (GCAM, MESSAGE, REMIND, TIAM-WORLD), production processes with CCS dominate over conversion pathways without CCS in the long-term. Solar-thermal and geo-thermal heating systems are potentially the most relevant non-biomass renewable options for the buildings sector. As pointed out in Section 2.5, only a few EMF27 models consider these options. While deployment can be substantial for individual technologies, non-biomass renewables represent a very small share of non-electric energy sources across all EMF27 scenarios.

Given ample opportunities to produce electricity from non-biomass renewables, their overall climate mitigation potential depends critically on the scope of electrification of end use. A larger portion of end uses become electrified in low stabilization scenarios, cf. also Krey et al. (2013). In some models, electricity use under climate policy even exceeds baseline levels (cf. also Fig. 2a).

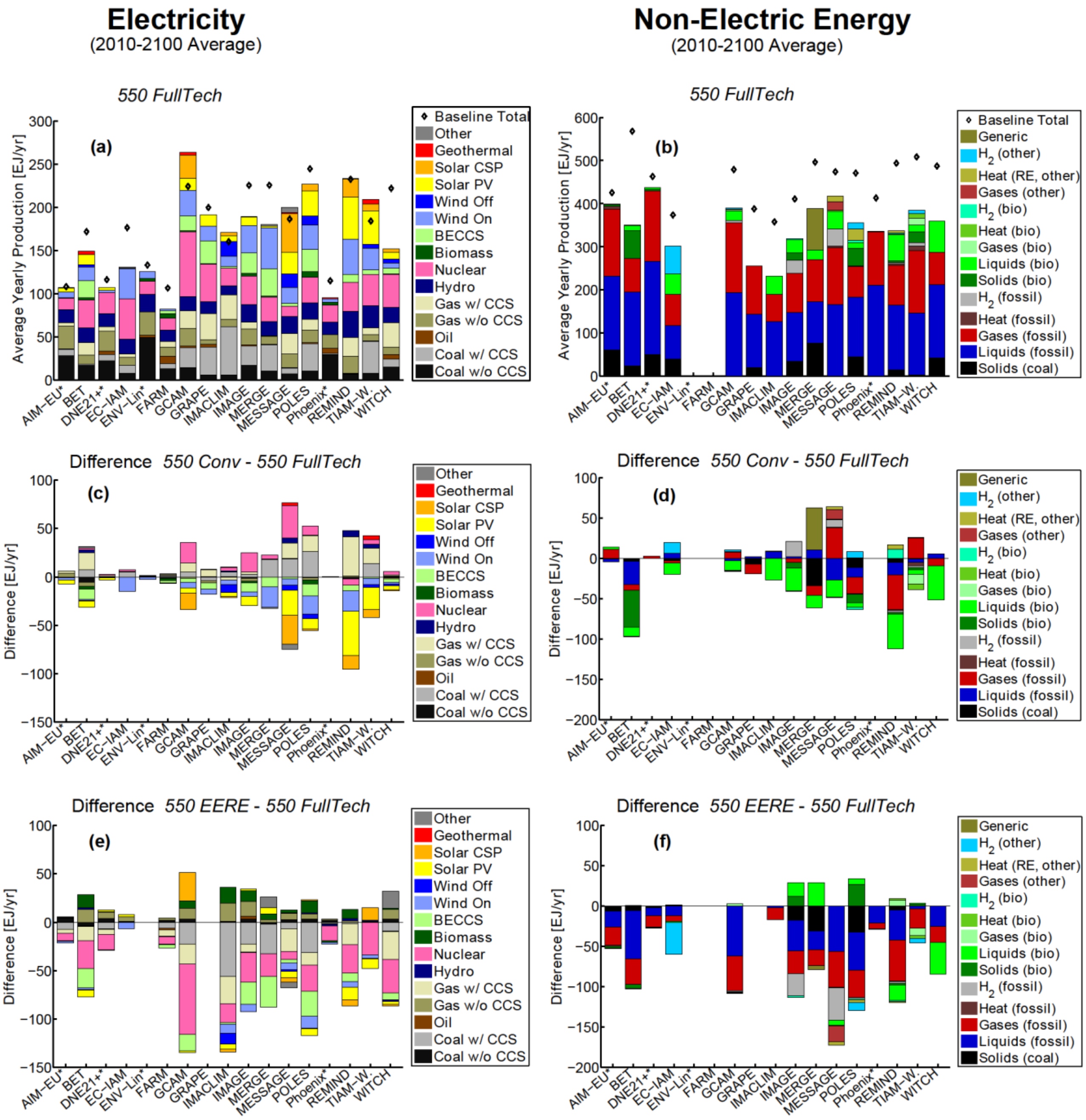
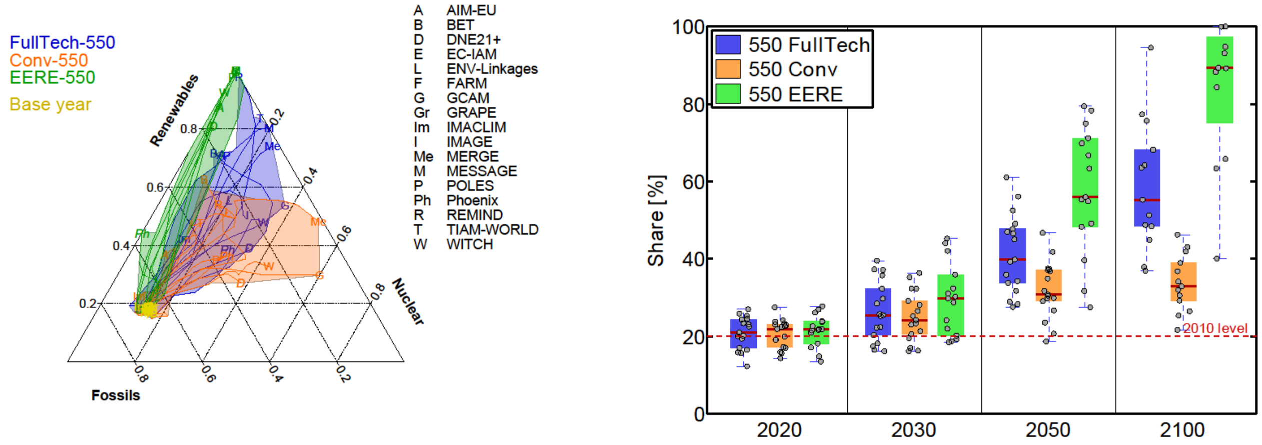


