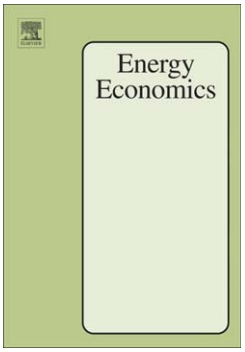

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Assessment of wind and solar power in global low-carbon energy scenarios: An introduction

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Glossary:

ADVANCE – Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies (a collaborative project funded by the European Union's 7th Framework Program)
AR5 – Fifth Assessment Report of the IPCC
BECCS – Bioenergy in combination with CCS
CCS – Carbon Capture and Storage
CES – Constant Elasticity of Substitution
CSP – Concentrating Solar Power
FF&I – Fossil Fuels and Industry
IAM – Integrated Assessment Model
IPCC – Intergovernmental Panel on Climate Change
LAM – Latin America
LCOE – Levelized Cost of Electricity
MAF – Middle East and Africa
PV – Photovoltaics
RLDC – Residual Load Duration Curve
VRE – Variable Renewable Energies

This preface introduces the special section on the assessment of wind and solar in global low-carbon energy scenarios. The special section documents the results of a coordinated research effort to improve the representation of variable renewable energies (VRE), including wind and solar power, in Integrated Assessment Models (IAM) and presents an overview of the results obtained in the underlying coordinated model inter-comparison exercise.

Keywords: Variable Renewable Energy; Wind and Solar Power; Electricity Supply; Climate Change Mitigation; Integrated Assessment Modeling; System Integration Challenges

1. Motivation and Overview

Climate change mitigation has become a major consideration in the development of energy policy. On the global level, electricity supply is the single largest energy-related CO_2 emissions source, having accounted for ~13.5 $GtCO_2$ in 2014, which is more than 40 % of global energy-related CO_2 emissions (IEA, 2016). Electricity plays an increasingly important role in energy supply; and since 1980, electricity demand has risen by more than 3% per year, roughly twice as fast as total final energy demand (IEA, 2014a, 2015).

Integrated Assessment Models (IAMs) with detailed process representation are one of the main set of tools to explore the long-term energy system transformation pathways needed for stringent climate change mitigation. Most models agree that the power sector is a comparatively low-hanging fruit for emission reductions, but there are substantial differences regarding the projected role of the variable renewable energies (VRE) wind and solar in the decarbonization of the power sector for climate change mitigation.

The recent scientific literature on low-stabilization scenarios highlighted three key characteristics of electricity sector transformation in a carbon constrained world: (a) a rapid and almost full-scale decarbonization of power supply, (b) a higher degree of technology flexibility than in other sectors of the energy system, with nuclear, renewables, and CCS as alternative mitigation options, and (c) an increased share of electricity in final energy due to accelerated electrification of energy end-use (Bruckner et al., 2014; Clarke et al., 2014; Krey et al., 2014; Kriegler et al., 2014; Williams et al., 2012). Renewable energy was identified as an important contributor to climate change mitigation in the IPCC's Fifth Assessment Report (Bruckner et al., 2014; Clarke et al., 2014) and Special Report on Renewable Energy Sources (Fischedick et al., 2011; Krey and Clarke, 2011). For instance, in all climate change mitigation scenarios of the EMF-27 study (Kriegler et al., 2014), the share of renewables in electricity supply increased considerably relative to present day, and relative to a baseline scenario without any climate policies (Luderer et al., 2014). However, this and several other previous model comparison exercises (Blair et al., 2009; Fischedick et al., 2011; Krey and Clarke, 2011) also exposed decisive differences among participating models in renewable energy deployment levels. One of the main reasons for these differences was the relatively coarse representation of VRE integration challenges, particularly in global IAMs. For example, some models applied firm upper bounds on VRE penetration, while others used simple approaches to represent flexibility requirements for VRE.

In this introductory article, we provide an overview of the ADVANCE model comparison on the role of variable renewable energy sources for power sector decarbonization. Hereby, the focus is on the future of wind and solar power, and the determinants of their future deployment. We define variable renewable energy (VRE) as the sum of wind and solar electricity production, since both are characterized by variability and uncertainty of supply. We include concentrating solar power (CSP) in this definition, even though CSP can be combined with large heat storage facilities to reduce variability, or even become fully dispatchable depending on the size of the storage unit. Wind and solar energy have a large technical potential for low-carbon electricity supply for several reasons:

(i) Wind energy and in particular solar energy are characterized by a large resource base which does not deplete over time (Arvizu et al., 2011; Wiser et al., 2011);
(ii) Wind and solar technologies have been rapidly maturing over the past decades and retain many characteristics of technologies with considerable further technology development potential. They have experienced substantial cost reductions in recent years. For solar PV further decreases due to technological learning is expected for the future (IEA, 2014b; Pietzcker et al., 2014);
(iii) With average market growth rates of more than 40% p.a. for solar PV and 20% for wind power over the last decade (REN21, 2015, p. 21), they are expected to be key drivers for a stabilization and eventual reduction of carbon intensity of electricity supply in the near term (IEA, 2016);
(iv) Recent studies on prospective life-cycle assessment of energy technologies suggest that wind and solar energy are subject to fewer sustainability concerns than other low-carbon power supply options, such as carbon capture and storage, nuclear or hydro-power (Berrill et al., 2016; Hertwich et al., 2015).

The goals of this study were (a) to improve the representation of VRE in integrated assessment models, (b) to further advance the understanding of the potential role of VRE for power sector decarbonization, and (c) to better understand the remaining differences in results regarding VRE deployment across models. A total of six integrated assessment models participated in the study. These models represent a range of different methodological approaches and alternative assumptions (see Section 2 on methods). The coordinated scenario exercise enables an explicit representation of model-related uncertainties, but also helps to identify robust insights across models.

