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Long-run power storage requirements for high shares of renewables: Results and sensitivities

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ABSTRACT

We use the model DIETER, introduced in a companion paper, to analyze the role of power storage in systems with high shares of variable renewable energy sources. The model captures multiple system values of power storage related to arbitrage, capacity, and reserve provision. We apply the model to a greenfield setting that is loosely calibrated to the German power system, but may be considered as a more generic case of a thermal power system with increasing shares of variable renewables. In a baseline scenario, we find that power storage requirements remain moderate up to a renewable share of around 80%, as other options on both the supply and demand side may also offer flexibility at low cost. Yet storage plays an important role in the provision of reserves. If the renewable share further increases to 100%, the need for power storage grows substantially. As long-run parameter assumptions are highly uncertain, we carry out a range of sensitivity analyses. As a general finding, storage requirements strongly depend on the costs and availabilities of other flexibility options, particularly regarding flexible power generation from biomass. We conclude that power storage becomes an increasingly important element of a transition toward a fully renewable-based power system, and gains further relevance if other potential sources of flexibility are limited.

1. Introduction

In [1], we introduce a new open-source model, DIETER, the Dispatch and Investment Evaluation Tool with Endogenous Renewables. This model minimizes total system costs and addresses important domains, derived from a dedicated literature review, of power storage requirements in systems with high shares of variable renewable energy sources (RES): an hourly resolution, a consideration of all contiguous hours of a full year, a representation of balancing reserves, and detailed constraints with respect to demand-side management. The model captures multiple system values of power storage related to arbitrage, capacity, and reserve provision. Nonetheless, the model is computationally efficient, which allows for carrying out numerous sensitivity analyses.

In this article, we use DIETER to analyze the role of power storage in systems with high shares of variable renewable energy sources. We abstract from path dependencies by simultaneously optimizing the full power system with all capacities being endogenous variables. We apply the model to a long-term greenfield setting that is loosely calibrated to the German power system. In Germany, the share of renewable sources in gross power demand has increased from around 3% in the early 1990s to nearly 32% in 2016. In the context of the *Energiewende*, Germany's ambitious long-term energy transition, the German government is aiming for a renewables share of at least 80% by 2050.[1] In the long run, comparable or even higher shares of renewable energy sources may also be required in many other countries in the context of tighter carbon constraints. Although our analysis focuses on the German case, it can be considered as a generic example of a thermal power system with increasing shares of variable renewable energy sources. In order to guarantee complete traceability and transparency of our analysis, both the model and all input parameters are provided under dedicated open-source licenses.[2]

The remainder of this paper is structured as follows: Section 2 introduces all relevant input parameters and the scenarios studied. Results of the baseline scenario and numerous sensitivities are presented in Section 3. Limitations of the model application and

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[1] This target is stated in numerous government documents and is also included in the 2012, 2014, and 2017 versions of the German Renewable Energy Sources Act (*Erneuerbare-Energien-Gesetz*, EEG).

[2] DIETER may be freely used and modified by anyone. The code is licensed under the MIT License. Input data is licensed under the Creative Commons Attribution-ShareAlike 4.0 International Public License. To view a copy of these licenses, visit http://opensource.org/licenses/MIT and http://creativecommons.org/licenses/by-sa/4.0/. This article refers to model version 1.0.2. Different model versions and further information are provided at http://www.diw.de/dieter.

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potential impacts on results are discussed in Section 4. The final Section 5 concludes.

2. Input data and scenarios

2.1. Input data

The model is loosely calibrated to the German power system with regard to demand, hourly availabilities of variable renewable energy sources, as well as constraints for offshore wind power, biomass, pumped-hydro storage, and demand-side management (DSM).[3] Hourly load values are taken from ENTSO-E [2] for the year 2013. For the fraction of reserves called, we divide the mean hourly reserves actually activated, provided by the German TSOs [3], by the contracted capacities at that point [4].

Aside from time-related input data, which is based on the year 2013 under baseline assumptions, all technology-specific input parameters reflect a 2050 perspective. Tables B.1–B.5 in Appendix B contain a detailed representation of all technology-specific assumptions of the baseline, including respective units and data sources. Annualized fixed costs are generally calculated by drawinging on overnight investment costs, fixed costs not related to power generation (where applicable), specific technical lifetimes, and an assumed interest rate of 4%. Monetary values are generally stated in real prices of 2010.

Regarding thermal generation technologies, we include hard coal, combined cycle natural gas (CCGT) and two types of open cycle natural gas turbines (OCGT)—an "efficient" one with lower marginal but higher investment costs and an "inefficient" type for which the opposite is true. By assumption, investments into nuclear, lignite, and run-of-river hydro power are not possible. In case of nuclear, this reflects the legal situation in Germany. Lignite plants, which have high specific CO_2 emissions, are assumed not to be compatible with a long-term, low-emission, renewable-based system.[4] Run-of-river is excluded because, on the one hand, potentials in Germany are small; and on the other, it is a non-dispatchable low-cost technology, such that unlimited investment opportunities would render model results trivial.