Figure 2. Yearly electricity (left column) and non-electric secondary energy production (right column) averaged from 2010–2100 for the *550 FullTech* scenarios (a,b), as well as differences of *550 Conv* to *550 FullTech* (c,d) and *550 EERE* to *550 FullTech* (e,f)*.* The diamond markers indicate totals in the *Base FullTech* scenarios. *For AIM-EU, DNE21+, and ENV-Linkages, we used the 2010–2050 time span.

(a) Relative contributions to electricity production **(b)** RES shares in electricity production



(c) Relative contributions non-electric energy **(d)** RES shares in non-electric energy

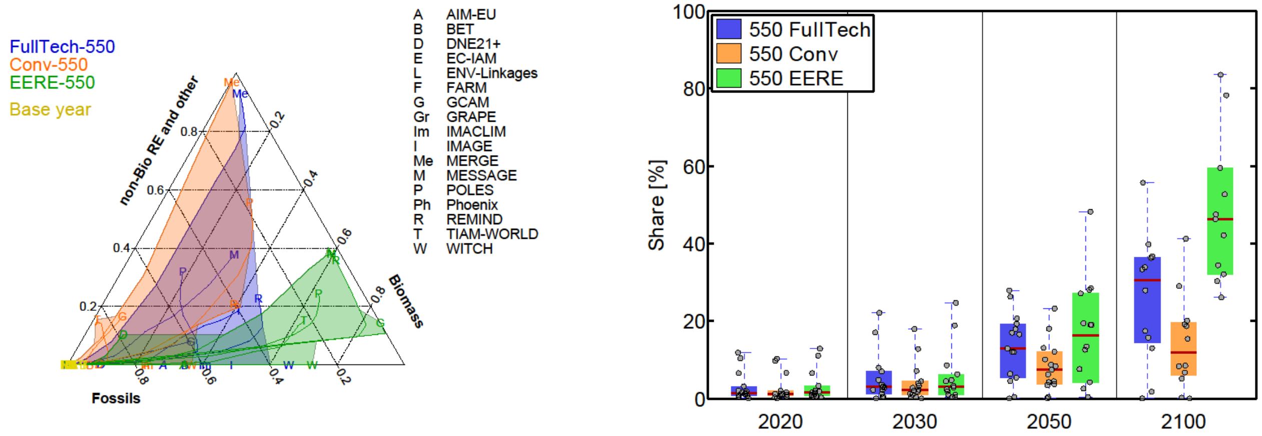


Figure 3. Shares of RES in electric (a,b) and non-electric (c,d) secondary energy supply.

3.2 Substitution between RES and other low-carbon supply options

By exploring the technology variations in the EMF27 scenario set, we can determine if the large-scale deployment of wind, solar, and bioenergy power is critical for climate change mitigation (*Conv* scenario with limited RE availability), and if mitigation targets can be reached solely relying on energy efficiency and renewables (*EERE* scenario).

