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The role of grid extensions in a cost-efficient transformation of the European electricity system until 2050

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HIGHLIGHTS

- ▶ Determination of optimal generation capacities and transmission grid extensions.
- ▶ Iterative optimization with market model and load flow analysis.
- ▶ Grid extensions are crucial to achieve climate protection targets cost-efficiently.
- ▶ Grid extensions allow using most favorable sites for renewables in Europe.
- ▶ Grid extensions are mostly preferred to investments in storage units.

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ABSTRACT

A strong and intermeshed electricity grid allows the cost-efficient achievement of renewable energy targets by enabling the use of favorable sites and by facilitating the balancing of stochastic infeed from renewables and electricity demand. However, construction of new lines is currently proceeding slowly in Europe. This paper quantifies the benefits of optimal transmission grid extensions for Europe up to 2050 by iterating an investment and dispatch optimization model with a load flow based grid model. We find that large grid extensions, allowing the full exploitation of the most favorable RES-E sites throughout Europe, are beneficial from a least-cost perspective. If the electricity network were to be cost-optimally extended, 228,000 km would be built before 2050 (+76% compared to today). Only for sites located furthest from large consumption areas in Central Europe would the value of grid extensions not always outweigh its costs. Furthermore, the capacity of transmission lines connecting favorable RES-E sites with demand centers is cost-optimally dimensioned to almost entirely export all RES-E generation that exceeds local electricity demand. Only in periods with the highest infeed of fluctuating renewables, electricity is stored. When optimal grid extensions are impeded, storage investments are chosen to a larger extent.

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1. Introduction and background

In an effort to fight global warming, many countries attempt to reduce CO_2 emissions in the power sector by significantly increasing the proportion of renewable energies in electricity production (RES-E). A highly intermeshed electricity transmission grid may contribute to a cost-efficient achievement of this target by enabling the use of the most favorable RES-E sites and by facilitating the integration of the stochastic infeed of fluctuating RES-E capacities and electricity demand.

In Europe, a large share of the renewable generation is expected to come from wind and solar power. However, the most favorable wind and solar sites are located far from load centers and have stochastic generation. Hence, additional transmission lines are needed to access these sites. Moreover, as wind speed, solar radiation and regional loads are not entirely correlated within a large system, a highly intermeshed electricity transmission grid reduces the need for back-up capacities. Electricity systems can also benefit from a more efficient usage of storage options and regional resources, such as lignite in connection with carbon capture and storage. Although the need for transmission grid extensions in the transformation towards a low-carbon and renewable-based electricity system has been mostly accepted, the construction of new lines is often proceeding very slowly in areas with high population density (see e.g., [1]).

In this paper, we quantify the benefits related with optimal transmission grid extensions for Europe up to 2050 compared to

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moderate interconnector extensions given that ambitious RES-E and CO_2 reduction targets are achieved. We iterate a large-scale dynamic investment and dispatch optimization model for Europe with a load flow based transmission grid model. The approach allows us to determine the optimal deployment of electricity generation technologies and transmission grid extensions from a system integrated perspective and to compare the results to a scenario with exogenous, moderate interconnector extensions.

Whereas the cost-efficient deployment of conventional and renewable technologies in the context of climate protection targets has been analyzed in various papers in recent years (e.g., [2–5]), the transmission grid is often not considered in economic optimization models (e.g., [5]). When considered, it is taken into account by exogenous transmission constraints (e.g., [2,4]) or treated in a context of a radial and not an intermeshed electricity network, implying that a consideration of load flows is not necessary (e.g., [3]).

To consider grid extensions in an intermeshed electricity network is challenging, as different characteristics and rules apply to commercial and physical electricity exchanges between two regions (see e.g., [6] or [7]). Specifically, a commercial trading activity with electricity as underlying is bilateral, whereas the physical settlement generally impacts the entire system. As such, in an intermeshed network, the exact location, size of transmission line extensions and thus the costs required to achieve a certain extension of commercial transfer capacities are specific to the particular structure of the generation system at a certain point in time and have to be identified by load flow analysis.

One of the first attempts to integrate load flow analysis in electricity market models was undertaken by Schweppe et al. [8], who present an economic electricity dispatch model that includes a linearized Direct-Current (DC) load flow model. Applications of this approach can be found in [9] for the Austrian electricity system or in [10] for England and Wales. A European electricity market model including the transmission network via a DC load flow approach is presented in [11]. An earlier version of this model is also applied in [12] to analyze the impact of wind energy extension scenarios in 2020 on the European high voltage grid. The authors use an iterative approach to extend transmission lines based on differences in electricity prices between different nodes. Generation capacities are, however, treated exogenously. Models incorporating endogenous investments in generation and grid capacities are presented e.g., in [13–15]. Whereas in [13,14] the models are run on a low temporal resolution and applied to test systems with only a few technologies,[1] [15] present a model for the electricity and transmission system in Great Britain that is run with comparatively high temporal resolution and a large technological range.