The major source for cost parameters for conventional generators and biomass plants is the DIW Data Documentation [5], of which medium projections for 2050 are used. Supplementary information stems from VGB PowerTech [6], and VDE [7] for load change flexibility. Marginal production costs of conventional plants are calculated based on the carbon content of the fuel [8], an assumed CO_2 price of 100 Euro per tonne, and specific efficiency and fuel costs. Fuel prices follow the "medium" price path within [9], except for lignite [10].

Regarding variable renewable technologies, we include onshore and offshore wind power as well as solar photovoltaics. In addition, investments in dispatchable biomass generators—which are treated like conventional thermal plants in the model formulation—are possible. Cost data for renewables also comes from the DIW Data Documentation [5]. Under baseline assumptions, a cap on offshore wind power installations of 32 GW is assumed [9]. We further assume a yearly biomass budget of 60 TWh in the baseline [11]. We calculate hourly renewable availability factors by dividing the 2013 hourly in-feed of onshore wind [12–15], offshore wind [14], and solar photovoltaics (PV) [16–19], provided by the German TSOs, by the installed capacity in the same year [20].[5]

Building on the "Roadmap Storage" [21], we consider seven distinct storage technologies that vary with respect to specific investments into power and energy as well as roundtrip efficiency. In most scenarios, investment choices are restricted to three of these technologies: lithium-ion batteries (Li-ion, as an example for a short-term storage technology), pumped-hydro storage (PHS, medium-term), and power-to-gas (P2G, long-term).[6] The remaining four technologies are included only in a sensitivity analysis. These are considered to be either risky with respect to environmental or security concerns, such as lead acid batteries and sodium-sulfur (NaS) batteries, or not to be cost-competitive with the other storage options like redox flow batteries and advanced adiabatic compressed air energy storage (AA-CAES). For DSM potentials and costs, we largely draw upon [23] who assemble evidence from numerous academic and applied studies, as well as on [24–26].

2.2. Scenario definition

The model is implemented in the General Algebraic Modeling System (GAMS) and solved with the commercial solver CPLEX.[7] We apply the model to a baseline scenario and to numerous sensitivities, while always varying the requirement for the minimum renewable share between 60%, 70%, 80%, 90%, and 100%. In order to study the effects of deviating parameter assumptions, we carry out various sensitivity analyses (Table 1).

A first group of sensitivities deals with different assumptions on the costs and availabilities of power storage technologies: availability of additional storage technologies, deviations of specific investment costs, and a tighter energy cap for pumped-hydro storage. Next, we consider two extreme variations of the assumed DSM potentials, zero or double compared to the baseline. Another group of sensitivities relates to costs and availabilities of renewables. This includes alternative assumptions on offshore wind power costs and potentials—a very important sensitivity for transferring results to other countries with higher or lower offshore wind potentials compared to Germany—smoother onshore wind profiles,[8] and alternative specific investments for PV. Moreover, we include a sensitivity on the availability of biomass and a worst case with respect to variable renewable feed-in by assuming a week of "dark winter-no wind", during which electricity demand is high, but no power generation from onshore wind, offshore wind, or PV is possible. Moreover, we vary the level of required reserves, which may be considered both as a sensitivity with respect to a distinctive model feature or a parameter assumption.

In Appendix A.2, we also provide capacity outcomes for sensitivity analyses with respect to alternative base years. While the patterns of renewable feed-in and load are based on 2013 German data in all aforementioned model runs, we test the effect of alternatively drawing on 2011 or 2012 data. Yet the results are not fully comparable to 2013, as offshore wind feed-in data is less reliable, being based on very few single wind turbines, such that results may be distorted with respect to one decisive variable, that is, offshore wind power deployment.

3. Results

3.1. Baseline scenario

Under baseline assumptions, we determine a renewable share of around 76.4% in the unrestricted case.[9] Photovoltaics and onshore wind power have the largest capacities installed (Fig. 1). If the minimum renewable share approaches 100%, overall capacities in-

[3] All input data is freely available under a Creative Commons Attribution-ShareAlike 4.0 International Public License under http://www.diw.de/dieter.

[4] This assumption appears not to be critical. Additional model runs that include a lignite option parametrized according to Table B.1 show that no such investments take place under the assumed baseline CO_2 price of 100 Euro per tonne, as lignite plants incur both high investments and high variable costs.

[5] For convenience, we impose a linear expansion path on the installed capacities between the beginning and the end of 2013.

[6] Here, "power-to-gas" involves the use of electricity to generate hydrogen and later reconversion to electricity. A more precise, but rather lengthy term would be "power-to-hydrogen-to-power".

[7] Whereas the source code and all input parameters are available under open-source licenses, GAMS and CPLEX are proprietary software.

[8] Profiles are taken from [27].

[9] As the model restriction on the minimal renewable share is not binding for minimum shares of both 60% and 70%, these can be interpreted as "unrestricted" cases. The same reasoning applies in the following. For the sake of consistency, we always show results for 60%, 70%, 80%, 90%, and 100%, respectively.