In the *FullTech* climate policy scenarios, the models agree on the strong decrease of fossil-based electricity without CCS, but show a variety of decarbonization pathways (Fig. 2a and 3a,b). For some models (REMIND, MESSAGE, POLES, TIAM-WORLD), nuclear and CCS are mostly relevant in the medium-term, while power supply is dominated by RES in the long-term. In other models (WITCH, EC-IAM, IMACLIM), nuclear, RES, and CCS contribute in roughly equal shares throughout the century. Electricity supply is very responsive to the technology variations in the EMF27 scenarios. CCS, nuclear, and renewables are alternative low-carbon options that represent good substitutes in carbon-constrained scenarios. The limitations on wind, solar, and bioenergy use imposed in the *Conv* scenario result in higher deployment of CCS and nuclear (Fig. 2c, 3b). Similarly, more wind, solar, and CCS technologies are used in the nuclear phase-out scenarios (NucOff; cf. Krey et al. 2013) while more wind, solar, and nuclear use results from the unavailability of CCS (NoCCS; cf. Fig. S3.1 and Krey et al. 2013).

Limited bioenergy availability has a considerable impact on non-electric energy supply in the *Conv* scenario (Fig. 2b,e). In most models, the supply of liquids, gases and solids decreases substantially compared to the *FullTech* scenario. There are two main reasons for this pattern. First, there is a lack of non-electric low-carbon substitutes for biofuels in most models[2]. Second, bioenergy has the potential to create negative emissions via combination with CCS (BECCS; see also Rose et al., this issue). Reducing bioenergy availability results in less negative emissions, resulting in less leeway for the continued use of fossil fuels for non-electric energy.

In the *EERE* scenario, the overall energy demand is lower than in the *FullTech* scenario (Fig. 2e,f). On the other hand, with CCS and nuclear unavailable, renewables are the only long-term low-carbon options for electricity supply. As a result, the share of RES in electricity supply is generally substantially higher in *EERE* than in *FullTech*, while deployment levels in absolute terms are similar. In many models, more coal and gas without CCS are used for electricity supply, resulting in a higher share of freely emitting sources than in *FullTech*. At the same time, the lack of the BECCS option to create negative emissions decreases the cumulative fossil use that is permissible within the climate constraint. This restriction results in additional reductions in fossil fuel use for non-electric energy in the *550 EERE* scenario. Biofuels increase only slightly in absolute terms, but their share is substantially higher than in the *FullTech* scenario.

3.3 The impact of RE availability on mitigation costs

The different roles that low-carbon energy technologies play in electric and non-electric energy are important factors for explaining the impact of technology constraints on the costs and feasibility of

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[2] MERGE and EC-IAM are an important exception as they represent generic carbon-free backstop technologies for non-electric energy or hydrogen.

climate targets. Fig. 4 displays the costs of reaching the 550 and 450 ppm climate policy targets under limited technology scenarios normalized to the costs in the corresponding *FullTech* scenarios. For the *Conv* scenarios, the EMF27 models show that limited availability of wind, solar, and bioenergy results in a substantial cost increase. This finding is in line with earlier studies, which found similar cost increases by examining climate policy scenarios with restrictions on the expansion of RE (Edenhofer et al. 2010; Pugh et al. 2011; Luderer et al. 2012). The EMF scenarios allow us to separate the effects of bioenergy availability (*LimBio* scenario) from limitations on wind and solar-power use (*LimSW* scenario). The models consistently find higher cost penalties for limiting biomass than for limiting solar and wind power in both the 550 and 450 ppm climate mitigation scenarios. This is explained by the fact that in case of limitations on wind and solar power other low-carbon alternatives such as nuclear or CCS are readily available, while biomass is much harder to substitute (see discussion in Sections 2.4 and 3.2). The cost increases escalate if biomass, and wind and solar use are limited simultaneously (*Conv* scenarios).