Each modeling team participating in this study documented their methodological approach and an application to specific research questions in dedicated articles. Ueckerdt et al. (2016) demonstrate how the most crucial integration challenges related to VRE can be captured using Residual Load Duration Curves (RLDCs), and analyze how these integration challenges differ across world regions. Johnson et al. (this issue) use constraints on flexibility and firm capacity parameterized to the RLDCs to represent wind and solar variability in the context of the partial-equilibrium, systems-engineering model MESSAGE. Carrara and Marangoni (this issue) compare the introduction of flexibility and firm capacity constraints with the effects of changing the elasticities and nesting structure of the constant elasticity of substitution (CES) production function of the general equilibrium framework WITCH. Dai et al. (this issue) integrate electricity storage and curtailment requirements induced by wind and solar power in the AIM/CGE model, and explore implications for the costs of climate change mitigation. Despres et al. (this issue) couple the POLES long-term energy-economy model to a short-term dispatch-model of the power sector to analyze the potential of electricity storage for VRE integration. De Boer and Van Vuuren (this issue) use RLDCs to capture renewable integration challenges, and present the effects of this improved methodology on the results of the long-term energy simulation model TIMER which is part of the modelling framework IMAGE. In addition to the global modeling papers, Scholz et al. (this issue) use REMix, an hourly dispatch and investment model of the European electricity system, to provide a detailed analysis of grid, storage and curtailment requirements for alternative system transformations with varying shares of wind and solar power.

The paper by Pietzcker et al. (this issue) offers a comparison and evaluation of the six newly-developed modeling approaches for representing VRE integration challenges in IAMs, highlighting their strengths and limitations and assessing the effect of the technical improvement relative to the respective previous model versions.

Beyond integration, this project also worked towards improved estimates of wind and solar resource potentials. The wind resource data and underlying methodology are documented in Eurek et al. (this issue), whereas the solar resource data set is published in a separate article (Pietzcker et al., 2014).

In the remainder of this introductory article, we provide an overview of the coordinated scenario exercise and present a comparison of model results. In Section 2, we introduce the harmonized set of scenarios used in this assessment. Section 3 provides an overview of the integrated assessment models that participated in the studies. Section 4 presents results on the contribution of VRE to electricity supply in scenarios with and without 2°C-consistent climate policy and the relative importance of different VRE technologies. In Section 5, we explore how VRE deployment levels depend on technology costs, resource availability and integration challenges as well as societal choices regarding climate policy and technologies. The concluding Section 6 finally offers a summary of key findings and policy relevant insights.

2. Design of the scenario exercise

To explore a variety of alternative renewable electricity futures, we considered a number of alternative climate policy and technology scenarios (Table 1). In addition, we analyzed the sensitivity of the VRE deployment results to key model input assumptions by varying (i) capital costs of wind and solar technologies, (ii) VRE resource potentials, and (iii) the representation of VRE integration challenges. Table 2 provides an overview of the sensitivity cases considered.

Table 1: Overview of policy scenarios with varying assumptions about carbon pricing and technology availability.

Name	Short	Carbon regulation	Technology availability
Baseline	Base	No carbon price	Full portfolio
2°C Policy	2°C	2000-2100 CO_2 budget limited to 1550 $GtCO_2$	Full portfolio
Tax30	Tax30	30$/tCO2 tax in 2020, increasing at 5% per year.	Full portfolio
RE Tax30	RE Tax30	30$/tCO2 tax in 2020, increasing at 5% per year.	Nuclear phase-out, no CCS in the power sector

Table 2: Overview of sensitivity and diagnostic scenarios. All scenarios listed here assume carbon pricing as in the *Tax30* scenario.

Name	Short	Change over Tax-30 case
Low Cost	LowCost	Capital costs for wind and solar power technologies decreased by 50%
High Cost	HiCost	Capital costs for wind and solar power technologies increased by 50%
High Resource	HiRes	Resource potentials in each resource quality grade doubled
Low Resource	LowRes	Resource potentials in each resource quality grade halved
Generous Integration	GenInt	Low challenges to VRE integration, e.g. due to more optimistic assumptions about flexibility provision, grid expansion and storage
Strict Integration	StrInt	High challenges to VRE integration, e.g. due to more pessimistic assumptions about flexibility provision, grid expansion and storage
All Optimistic	AllOpt	Combination of *Low Cost, High Resource* and *Generous Integration* assumptions.
All Pessimistic	AllPess	Combination of *High Cost, Low Resource* and *Strict Integration* assumptions.
Very Low Cost	VLC	Levelized costs of wind/solar power reduced to ~20% of cheapest conventional technology (counterfactual)
Full Integration	FullInt	Neglect wind and solar integration challenges (counterfactual)

As a reference point for comparison along the policy dimension, we consider baseline scenarios *(Base)* without any carbon pricing, and the full portfolio of technologies available. These scenarios result in cumulative 2000-2100 fossil fuel and industry (FF&I) CO2 emissions of 4600 to 5600 GtCO2. In addition, we consider two different types of CO2 pricing scenarios. In the *2°C Policy* scenarios, a constraint of 1550 GtCO2 is imposed on the cumulative 2000-2100 budget of FF&I and land-use CO2 emissions. As discussed in the IPCC AR5, this budget is broadly consistent with a long-term CO2e-concentration of 480-530 ppm and limiting global warming below 2°C with a medium likelihood (Clarke et al., 2014, Section 6.3.2). In the *Tax30* scenarios, a fixed trajectory for the CO2-Price is prescribed, starting at 30$US2005/tCO2 in 2020 and increasing exponentially at 5% per year. Due to differences in models' responsiveness to the carbon price signal (Kriegler et al., 2015), the *Tax30* scenarios results in different FF&I CO2 budgets and climate outcomes, ranging from 920 GtCO2 to 2500 GtCO2 over the 2000-2100 period.

Along the technology dimension, we distinguish between scenarios with full technology availability, and a scenario variant that relies solely on renewables for decarbonizing power supply (*RE Tax30* scenario). The latter scenario assumes a phase-out of nuclear power and a ban on carbon capture and storage (CCS) technologies for power supply. The nuclear phase-out is implemented as a ban on new investments, thus nuclear power declines gradually as existing plants retire. While CCS is unavailable for power supply, it remains available in other sectors where there is no direct competition with VRE, such as industrial processes, or the generation of hydrogen or synthetic fuels, see e.g. Koelbl et al. (2014). This also maintains the option of generating negative emissions by combining bioenergy use with CCS in non-power sectors (Rose et al., 2013), which is an important enabling factor for limiting climate change in line with the 2°C target (Kriegler et al., 2014).

