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

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ABSTRACT

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.

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

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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. 2017-in this issue) 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. 2017-in 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 2017-in 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. 2017-in 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. (Després et al. 2017-in 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 2017-in 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 modeling framework IMAGE. In addition to the global modeling papers, (Scholz et al. 2017-in 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. 2017-in 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. 2017-in 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.

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$/$tCO_2$ tax in 2020, increasing at 5% per year.	Full portfolio
RE Tax30	RE Tax30	30$/$tCO_2$ tax in 2020, increasing at 5% per year.	Nuclear phase-out, no CCS in the power sector