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Representing power sector variability and the integration of variable renewables in long-term energy-economy models using residual load duration curves

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ABSTRACT

We introduce a new method for incorporating short-term temporal variability of both power demand and VRE (variable renewables) into long-term energy-economy models: the RLDC approach. The core of the implementation is a representation of RLDCs (residual load duration curves), which change endogenously depending on the share and mix of VRE. The approach captures major VRE integration challenges and the energy system's response to growing VRE shares without a considerable increase of numerical complexity. The approach also allows for an endogenous representation of power-to-gas storage and the simultaneous optimization of long-term investment and short-term dispatch decisions of non-VRE plants. As an example, we apply the RLDC approach to REMIND-D, a long-term energy-economy model of Germany, which was based on the global model REMIND-R 1.2. Representing variability results in significantly more non-VRE capacity and reduces the generation of VRE in 2050 by about one-third in baseline and ambitious mitigation scenarios. Explicit modeling of variability increases mitigation costs by about one fifth, but power-to-gas storage can alleviate this increase by one third. Implementing the RLDC approach in a long-term energy-economy model would allow improving the robustness and credibility of scenarios results, such as mitigation costs estimates and the role of VRE.

1. Introduction

There is broad evidence that anthropogenic climate change is threatening the welfare and development of human societies [1–3]. Combustion of fossil fuels is the main driver of anthropogenic climate change, causing over 60% of global greenhouse gas emissions [4,5], which is why climate change mitigation requires a transformation of the global energy system towards low-carbon technologies. Identifying mitigation scenarios that minimize the macroeconomic costs (so-called mitigation costs) of achieving a prescribed climate target requires long-term numerical energy-economy models that capture key interactions between the energy, economic and climate systems, as well as interactions within the energy system itself (heat, transport and power sector).

The power sector appears to be a centerpiece for climate change mitigation. Most mitigation scenarios show that the power sector decarbonizes earlier and more extensively than the non-electric energy part of the energy system [6–9]. Electricity can be supplied by a number of comparably low-cost mitigation options such as renewable energy sources, carbon capture and storage and nuclear power, whereas supplying non-electric energy demand with low greenhouse gas emissions relies strongly on biomass. Electrification is also an important mitigation strategy for transport and residential heating.

Future power systems will likely show a significant share of renewable energy of which a large contribution will come from the *variable*[1] renewable energy sources (VRE) wind and solar PV

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[1] "Variable" (or sometimes intermittent) is used to describe generators that rely on fluctuating weather conditions (wind and solar plants) and thus can hardly be controlled in their power output.

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(photovoltaics). This is not only indicated by current high growth rates, ambitious policy targets and renewable support schemes, but also estimated in mitigation scenarios based on long-term energy-economy models [6,10–14]. The recent EMF27 model comparison [14] shows that for all but one model, renewables provide more than 35% of power supply in the second half of the century, and half of the models show renewables share of 59% or higher. In those scenarios with high overall renewable deployment wind and solar PV contribute the major electricity share (>40%) in the second half of the century.

However, long-term energy-economy models have a deficit that leads to inaccurate or even biased results: Typically, they only have a crude representation of power sector variability, which needs to be improved in particular to give an accurate account of the economics of VRE (variable renewables) [14,15]. This includes both variable power demand as well as VRE like wind and solar and their integration into energy systems. Variability on temporal scales from minutes to years shapes the economics of the power sector. As demand is inherently variable and electricity cannot be stored easily, a heterogeneous mix of power-generating technologies is optimal, rather than a single technology [16–20]. If a model does not represent the variability of demand there is a tendency to bias the results towards more base-load technologies and to underestimate the total costs of power supply. Neglecting the variability of VRE intensifies this bias since VRE variability imposes costs on the power system as a whole. These costs are often termed integration costs and can be substantial at high VRE shares [21,22]. Consequently, the economic value and optimal deployment of VRE strongly decrease due to their variability [23–27]. For wind this amounts to 25–35 €/MWh at a share of 30–40%, according to an extensive literature review [22]. For a fundamental analysis of the impacts of power sector variability (demand and VRE) on the economics of electricity see Ref. [28].