Integrated assessment models models typically represent renewable resource potentials differentiated by resource quality. For the present study, modeling teams used recent and refined sets of wind and solar resource potential estimates based on Eurek et al. (this issue) for onshore and offshore wind, and on Pietzcker et al. (2014) for solar PV and CSP. These data sets are derived from meteorological data combined with geographically explicit information about exclusion areas. They provide yearly electricity supply potentials (in units of PWh/a) for bins of a given resource quality, typically measured in capacity factors[1] that can be achieved under reference technology assumptions.

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[1] The capacity factor gives the average utilization rate of a VRE unit. It can be calculated as yearly electricity output (in kWh) per unit of capacity (in kW) installed divided by the 8760 hours that are in a year.

Figure 1 shows the harmonized default wind onshore, solar PV and solar CSP resource potentials used in this study for several major economies and macro regions. To make the potentials comparable across countries of different size and population, we normalized them to the long-term electricity demand projected by the models. The data show high quality solar resources are abundantly available in the USA, Latin America (LAM), Middle East and Africa (MAF). For China, Europe and India the total PV resource potential is still large, but marginal capacity factors at deployment levels typically observed in climate policy scenarios are substantially lower than in the solar-intensive regions. Not surprisingly, CSP resource potential is strongly correlated with PV resource potential, but shows even stronger regional differentiation. Since concentrating solar power requires direct sunlight, suitable locations are confined to the lower latitude subtropical and tropical regions with limited cloudiness. Thus, CSP potential is of high quality for regions with high-quality PV potential, but much smaller in regions with fair PV potential. Onshore wind resources are large and of high quality for the USA, Europe, and Latin America. China, Middle East and Africa also have substantial potentials, but the resource quality is more heterogeneous. Due to projected strong growth in power demand for these regions, they would have to rely on lower-quality resources to supply large shares of their electricity demand by wind compared to the resource-rich regions. For India and Japan, estimated technical potentials for onshore wind are smaller than electricity demand projected for the long-term. These two countries also stand out among the major economies as comparatively resource-poor in a combined perspective on wind and solar potentials.

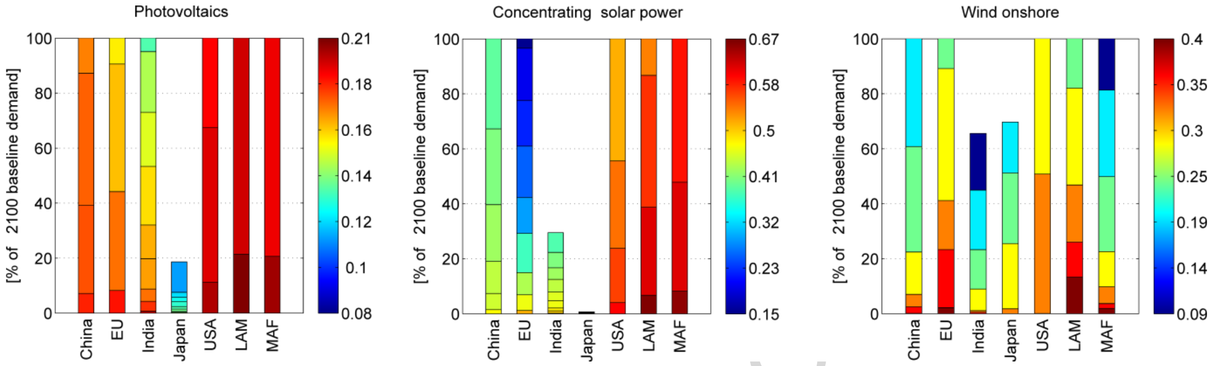

Figure 1: Resource potentials of onshore wind, solar photovoltaics, and concentrating solar power for China, EU, India, Japan, USA, as well as aggregates for the Latin America (LAM), Middle East and North Africa (MAF) macro regions. The potentials are normalized to the baseline electricity demand projected for 2100 averaged across models. The color scale indicates the achievable capacity factor[2].

Due to many real-world constraints related to competing land uses, policy regulation, accessibility or environmental conservation, there is substantial uncertainty about the implementable economic and sustainable renewable resource potential. We therefore considered the *Low Resource* and *High Resource* sensitivity scenarios, in which the assumed potential for each resource quality bin were halved or doubled, respectively.

Technology cost developments are represented in terms of specific capital costs ($/kW) of wind or solar plants, which determine the power generation costs for a given resource quality. These cost assumptions were increased by 50% for the *High Cost* scenario, and decreased by 50% in the *Low Cost* scenario,

The sensitivity analysis along the third dimension, the representation of integration challenges, requires specific care in conducting: While the models are relatively similar in their description of wind and solar resources and costs, a variety of different approaches are applied to represent integration challenges, as discussed in the companion article by Pietzcker et al. (this issue). To realize the strict/generous integration scenarios, each team varied their parameterization of integration challenges in order to approximately halve/double the challenges. A detailed description of the model-specific changes can be found in the supplementary material in Table S1.

In addition, we introduced two diagnostic scenarios to further analyze relative importance of VRE integration challenges and direct VRE production costs. In *Very Low*

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[2] For the calculation of CSP capacity factors we assume that peak solar thermal energy collection from the solar field exceeds the generator capacity by a factor of three and is combined with 12h of thermal storage.

Cost, all VRE cost components were reduced such that resulting levelized costs of electricity are around 20% of those of cheapest fossil competitors. This scenario allows exploring the limitations induced by explicit or implicit integration constraints implemented in the models. Vice versa, in the *Full Integration* scenario, integration challenges were artificially removed by treating VRE electricity as if it were fully dispatchable. It is important to note that these two scenarios are counterfactual – they are purely used for diagnostics and not meant to explore plausible real-world outcomes.