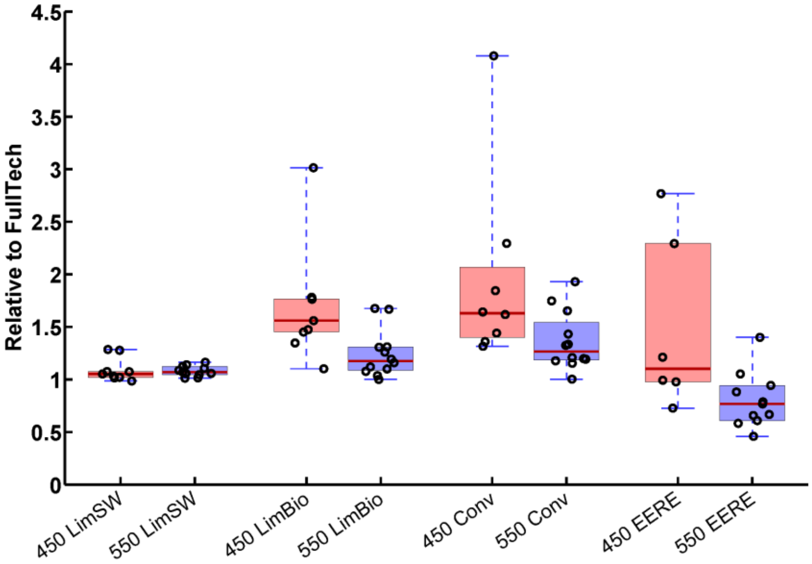


Figure 4. Climate policy costs for scenarios with reduced technology portfolios, indexed relative to the corresponding *FullTech* scenario. See Kriegler et al. (this issue) for a discussion of mitigation cost metrics.

The *EERE* scenarios, which rely solely on energy efficiency and renewables for mitigation, offer a complementary perspective on the role of renewables for climate change mitigation. In terms of policy costs, two forces are at play. On the one hand, the lower baseline energy demand results in lower baseline emissions, and thus, a smaller mitigation gap towards the climate target. On the other hand, the unavailability of CCS and nuclear makes the mitigation effort more difficult than in the *FullTech* scenarios. This explains the wide range of policy cost outcomes. In the 550-ppm case, all models except DNE21+, MERGE, and POLES show lower costs in the *EERE* scenario than in *FullTech*. In the 450-ppm scenario, the split becomes more extreme: almost half the models found the 450 ppm target infeasible in the *EERE* setting, while in most of the other models (such as WITCH and Phoenix), policy costs in the *EERE* scenario are lower than in *FullTech.*

4 Determinants of wind and solar power deployment

As noted in Section 2, the observed deployment levels of different renewable energy sources differ strongly across the models participating in EMF27. The objective of this section is to relate RE deployment levels to model assumptions and characteristics. We discuss three key determinants of deployment levels: direct economic costs, resource availability, and systems-integration constraints. While they provide valuable insights, none of these factors taken by themselves can explain the range of RE deployment results across the various models. This indicates that the relative importance of these determinants depends on model-specific assumptions and region-specific circumstances. Detailed information and data about RE parameters and assumptions are available for the seven models that participated in the EMF27 RE subgroup (DNE21+, GCAM, IMAGE, MERGE, MESSAGE, POLES and REMIND). The diagnostic analysis in this section focuses on these models and the USA and China model regions.

4.1 Technology costs and competition with other technologies

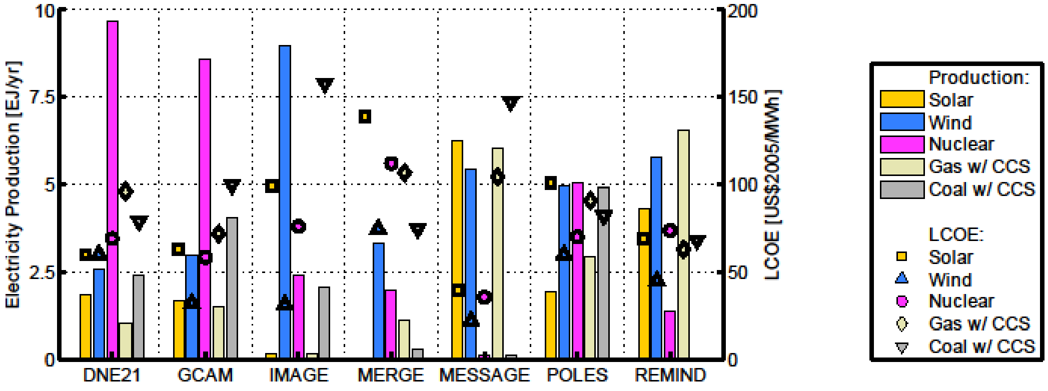
Technology choices in energy-economic models are typically the result of a cost minimizing or welfare maximizing optimization procedure, or an explicit selection based on levelized costs. Electricity generation costs of RES vis-à-vis nuclear and CCS therefore have a crucial influence on the economic deployment potential in the context of climate change mitigation. However, not only direct technology costs but also indirect factors, such as integration costs, resource potentials and other constraints represented in the models affect deployment levels.