Accounting for short-term power sector variability in models that focus on long-term transformation pathways of the energy system is highly challenging, due to the trade-off between model scope and detail in the presence of numerical and complexity limits. Long-term energy-economy models have a very wide scope, i.e., coverage of multiple sectors, a centennial perspective on mitigation challenges, often a global perspective, and a representation of the major drivers of climate change and mitigation options. Inevitably, this limits the level of detail that can be represented. Many models use a temporal resolution for investment decisions of 5–10 years. Power demand and supply are aggregated and balanced in terms of annual averages, in contrast to actual electricity demand, wind speeds, and solar radiation variability time scales. Numerical constraints prohibit increasing the resolution of long-term energy-economy models to a degree that would allow for an explicit representation of variability. To keep model complexity manageable, one needs a lean, yet accurate representation of power sector variability and VRE integration that successfully bridges relevant timescales.

Most long-term energy-economy models use stylized representations covering different aspects of variability; these representations have limitations and leave room for refinement [14,29,30]. A review of 17 long-term energy-economy models [14] reveals a range of methods to represent VRE variability spanning from highly stylized economic approaches over constraint and cost-penalty based methods to investment requirements in integration options. Two of these models have no dedicated representation of variability, but account for the imperfect substitutability between different power sources using CES (constant elasticity of substitution) production functions. Such an approach is highly stylized and tends to preserve power supply structures as observed today, making it difficult to explore the types of transformative changes required for low stabilization. One common approach is to limit the maximum generation share of wind and solar by means of an exogenous constraint, e.g., to 15% each. This rigid approach might be overly pessimistic as dedicated studies and real-world experience indicate that VRE integration poses no insurmountable technical barrier [31]. A less rigid approach is the imposition of an integration cost penalty per generated unit of electricity from VRE that increases with the VRE generation share (see e.g. Ref. [32]). While representing monetary integration challenges, this approach is not capable of capturing the pivotal impacts of VRE on the non-VRE part of the power system. Increasing shares of VRE result in a substantial reduction of full-load hours of dispatchable power plants, and thus alters optimal investments in the non-VRE part of the energy system [33]. Another prominent approach is to impose fixed investments in specific integration options with rising VRE shares, e.g., firm capacity from gas-fired power plants, electricity storage or transmission infrastructure. However, a single integration option is unlikely to mitigate all aspects of variability, these approaches are difficult to parameterize and the preselection of specific integration options hampers the opportunity for the model to determine a cost-effective way to cope with variability.

Another common approach is to introduce “time slices”, as implemented, e.g., in the TIMES model class [34], the LIMES model [35,36] or the ReEDS model [37,38]. Time slices capture different representative situations in the power sector, such as winter vs. summer, day vs. night and weekday vs. weekend. This concept is quite successful in capturing the variability of demand with a low number of time slices, as demand follows very regular patterns. However, an adequate representation of the correlation between demand on the one hand, and the more complex patterns of wind and solar power on the other, requires a relatively large number of time slices, leading to high numerical complexity [39,40].

Finally, the MESSAGE model [29] introduces an additional balance equation for “flexibility”, in which flexible generation from an endogenous mix of dispatchable plants and electricity storage technologies balances flexibility requirements from variable demand and VRE supply, characterized by a single constraint. The parameterization does not build on technical parameters or have a rigorous definition, but is derived from a limited ensemble of scenarios of a generic unit-commitment model with six nodes. It is unclear to what extent the approach represents power-sector variability for a range of regions and system configurations. A refinement might entail a more comprehensive parameterization and potentially a differentiated representation of different aspects of variability, for example by finding specific “flexibility” constraints for different time scales of load balancing.

The research community using long-term energy-economy models works on consolidating different approaches and developing best practices. Explicit modeling of some aspects of variability, implicit representations of other aspects using exogenous parameters, and/or soft-coupling with high-resolution models can be part of the solution. In correspondence to the above limitations of the prevalent approaches we suggest three criteria that a sound representation of variability should fulfill. First, it should be comprehensive, i.e., it should represent the most important aspects of demand and renewable supply variability. Second, it should be robust, i.e., its parameterization should be valid for a broad range of different energy system configurations. To this end the representation should either build on a rigorous definition of economic impacts of variability or on physical constraints that capture variability such that the correct economic impacts are induced. Third, a representation should be flexible, i.e., it should allow for an endogenous choice of different integration options, including adjustments of the non-VRE part of the energy system.