Lastly, to explore the combined effects of resource, technology and integration assumptions, we calculate an *All Optimistic* scenario with high resource, low cost and generous integration assumptions, as well as an *All Pessimistic* scenario with low resource, high cost and strict integration assumptions.

3. Participating integrated assessment models

Six different integrated assessment models participated in this study. While they all have a detailed process-based representation of the energy-economy-climate system, they employ a variety of alternative modeling paradigms. All six models have participated in a number of past model comparison exercises (e.g., Kriegler et al., 2014; McJeon et al., 2014; Riahi et al., 2015) and are representative of the types of methods used for the study of energy transformation pathways in the integrated assessment modeling literature (see Clarke et al., 2014, for a recent overview).

Table 3 provides an overview of the characteristics of the participating models. REMIND (Bauer et al., 2012; Luderer et al., 2013; Ueckerdt et al., 2016) and WITCH (Bosetti et al., 2014; Carrara and Marangoni, this issue; Emmerling et al., 2016) are intertemporal general equilibrium models with an explicit description of macro-economic growth. MESSAGE (Johnson et al., this issue; Messner and Schrattenholzer, 2000; Riahi et al., 2012) is a partial equilibrium model soft-coupled to a macro-economic growth model. All three models assume perfect foresight, and thus can derive mitigation strategies that are inter-temporally cost-optimal. While MESSAGE has a detailed linear energy system representation, REMIND and WITCH feature a non-linear description of energy and macro-economic systems and represent technological change endogenously. AIM/CGE (Dai et al., this issue; Fujimori et al., 2015; Fujimori, 2016), IMAGE (De Boer and Van Vuuren, this issue; van Ruijven et al., 2012; Vuuren et al., 2010) and POLES (Després et al., this issue; Kitous et al., 2010) are recursive dynamic modeling systems, thus assuming imperfect foresight. IMAGE and POLES are simulation models with a partial-equilibrium representation of the energy system. They feature a high level of detail in energy supply and demand technologies. AIM/CGE, by contrast, is a computable general equilibrium model, with a stronger focus on macro-economic detail. While it can analyze the effects of climate and energy policies on multiple economic sectors, it is more limited in its representation of energy system technology detail.

Table 3: Overview of models used. See glossary for abbreviations.

	Model class	Characteristics	Power system representation
AIM/CGE	Computable general equilibrium model	▪ Imperfect foresight ▪ Multiple economic sectors represented ▪ Endogenous technological change	▪ Logit nesting for technology investment ▪ Short-term storage and curtailment exogenous functions of wind and solar share, parameterized based on ADVANCE RLDCs
IMAGE	Recursive dynamic partial equilibrium	▪ Simulation model with imperfect foresight ▪ High technology detail ▪ Endogenous technological change	▪ Multinomial logit used for investments into ADVANCE RLDC load bands ▪ Short-term storage and curtailment exogenous functions of wind and solar share, parameterized based on ADVANCE RLDCs
MESSAGE	Partial equilibrium energy system model soft-coupled to macroeconomic growth model.	▪ Perfect foresight ▪ High technology detail ▪ Inter-temporal optimization	▪ Linear substitution ▪ System flexibility, curtailment, and capacity reserve constraints parameterized based on ADVANCE RLDCs ▪ Endogenous investments into power-to-hydrogen for long-term storage and generic electricity storage for the short-term
POLES	Recursive dynamic partial equilibrium	▪ Simulation model with imperfect foresight ▪ High technology detail ▪ High spatial resolution	▪ For European Union (EU): coupled to a dispatch model, investments based on own RLDC ▪ For non-EU: Operation and logit technology investment based on own RLDC ▪ Multiple within-day storage technologies
REMIND	Inter-temporal general equilibrium model	▪ Perfect foresight ▪ Endogenous technological change ▪ Inter-temporal optimization	▪ Linear substitution ▪ Investments and operation based on ADVANCE-RLDC, accounting for short-term storage and curtailment ▪ Power-to-hydrogen for long-term storage
WITCH	Inter-temporal general equilibrium model	▪ Perfect foresight ▪ Endogenous technological change ▪ Inter-temporal optimization	▪ CES-based substitution between power technologies ▪ Flexibility and capacity constraints ▪ Endogenous investments into a generic storage technology

4. VRE deployment in scenarios with and without long-term climate stabilization

In this section, we evaluate the evolution of electricity supply under an example climate change mitigation scenario. The analysis is not intended to comment on the efficacy of climate policy options per se, but evaluate the effect of a possible climate change mitigation policy. In this case, we have used a *2°C* scenario (e.g. achieving *2°C stabilization by 2100*) on the evolution of power generation. Both in baseline and climate policy scenarios, global electricity demand increases substantially. In the *Baseline*, i.e. in the absence of climate policies, global electricity demand increases to 320-360 EJ/yr by the end of the century, a four to five-fold increase relative to 2010 levels. The introduction of climate policies has two important opposing effects (Kriegler et al, 2014). On the one hand, it incentivizes energy efficiency improvements, resulting in lower overall final energy. On the other hand, since electricity supply can be more easily decarbonized than other non-electric final energy carriers, climate policies also tend to result in an acceleration of the electrification of energy end use. As models emphasize the two effects differently, they show varied responses to the introduction of climate policies in terms of electricity demand. In some models (IMAGE, POLES, WITCH) electricity demand declines relative to baseline, indicating that energy efficiency improvements play a particularly large role or electrification opportunities are limited. In the other models (AIM/CGE, MESSAGE, REMIND), by contrast, long-term electricity demand in the policy scenario is observed to be larger than in the baseline scenario, i.e. the acceleration of electrification dominates the efficiency improvements.

In all scenarios, even in the baseline, the share of wind and solar power in electricity supply increases substantially relative to present-day levels (Figure 2a). This shows that in some regions, up to a certain share, wind and in some cases solar power become competitive even without carbon pricing. In climate policy scenarios, wind and solar power are expanded massively. Even if the full portfolio of technology options is available, they account for 37-75% of electricity supply by 2050, and 53-89% by 2100. The remaining share is largely covered by other RE (hydro and bioenergy, typically in combination with CCS), as well as nuclear and fossil CCS plants (Figure 2b). Freely emitting fossil power sources only play a marginal role in the 2nd half of the century, as the power sector is almost fully decarbonized by then.