Since no fuel costs are incurred for wind and solar power, their levelized costs of electricity generation (LCOEs) at a given location are largely driven by capital cost. Most models project capital costs in the range of 800–1400 $/kW for solar PV and 750–1000 $/kW for wind onshore in 2050 (Table S2.1). For IMAGE, capital costs for onshore wind turbines are considerably lower than in the other models, while MERGE has substantially higher costs for solar power. REMIND, IMAGE, and POLES treat technological learning endogenously, resulting in lower capital costs in the policy scenarios compared to the baseline. Figure 5 contrasts LCOE and deployment levels for solar, wind, nuclear, gas CCS, and coal CCS in the USA and China averaged over all installations in 2050 for the *450 FullTech* scenario. Deployment levels within one model roughly mirror LCOE patterns in the sense that technologies with lower LCOEs tend to be deployed at higher levels. However, average direct LCOEs are an imperfect indicator of technology use, as in several cases the order of technology deployment is not in line with relative costs. This is because direct LCOEs only account for capital costs, O&M costs, fuel costs and residual CO_2 emissions, but do not reflect other economic or physical constraints implemented in the models, such as integration costs, risk premiums or constraints on waste or CO_2 storage capacities in the case of nuclear and CCS. In addition, the LCOEs are calculated for one point in time and do not account for intertemporal effects, such as the inertia in capital turnover, or the anticipation of learning-by-doing.

By 2050, models project direct costs of wind power to be comparable or even lower than electricity production from nuclear or fossil CCS plants. For all the models except DNE21+ and MESSAGE, onshore wind power deployment is considerable in the USA and China. Solar energy tends to be more expensive than wind power. In some of the models, limitations on resource size and quality limitations are a constraint for wind deployment in China, which explains the comparatively low onshore wind deployment levels in DNE21+, IMAGE and MESSAGE (see Section 4.2).

Due to high cost assumptions, solar power is not deployed in MERGE, and remains insignificant in IMAGE. Solar power is more important in the other models, which all see more than 5 EJ/yr of electricity produced from solar technologies in China. In REMIND, which operates under perfect foresight, the anticipation of benefits from technological learning results in an earlier and higher deployment of solar PV, despite temporarily higher LCOEs.

(a) USA *450 FullTech*



(b) China *450 FullTech*

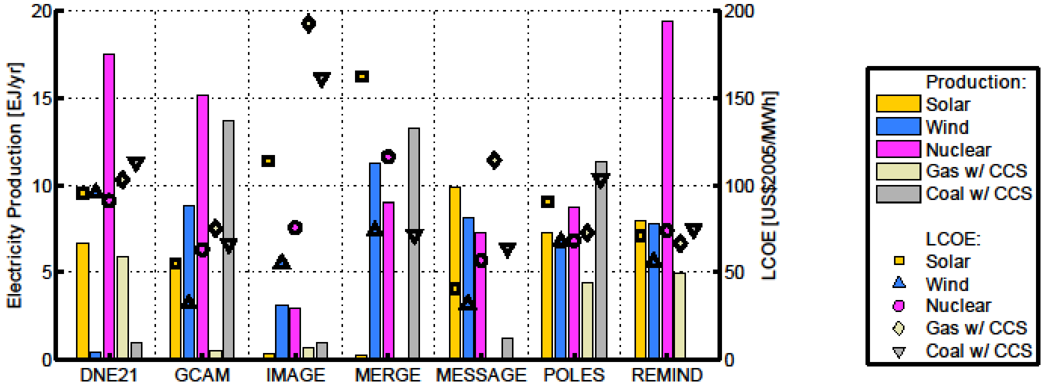


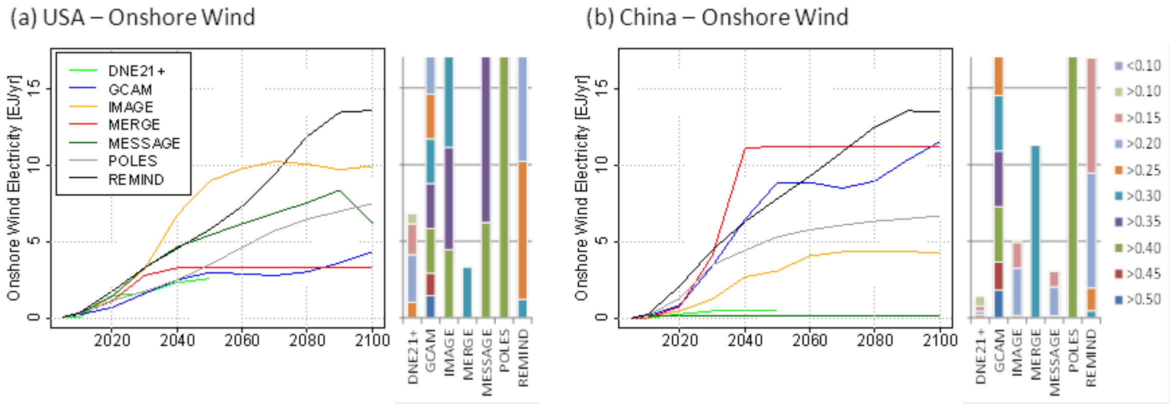
Figure 5. Deployment levels of selected low-carbon technologies (bars, left axis) and corresponding average direct LCOE (markers, right axis) for the *450-FullTech* Scenario in 2050. Upper row: USA; lower row: China.