For the large-scale optimization of the European power system, we use an iterative approach to analyze simultaneously optimal grid extensions and optimal generation capacity investments in the context of reaching climate protection targets. One major contribution of our analysis is to quantify to what extent grid extensions are cost-optimally preferred to other options in terms of meeting RES-E and CO_2 reduction targets and balancing fluctuating RES-E. These options include RES-E curtailment, larger use of storage units, generation options being located closer to consumption areas and/or larger shares of dispatchable RES-E. In addition, we quantify the economic effects of delayed interconnector extensions currently observed in Europe, e.g., due to long authorization procedures and opposition from the local population.

The remainder of the paper is structured as follows: In Section 2, we describe the simulation models and the iteration performed between them. Section 3 covers the scenario definitions and results of the scenario analysis. In Section 4, we draw conclusions and provide an outlook of further possible research.

2. Methodology

In the following we describe the electricity market model, the load flow based grid model and the iterative process performed between the two models.

2.1. Electricity market model

We use a dynamic linear dispatch and investment model for Europe, incorporating conventional thermal, nuclear, storage and renewable technologies. The model is an extended version of the long-term investment and dispatch model from the Institute of Energy Economics (University of Cologne) as presented in [16]. Earlier versions of the model have been applied e.g., by [17,18]. For this analysis, the model has been extended by adding endogenous investments in renewable energy technologies. Table 1 provides an overview of the most important model sets, parameters and variables.

The objective of the model is to minimize total system costs, comprising investment, fix operation and maintenance, variable production and ramping costs (Eq. (1)). In addition, combined heat and power plants can yield revenues from the heat market, reducing the objective value.[2] While minimizing total system costs, the model has to ensure that hourly electricity demand within each market region is met (Eq. (2)) and that the peak demand (increased by a security margin) is guaranteed by securely available installed capacities (Eq. (3)).[3] In addition, net imports within the peak demand hour can contribute to this requirement. Eq. (4) formalizes a European-wide RES-E quota and Eq. (5) limits European-wide CO_2 emissions.

$$\begin{aligned}\min \quad TCOST = &\sum_{y\in Y}\sum_{c\in C}\sum_{a\in A}\Bigg[dr_y\cdot\Bigg(AD_{y,c,a}\cdot an_a + IN_{y,c,a}\cdot fc_a\\ &+\sum_{d\in D}\sum_{h\in H}\left(GE^{d,h}_{y,c,a}\cdot\left(\frac{fu_{y,a}}{\eta_a}\right)+CU^{d,h}_{y,c,a}\cdot\left(\frac{fu_{y,a}}{\eta_a}+ac_a\right)\right.\\ &\left.-GE^{d,h}_{y,c,a}\cdot hr_a\cdot hp_y\right)\Bigg)\Bigg] \end{aligned} \tag{1}$$

$$\text{s.t.} \sum_{a\in A} GE^{d,h}_{y,c,a} + \sum_{c'\in C} IM^{d,h}_{y,c,c'} - \sum_{s\in A} ST^{d,h}_{y,c,s} = de^{d,h}_{y,c} \tag{2}$$

$$\sum_{a\in A}\left[\tau^{d,h}_{y,c,a}\cdot IN_{y,c,a}\right] + \sum_{c'\in C}\left[\tau^{d,h}_{y,c,c'}\cdot IM^{d,h}_{y,c,c'}\right] \geqslant pd^{d,h}_{y,c} \tag{3}$$

$$\sum_{c\in C}\sum_{r\in A}\sum_{d\in D}\sum_{h\in H} GE^{d,h}_{y,c,r} \geqslant \omega_y\cdot\sum_{c\in C}\sum_{d\in D}\sum_{h\in H} de^{d,h}_{y,c} \tag{4}$$

$$\sum_{a\in A}\left[\sum_{c\in C}\sum_{d\in D}\sum_{h\in H}\frac{GE^{d,h}_{y,c,a}}{\eta(a)}\cdot ef_a\right] \leqslant cc_y \tag{5}$$

$$GE^{d,h}_{y,c,a} \leqslant av^{d,h}_{c,a}\cdot IN_{y,c,a} \tag{6}$$

$$\sum_{r\in A} sr_r\cdot IN_{y,e,r} \leqslant sp_{r,e} \tag{7}$$

$$\sum_{d\in D}\sum_{h\in H}\frac{GE^{d,h}_{y,c,a}}{\eta_a} \leqslant fp_{y,c,a} \tag{8}$$

Further important model equations bind the electricity infeed and/or the construction of technologies. Infeed and construction

[1] [13] apply their model to a system with 7 existing and 11 possible future generating units. The simulation is done for a 10-year horizon, with each year consisting of 4 load levels. [14] present a case study for a 30 bus system, 6 generation firms and one dispatch period.

[2] The chosen representation of cogeneration plants neglects seasonalities of the demand for district heating. Process heat demand is, in contrast, rather constant throughout the year.

[3] We use a typical day approach, taking into account seasonal and hourly demand profiles, seasonal and hourly variability of wind speeds and solar radiation and seasonal inflow patterns of hydro storages. Within our analysis, we model 4 typical days to represent seasonal demand and RES-E infeed structures. In addition, days were divided into 6 slices, such that in total 24 dispatch periods per year are modeled.

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