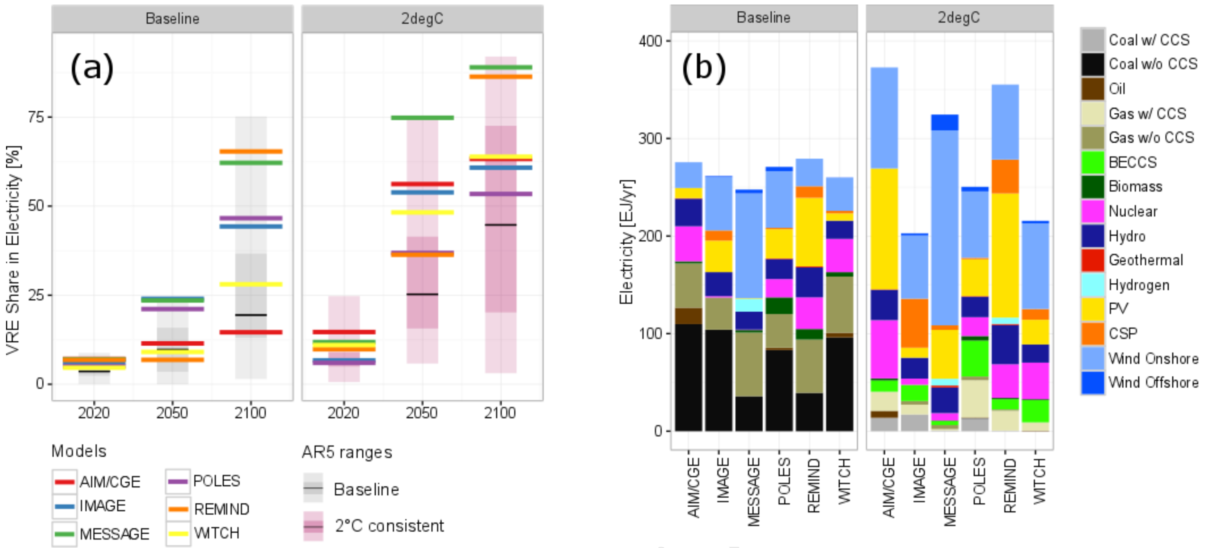

Figure 2: Share of VRE in electricity supply (a), and long-term (2050-2100 average) electricity supply mix (b) for the *Baseline* and *2°C* scenarios. The shaded areas in (a) indicate 25th-75th-percentile ranges (dark shading) or full ranges (light shading) of scenarios from the AR5 data base without climate policy (grey), or 2°C-consistent[3] (purple). The black line indicates the median of the full range of scenarios from the AR5 data base for the respective scenarios.[4]

While better accounting for the variability and additional costs of integration, the improved representation of VRE in the models still results in a more prominent role of wind and solar for power supply as compared with the AR5 range (Figure 2a). All ADVANCE baseline scenarios with the exception of AIM/CGE have VRE shares at or above the median of AR5 baseline scenarios in the 2nd half of the 21st century. Similarly, VRE shares of all ADVANCE 2°C scenarios are above the median of IPCC AR5 scenarios with a comparable climate target (which were based on prior versions of these models (and other models) that did not incorporate the advances in methodologies presented in this paper and issue).

There is general agreement across the models about the overall role of VRE in deep decarbonization scenarios. Regarding technology choice within the portfolio of VRE technologies, we find that both wind and solar can contribute substantially to carbon-free electricity supply in a climate constrained world (Figure 2b). This indicates a certain degree of complementarity between these two sources, and reflects the heterogeneity of resource availability and different temporal supply characteristics. Some regions are particularly sunny, while others are better suited for wind power.

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[3] "2°C consistent" refers to the IPCC scenario categories I and II, which result in a stabilization of GHG concentrations at 430-530 ppm CO2e by 2100.

[4] Note that small shares of bioenergy with CCS (BECCS) remain in the MESSAGE and REMIND RE 2°C scenarios. These are due to co-production of electricity in biomass-to-liquids plants.

Wind and solar also have different patterns of temporal variability, therefore a mix of solar and wind supply tends to have lower integration challenges than a system that relies exclusively on a single VRE source (Denholm and Hand, 2011; Ueckerdt et al., 2015).

However, we also find that models differ substantially in the relative contribution of wind and solar. Under 2°C-consistent climate policy, some models (POLES, MESSAGE, WITCH) project a dominance of wind over solar power, while in others (AIM, IMAGE) wind and solar contribute similarly, with REMIND being the only model that projects a dominance of solar over wind power. These differences can be primarily attributed to differences in technology cost assumptions (Figure 3), and to a lesser extent to the technology-specific differences in the representation of integration challenges.

In MESSAGE, POLES and WITCH, onshore wind energy is projected to remain cheaper than solar power. This explains why wind is the most important carbon free-energy source in the *2°C* scenarios of these models. AIM/CGE, IMAGE and REMIND, by contrast, have relatively comparable wind and solar power generation costs in the long-term. They have much higher solar power shares than the other models, with AIM/CGE and REMIND favoring PV, while IMAGE mostly deploys CSP. The advantage of CSP in the power system context is the possibility of combining it with thermal storage to ease integration, and of co-firing gas or hydrogen to allow full dispatchability. IMAGE projects substantial cost reductions for this technology over the coming decades, and therefore its CSP share is more significant than in the other models. In REMIND, CSP is ramped up only in the 2nd half of the century, chiefly because integration challenges become more relevant in the long term with increasing VRE shares. The very high shares of PV in this model are largely enabled by substantial deployment of battery storage, which is particularly effective in smoothing the diurnal cycle of solar power production, albeit more expensive than thermal storage for CSP. Offshore wind energy plays a much smaller role than onshore wind in all models that represent this option explicitly (IMAGE, MESSAGE, POLES and WITCH), chiefly because it is significantly more expensive than the onshore option.