4.2 Renewable energy resource potentials

Another key determinant for RE deployment in model scenarios and in the real world is the quantity and quality of the resource. Resource quality has direct implications for economic costs (Section 4.1).

Figure 6 shows the onshore wind and solar PV technical resource potentials assumed by the selected models in the USA and China next to the respective deployment pathways in the *450 FullTech* scenario. This comparison reveals that assumptions about technical resource potentials at the regional level differ vastly across models. In both regions, the lowest and highest resource potential estimates differ by more than one order of magnitude across the models and in some cases, turn out to be binding for the observed deployment levels. In addition, resource quality—characterized by the capacity factors (see bar charts in Fig. 6 and Figs. S4.1–S4.3)—varies across the data sets by a factor of two in the best resource categories represented in the models. When comparing deployment levels with resource potentials at the regional level, the renewable resource data adopted by the different IAMs can explain some of the differences in the deployment of onshore wind turbines. For example, the upper end of the regional supply curve determines the maximum deployment in at least one model (MERGE), but others are close to the maximum deployment level as well (e.g. IMAGE in China). A similar comparison for solar PV shows that the resource potentials included in the models tend to be significantly higher than for wind (with the exception of POLES, where only rooftop PV is considered). Therefore, total resource availability typically is not a limiting factor for PV technology deployment. Instead, cost assumptions as well as competition with other technologies are much more relevant (Section 4.1).

In part, the differences in resource potentials are due to definitional issues, which make them difficult to compare. However, it is possible to trace many of these differences back to the original resource data sets employed by the models, which in turn, are based on different methodologies and show a considerable spread.



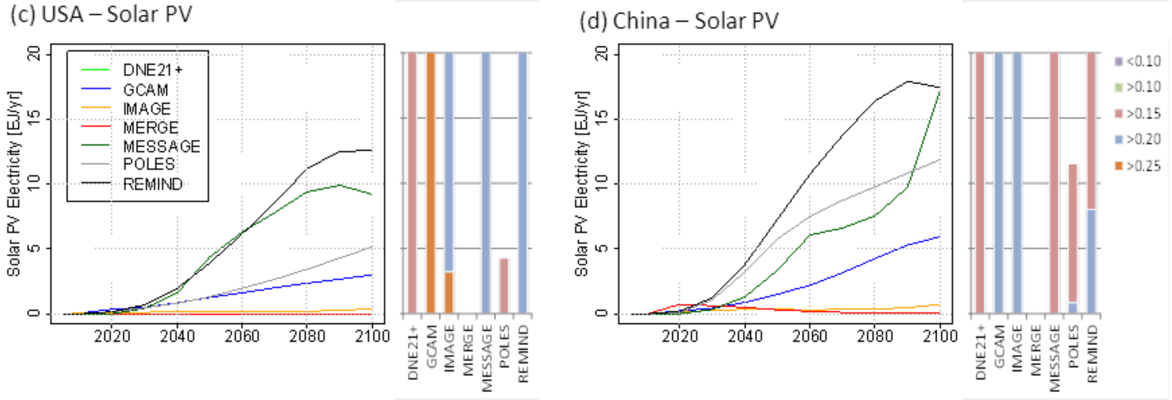


Figure 6. Onshore wind and solar PV deployment (lines) and resource potentials by capacity factor (bars) in the USA (left) and China (right) for the *450 FullTech* scenario. Note that regional definitions are not fully comparable in all cases and that for some models, offshore wind data are combined with onshore wind (see SM).