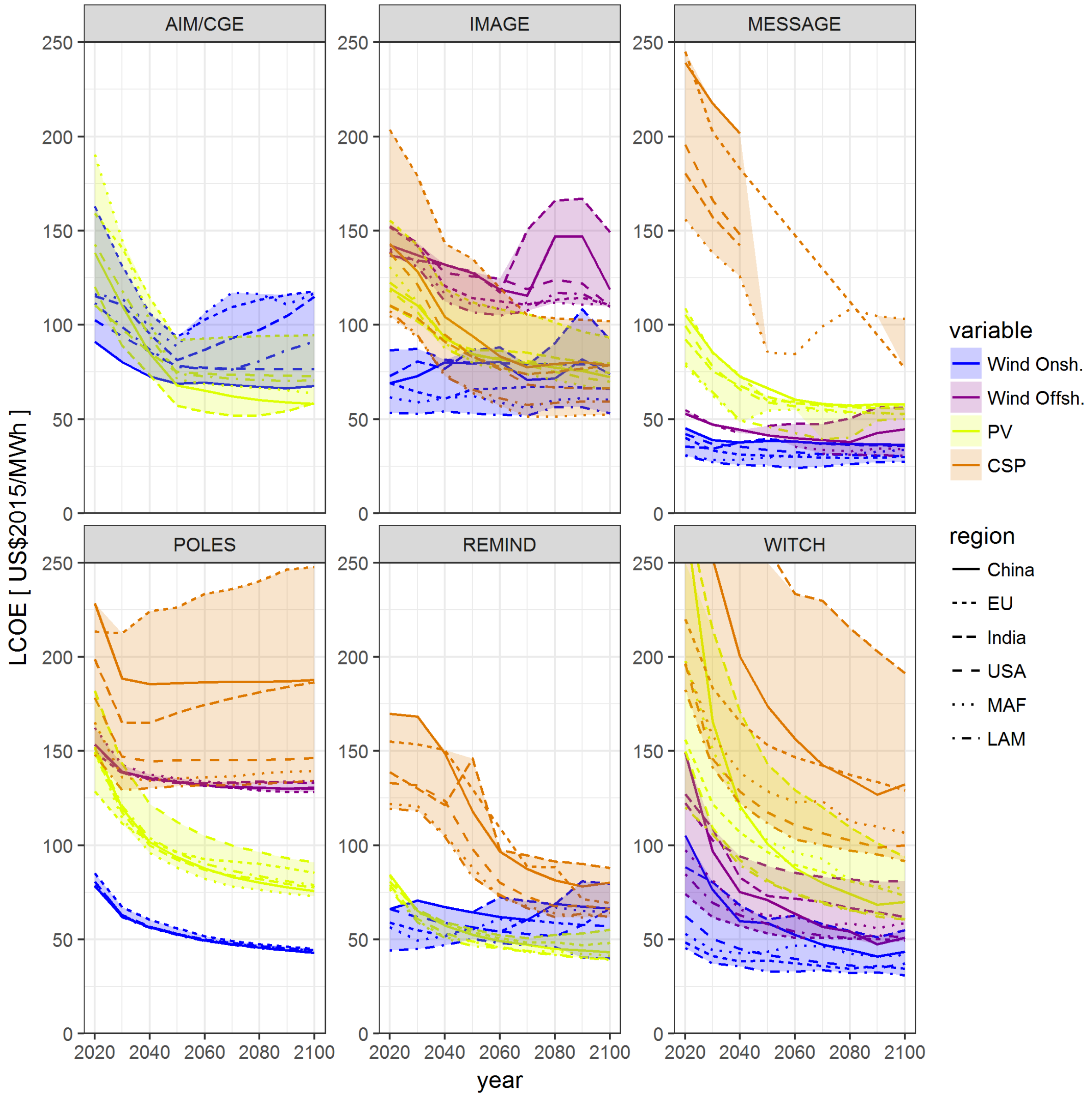

Figure 3: Levelized costs of electricity generation from a newly installed plant for onshore and offshore wind power, as well as solar PV and CSP for the *2°C* climate policy scenario for each model[5]. Region definitions as in Fig. 1.

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[5] Increasing LCOEs are due to decreasing capacity factors as the high-quality resource sites are used up and plants are deployed at lower-quality resource sites.

5. Sensitivity of VRE deployment to key assumptions

Climate change mitigation pathways documented in the integrated assessment modelling literature differ widely in their long-term VRE deployment levels. To shed new light on the key determinants of VRE use, we conducted systematic scenario variations of policy assumptions, resource and cost parameters (cf. detailed description of the scenarios in Section 2).

Figure 4 shows VRE deployment levels and their sensitivity to scenario assumptions. The results are presented both in absolute terms as well as in terms of the relative difference to the *Tax30* climate policy scenario, which serves as a common point of reference for the sensitivity analysis discussed in this section. To ensure comparability, all variations discussed here (with the exception of *Base*) have the same carbon price signal.

Consistent with the findings on climate stabilization scenarios (Section 4), we find that carbon pricing has a substantial impact on VRE deployment. According to all but one model, long-term VRE deployment levels would be at least 20 percentage points lower without the CO2 price (*Base* scenario) than in *Tax30*. Constraining the availability of nuclear and CCS technologies (*RE Tax30* scenario), by contrast, increases the share of VRE by 14-30% in all models with the exception of MESSAGE, which already features a 87% VRE share in the scenario with full technology availability.

When comparing the effect of policy and technology choices (*Base* and *RE Tax30* scenarios) to the scenarios with a Tax30 carbon price but with variations of parameter assumptions, we find that the latter tend to have a weaker effect on VRE deployments. Increasing (decreasing) technology costs by 50% results in a 7-21 %-point decrease (6-18 %-point increase) in wind and solar deployment *(HiCost* and *LowCost* cases). Major changes in the assumed resource potentials, by contrast, only have a surprisingly small effect. Doubling or halving the resource potential changes VRE use by 3 percentage points or less. Even in more resource-scarce countries like India or Japan, the sensitivity of VRE shares to resource assumptions remains within +/- 15%-points, much less than the sensitivity to technology costs (cf. Supplementary Figure S1). This result indicates that resource availability is barely a limiting factor for the future role of VRE, while economic competition with other low-carbon energy sources matters.