4.3 Systems integration of variable renewable energies (VRE)

One crucial drawback of wind and solar power is the spatial heterogeneity and temporal variability of their outputs. Many of the EMF27 scenarios describe electricity systems with high a penetration of variable renewable generation in excess of 30%. The need to match load and supply at all times in such systems can require major changes to the operation and design of current electricity systems. RE fluctuations occur on time scales that are much smaller than the annual to decadal time-scales typically resolved by IAMs focusing on the long-term transformations dynamics. Therefore, these models represent RE integration challenges in a rather stylized way. Table S4.3 provides an overview of the systems-integration mechanisms represented in the models. The most basic approach to reflecting integration challenges is to set an exogenous constraint on the maximum share of wind and solar power in electricity generation. For instance, BET limits the combined share of wind and solar to 30%. Similar constraints are implemented in AIM-Enduse, BET, EC-IAM, FARM, GRAPE, IMACLIM and POLES. These models tend to have relatively low overall RE shares in the electricity supply. Over the last years, experience with integrating VRE into power systems has increased (for instance, shares of wind and solar in total 2012 electricity generation were greater than 27% in Denmark), and first detailed power system studies have explored scenarios with VRE shares of 30%, 40% and higher (NREL 2010, 2012; Mills and Wiser 2012). These developments suggest that hard bounds may substantially overestimate integration challenges.

Other approaches make the economic trade-offs related to RE integration more explicit by introducing storage and backup requirements or cost penalties increasing with RE penetration, or by representing load duration curves. Many models use a combination of several approaches. The system-integration costs mapped by these approaches can be substantial. For instance, they amount to ~23 $/MWh at 20% PV and 15% wind penetration for REMIND in the *450 FullTech* scenario in the USA in 2050. Similarly, a cost penalty on wind deployment amounting to 15 $/MWh is applied in MERGE, while in GCAM integration costs are as high as 37$/MWh at 10-15% wind share. The lower end of this range is roughly consistent with the results obtained by detailed studies on integration costs (Mills and Wiser 2012; Ueckerdt et al. 2013; Hirth 2013).

Including integration challenges more explicitly in the models does not necessarily lead to lower VRE deployment: In several of the models considering integration challenges explicitly, wind and solar power combined account for more than 40% of electricity supply in the latter half of the 21st century (MESSAGE, REMIND and TIAM-WORLD) . On the other hand, integration challenges are crucial in explaining relatively low solar PV deployment levels in other models (GCAM and IMAGE). Future research is needed to validate the implicit and explicit integration costs represented in IAMs with detailed bottom-up studies spanning a larger scenario space with various combinations of VRE shares and flexibility options, as well as covering various regions.

5 Conclusions

This paper analyzes the role of RES in climate change mitigation based on a large set of state-of-the-art IAMs and the coordinated scenario set provided by the EMF27 study.

One important conclusion is that the relevance of RES is very different in the various energy supply sectors. Renewables can play an important or even dominant role in the power sector. In most models, the use of RES for electricity increases even without climate policies. In mitigation scenarios, RE deployment for electricity supply expands considerably, with an increasing share of wind power in all models and substantial long-term deployment of solar power in most models.

Another important insight from the EMF-study is that the decarbonization of fuels for transport, buildings and industry are crucial bottlenecks for reducing energy related emissions. Bioenergy is a versatile substitute for fossil fuels that can produce various energy carriers, and therefore is by far the most important mitigation option for non-electric energy production. The EMF27 scenarios suggest that renewable power in combination with electrification of end-use (e.g. via electric vehicles, electric arc furnaces, or geothermal heat pumps) is an important mitigation option. Beyond electrification, renewables can contribute via low-temperature heat. Solar-thermal energy systems account for a substantial share of heat supply in the few models in which they are represented. Given the potential importance of renewable heat supply, a broader and more refined representation in IAMs as well as efforts to improve bottom-up estimates of their deployment potential seem desirable.

Restricting the penetration of wind and solar energy to 20% of electricity supply has a relatively small effect on the costs of climate policy, if nuclear and CCS are available. This is not a surprise since wind, solar, nuclear and CCS are substitutes for low-carbon electricity. In contrast, limiting the availability of bioenergy to 100 EJ/yr results in significantly higher cost increases not only because of its importance for decarbonizing non-electric energy supply, but also the possibility of generating negative emissions by combining bioenergy production with CCS. Most EMF27 models also find it difficult or even impossible to reach the 450 ppm climate target by relying on energy efficiency and renewable energy alone, i.e., without CCS and nuclear energy.

While many of the findings regarding the potential role of RES for climate mitigation are rather robust, the deployment levels of individual technologies vary considerably across models. An in-depth analysis based on a subset of EMF27 models shows that the diversity of the results mirrors the wide range of assumptions on crucial parameters. In particular, there is a substantial discrepancy between the RE resource assumptions used in the models. Therefore, it is necessary to derive new global resource data sets for the most frequently discussed options (e.g., wind, solar PV, CSP) as well as for the less well-represented options (e.g., solar heat, geothermal heat). Moreover, there is substantial uncertainty about the future evolution of technology costs for RES and relevant competing low-carbon technologies. In the past, renewable technologies have shown considerable cost reduction potential. Improved estimates of future costs and an explicit treatment of related uncertainties will be important to improve further our understanding of the role of RES. Finally, spatial heterogeneity and temporal variability is an important characteristic of wind and solar energies. The EMF27 models represent the implications of variable RES in a variety of stylized ways, which can have potentially crucial effects on the results. Further research is necessary to develop improved, yet tractable methodologies.

References

Arvizu D, Balaya P, Cabeza LF, Hollands KGT, Jäger-Waldau A, Kondo M, Konseibo C, Meleshko V, Stein W, Tamaura Y, Xu H, Zilles R (2011) Direct Solar Energy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,.

Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Gabrielle B, Eng AG, Lucht W, Mapako M, Cerutti OM, McIntyre T, Minowa T, Pingoud K (2011) Bioenergy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)],. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,.

Edenhofer O, B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos (2010) The economics of low stabilization: model comparison of mitigation strategies and costs. The Energy Journal 31:11–48.

Hirth L (2013) The market value of variable renewables: The effect of solar wind power variability on their relative price. Energy Economics 38:218–236. doi:10.1016/j.eneco.2013.02.004.

IEA (2012) Energy Balances of non-OECD Countries - 2012 edition. International Energy Agency, Paris.

IPCC (2011) Special Report Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. v. Stechow (eds)]. Intergovernmental Panel on Climate Change.

Krey V, Clarke L (2011) Role of renewable energy in climate mitigation: a synthesis of recent scenarios. Climate Policy DOI: 10.1080/14693062.2011.579308.

Krey V, Luderer G, Clarke L, Kriegler E (2013) Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. Climatic Change:1–14. doi:10.1007/s10584-013-0947-5.

Kriegler E, Weyant JP, et al. (2013) The Role of Technology for Achieving Climate Policy Objectives: Overview of the EMF27 Study on Global Technology Strategies and Climate Policy Scenarios. Clim Change this issue.

Kumar A, Schei T, Ahenkorah A, Rodriguez RC, Devernay J-M, Freitas M, Hall D, Killingtveit Å, Liu Z (2011) Hydropower. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,.

Luderer G, Bosetti V, Jakob M, Leimbach M, Steckel J, Waisman H, Edenhofer O (2012) The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. Climatic Change 114:9–37. doi:10.1007/s10584-011-0105-x.

Mills A, Wiser R (2012) Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California. http://emp.lbl.gov/sites/all/files/lbnl-5445e.pdf.

NREL (2010) Western wind and solar integration study. National Renewable Energy Laboratory (NREL), Golden, CO. http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=981991.

NREL (2012) Renewable Electricity Futures Study. Hand, M.M. et al. NREL/TP-6A20-52409. National Renewable Energy Laboratory, Golden, CO.

Pugh G, Clarke L, Marlay R, Kyle P, Wise M, McJeon H, Chan G (2011) Energy R&D portfolio analysis based on climate change mitigation. Energy Economics 33:634–643. doi:10.1016/j.eneco.2010.11.007.

Rogner H-H, Aguilera RF, Bertani R, Bhattacharya SC, Dusseault MB, Gagnon L, Haberl H, Hoogwijk M, Johnson A, Rogner ML, Wagner H, Yakushev V (2012) Chapter 7 - Energy Resources and Potentials. In: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp 423–512. www.globalenergyassessment.org.

Rose S, Kriegler E, Bibas R, Calvin K, Popp A, Vuuren DP, Weyant JP (2013) Bioenergy in energy transformation and climate management. Clim Change.

Sathaye J, Lucon O, Rahman A, Christensen J, Denton F, Fujino J, Heath G, Mirza M, Rudnick H, Schlaepfer A, Shmakin A (2011) Renewable Energy in the Context of Sustainable Development. In: IPCC Special Report on Renewable Energy Sources and Climate change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C.von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,.

Turkenburg WC, Arent DJ, Bertani R, Faaij A, Hand M, Krewitt W, Larson ED, Lund J, Mehos M, Merrigan T, Mitchell C, Moreira JR, Sinke W, Sonntag-O'Brien V, Thresher B, van Sark W, Usher E, Usher E (2012) Chapter 11 - Renewable Energy. In: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp 761–900.

Ueckerdt F, Hirth L, Luderer G, Edenhofer O (2013) System LCOE: What are the Costs of Variable Renewables? Social Science Research Network, Rochester, NY. http://papers.ssrn.com/abstract=2200572.

Wiser R, Yang Z, Hand M, Hohmeyer O, Infield D, Jensen PH, Nikolaev V, O'Malley M, Sinden G, Zervos A (2011) Wind Energy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,.