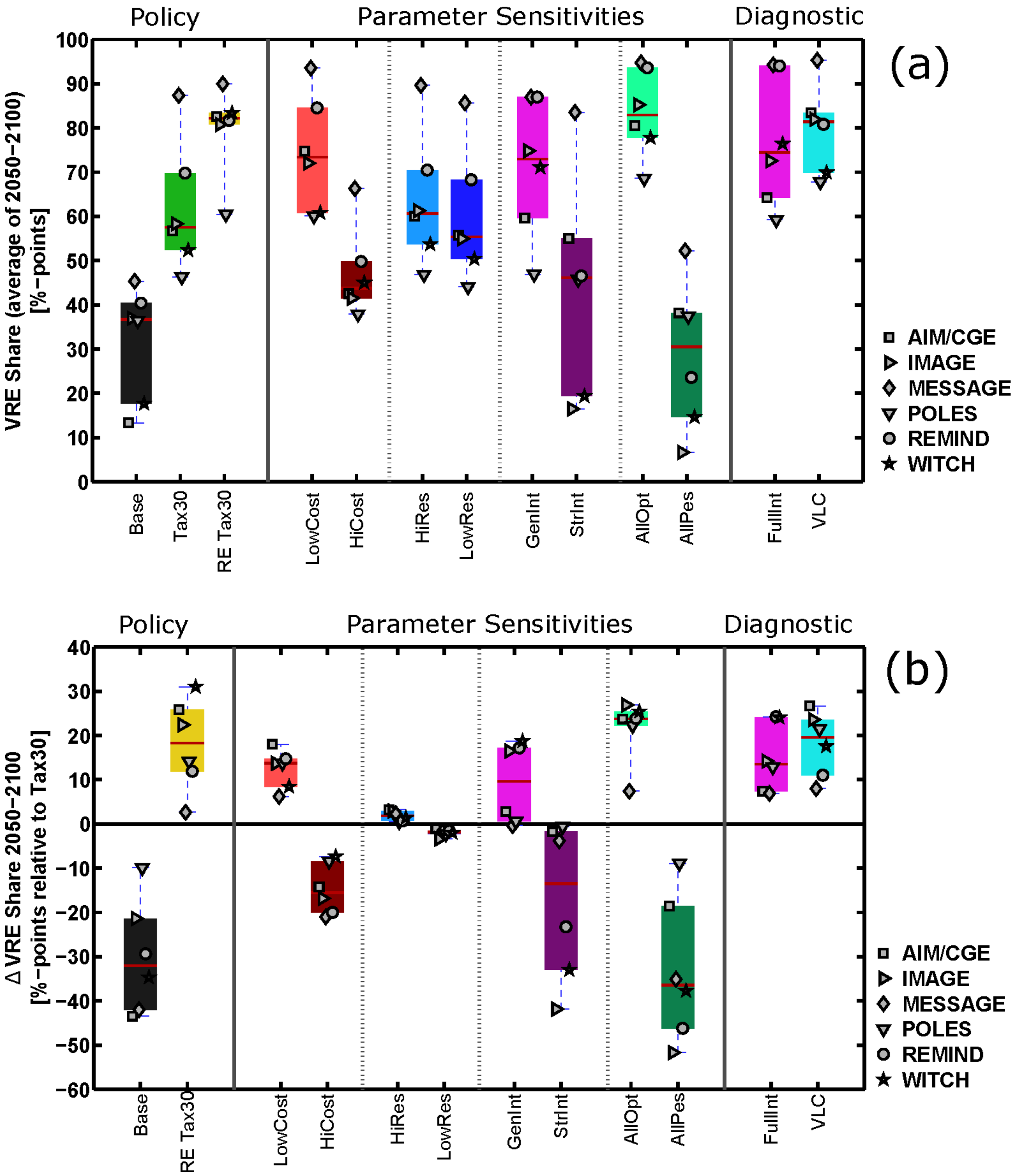

Figure 4: VRE shares in absolute terms (a), and differences relative to the Tax30 case (b) for policy scenarios, parameter sensitivities and diagnostic scenarios. *FullInt* and *VLC* show results from counterfactual diagnostic scenarios with either integration constraints removed, or direct technology costs reduced to a very low level. Note that all sensitivities assume the same carbon price path.

Importantly, not only direct generation costs but also the indirect costs incurred by the variability have an influence on cost-optimal VRE shares. The results from the REMIND, IMAGE and WITCH models suggest that integration assumptions can have a significant effect. For example, in all three models, the *Strict Integration* scenario assumptions lead to greater decreases in VRE deployment than the 50% increase in technology costs assumed in the *High Cost* case. Vice versa, the *Generous Integration* scenario assumptions lead to a greater increase in deployment than the *Low Cost* case.

The relevance of integration constraints can be further studied by considering the two counter-factual diagnostic scenarios. In the first scenario, *Full Integration,* any representations of integration constraints are removed. The resulting increase in VRE share compared to the Tax30 scenario of 7-24 %-points shows that the default integration challenges are sizable in each of the participating IAMs. More specifically, for all models but AIM/CGE, removing the default integration challenges has the same or a larger impact than halving the investment costs has. In the second scenario, *Very Low Cost*, technology costs are reduced such that resulting VRE LCOE are one fifth of the cheapest competing technology, while integration constraints remain unchanged from the default. This scenario indirectly elicits the strength of integration challenges and any other remaining inflexibilities in the modeling – if electricity from different sources were perfectly substitutable, VRE shares should reach close to 100% at such low prices. Models that produce VRE shares below 80 or even 70 percent in *Very Low Cost* assume strong barriers to substitution, even if VRE electricity is almost free of cost. VRE deployments in these counter-factual scenarios exceed those in the default *Tax30* scenario by 7-24% for the *Full Integration* case, and by 8-27% in the *Very Low Cost* case. These results show that for ambitious decarbonization scenarios and in the long term, integration challenges are of similar significance as direct technology costs. By combining either all optimistic or all pessimistic assumptions on technology cost, resource availability and integration challenges, the models span a wide range of possible VRE futures, and are able to reproduce the uncertainty range observed in the previous IAM literature. 2050-2100 average VRE deployment levels decrease to 7-52% in the *All Pessimistic* scenario, compared to 78-95% in the *All Optimistic* scenario.

6. Summary and Conclusions

Understanding the potential role and contribution of wind and solar energy is of key strategic importance for climate change mitigation. Incorporating larger shares of VRE imposes significant challenges for power system operations, and these challenges need to be appropriately represented in IAMs in order to improve the capabilities of the models to account for technology and operational advances, and for these models to more accurately inform policy decisions.

IAM-based long-term and global analyses are useful for general insights on power sector dynamics in the context of the overall decarbonization of the energy-economy system, and for estimating the potential role of different technologies. However, given the long-time horizon, the global scope and wide system boundaries of these models, the level of granularity that can be represented in IAMs is limited. Accordingly, the scenarios cannot represent short-term issues like frequency control, or spatially disaggregated information about where individual transmission lines should be placed. These more detailed aspects have been dealt with in more detailed models (Haller et al., 2012; Krishnan et al., 2016; Mai et al., 2014; Scholz et al., this issue), and key aspects are incorporated as best as possible in the IAMs (Pietzcker et al., this issue).

Using the improved modeling approaches developed during the ADVANCE project, we were able to provide a more robust picture of the potential role of renewables for future low-carbon electricity supply. The following five insights are of particular interest and policy relevance:

- Wind and solar technologies are likely to contribute substantially to the low-carbon transformation of the power sector in climate change mitigation scenarios. They combine for more than half of the electricity supply in 2°C-consistent policy scenarios in the long-term.
- Carbon pricing and the availability / social acceptance of non-renewable low-carbon power sources are the most important determinants of the role of VRE. Carbon prices in line with the 2°C limit will make wind and solar technologies immediately competitive in many world regions. If nuclear power or carbon capture and storage are removed from the portfolio of mitigation options, a much larger portion of electricity needs to be supplied from VRE.
- The methodological improvements of the IAMs, in particular with regard to the representation of integration challenges, have resulted in a more accurate representation and simultaneously indicate a greater potential role of VRE to contribute to mitigation. This is largely due to the fact that previous, simpler modeling approaches overemphasized integration challenges, and did not account for key integration options such as storage or large-area pooling through improved grid interconnection (Pietzcker et al., this issue). The shares of VRE in electricity supply in the 2°C-consistent scenarios from all six models are above the median of corresponding scenarios from the IPCC AR5 scenario data base.
- Our multi-dimensional sensitivity study shows that VRE integration challenges are of similar importance as direct technology costs in determining future VRE deployment levels.
- In large parts of the world, the availability of renewable energy resources is not a limiting factor. Our results suggest that in the global aggregate, VRE deployment levels are relatively robust to assumptions on the magnitude of the resource potential.

There is plenty of need for further research. Coping with variability and uncertainty of wind and solar power is a crucial challenge. Their future will hinge on technical solutions to VRE integration, as well as smart policy and market design to incentivize their deployment (Cochran et al., 2012; IEA, 2014c). More bottom-up research is required to assess the cost, potential and performance of the various integration options, such as large-scale pooling via improved grid interconnection, storage systems, or increasing the flexibility of electricity demand, as well as to understand how VRE can contribute to decarbonization of other sectors of the economy such as transportation and industry. Moreover, it is important to understand how these options can be combined. Since the temporal and spatial patterns of VRE supply and electricity demand depend strongly on local geographic conditions, such analyses need to be region-specific. Despite the progress made in this study, it remains challenging to adequately represent the short-term dynamics of power markets in the context of long-term IAMs.

Our results also confirm that technology costs are an important determinant of deployment, emphasizing the need for an improved understanding of the dynamics of technological change. The vast majority of previous energy-economic modeling studies have underestimated the speed with which costs of photovoltaic systems, and to a lesser extent also of wind turbines, have decreased over the last decade. Future technology costs are highly uncertain, in particular for the rapidly evolving renewable technologies, but also for competing low-carbon technologies such as CCS or nuclear.

In this study, we have explored how VRE deployment depends on VRE technology costs, VRE resources, VRE integration challenges, climate policy as well as the availability of competing technologies for low-carbon power supply. Importantly, there are other dimensions that are likely to affect the use of wind and solar power in the future, such as policies and institutional factors. These will affect real-world capital costs for VRE projects and the pace at which deployment can be scaled up. Models typically assume equal discount rates across regions and actors, as well as explicit or implicit constraints on the expansion rate of technologies (Wilson et al., 2013). Testing the sensitivity of VRE results on these assumptions is beyond the scope of this study, but an important subject of follow-up research.

Beyond techno-economic performance, the regulatory environment is a crucial determinant of VRE deployment. IAMs typically derive economically optimal technology use under the assumption of free markets. In the real world, VRE deployment is either facilitated or hindered by a complex system of power market regulations, including VRE-specific subsidies and fees, VRE deployment regulations, existence and specifications of capacity mechanisms, regulation of balancing power, grid connection procedures and fees, and many more (Hirth and Ziegenhagen, 2015; IEA, 2014c). These aspects were not within the scope of this work, but dedicated research would be valuable to better understand how these regulations interact with the techno-economic performance of technologies and the risk perception of investors to determine the real-world deployment of VRE. Modeling the power sector with multiple agents at a high temporal resolution is a promising approach to study the effect of alternative power market regulations on VRE integration and economic efficiency of power markets.

Lastly, societal acceptance is a decisive enabling factor for the system transformation required to decarbonize power supply. Further IAM research should therefore focus on characterizing the full spectrum of economic, environmental and societal cost, benefits and adverse side-effects of alternative transformation pathways. Such information is of great value for informing policymakers and societies about the consequences, implications and requirements of their choices.

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