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The effect of high levels of solar generation on congestion in the European electricity transmission grid

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HIGHLIGHTS

- We study transmission congestion in Europe with high levels of solar and wind power.
- Solar has a greater impact on the marginal cost of electricity than wind power.
- At solar power penetration levels > 20%, battery storage becomes competitive.
- Solar power correlates strongly with congestion 6–9 h after the solar peak.
- Wind power correlates with longer-term variations in congestion.

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ABSTRACT

The increasing levels of solar power affect the usage and development of electricity grids, both at local distribution level and with respect to potential congestion within the transmission grid. We use a cost-minimising investment model (ELIN) to determine the development of the European electricity generation system up to Year 2050, for two renewable-dominated scenarios: the Green Base scenario, with a Europe-wide, technology-neutral renewable certificate scheme; and the Net Metering scenario, with an additional net metering support scheme for solar power. The system compositions are extracted from the ELIN results for the years 2022 and 2032, and analysed in an hourly dispatch model (EPOD) to study the effects of solar power on marginal electricity costs and transmission congestion. From the results of the investment model, it is clear that the presence of a net metering subsidy scheme significantly affects both the pace at which solar power continues to expand and the geographical distribution of the new capacity. In the dispatch modelling, it can be seen that high penetration levels of solar power have a strong effect on the marginal costs of electricity, since production is concentrated around a few hours each day. At penetration levels of 20–30% of annual electricity demand, solar power production entails a predictable daily marginal cost difference between the solar peak and the evening price peak, which could make short-term storage competitive. Transmission congestion during summer is consistently higher in the systems from the Net Metering scenario than in those from the Green Base scenario, while the opposite is true during winter. Solar power production correlates strongly with congestion 6–9 h after the solar peak, whereas wind power correlates with congestion with respect to more slowly evolving and longer-term variations.

1. Introduction

The global electricity system will have to undergo significant changes in the coming decades, in order to tackle the challenge of limiting climate change, while maintaining a reliable and secure power supply [1]. In recent years, electricity generation from variable renewable sources, i.e., wind and solar power, has expanded rapidly in many regions around the world [2], due to decreasing investment costs and a strong focus on sustainability. Solar power has enjoyed a particularly fast growth during the last 5–10 years for a number of reasons, such as the conveniently small unit sizes, dramatic cost reductions, and strong subsidy schemes. It is likely that solar power will be an important component in a future low-carbon electricity supply [3], but just like wind power, its variable nature poses a challenge in terms of integration into the system.

One important measure to facilitate the integration of variable renewable electricity generation is trading through the transmission grid, which allows for geographical smoothing [4]. In scenarios with high penetration levels of variable renewables, several techno-economic modelling studies have found that transmission grid expansion can

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reduce curtailment [5], reduce the need for backup capacity and energy [6–8], and increase the economic benefits for baseload generators [9]. Further, Fürsch et al. [10] have shown that substantial grid extensions are warranted from a least-cost perspective, in order to reach an 80% share of renewables and 80% reductions in CO_2 emissions (as compared with Year 1990) by Year 2050. Because of the importance of the transmission system in the integration of variable renewables, it is necessary to better understand how the variability affects the usage of the grid.

A crucial step to understand the impact of wind and solar power on the transmission system is to study how they give rise to congestion. Congestion in the transmission grid is an important issue in the integration of variable renewables, since it can lead to curtailment [11]. Bird et al. [12] have reviewed international experiences on curtailment of wind and solar power and found that wind power is already being curtailed due to transmission congestion and although this has not yet occurred for solar power, it may become an issue as penetration levels increase.

Thus, there is a need to understand the effect that solar power has on congestion in the transmission system and how it differs from that of wind power. Within the electric power systems research community, the subject of congestion management has been studied for decades (see, e.g., the review by Kumar et al. [13]), and has more recently often focused on the increasing levels of variable renewable sources (see, e.g., Refs. [14,15]). These studies, however, deal primarily with the issues of designing market systems to distribute the costs of congestion and ensure efficient use of the grid. They do not investigate the effects that possible future generation mixes could have on the transmission grid and how continued expansions of wind and solar power might give rise to congestion in the system. The existing literature that deals with the impact of variable renewables on the transmission grid mainly focuses on least-cost scenarios that are dominated by wind power and only include modest levels of solar power. However, driven by the small unit sizes that enable consumers to become small-scale producers of electricity with the competitive advantage of competing with retail prices of electricity (an effect known as “grid parity”), solar power could expand beyond what is cost-optimal from a system perspective. Some grid integration studies (for example the recent work by Brown et al. [16]) include high levels of solar generation, but do not pinpoint the effect it has on the grid.

Therefore, in this study, we apply an investment model to investigate the development of the electricity supply system (in terms of technology mix) in future scenarios that include high levels of variable renewables with and without a strong subsidy for solar power. In addition, we extract system compositions for years 2022 and 2032, to carry out an in-depth analysis using a dispatch model with a higher temporal resolution. In this model, we investigate how solar power affects congestion and trade patterns in the transmission system, as well as the marginal cost of electricity. Further, the effects of solar power are compared to those of wind power to understand how these two technologies differ in terms of their effect on congestion. Based on this analysis, we can better understand the requirements that solar power imposes on the transmission system and how they differ from wind power.

2. Methods

We studied future scenarios using a cost-minimising linear investment model, ELIN, with subsequent analyses of the systems compositions derived from the ELIN results for those scenarios in a more detailed dispatch model, EPOD. The models have been developed over the past decade and are described in further detail by Göransson et al. [17].

2.1. The ELIN investment model

The ELIN (ELectricity INvestment model) model is a linear cost-minimisation model that places special emphasis on turnover in capital stock that occurs in response to a scenario description. The ELIN model spans the electricity generation systems in the EU-27[1] countries plus Norway and Switzerland, and minimises the total system cost over the period studied (for further details, see Odenberger et al. [18] and Odenberger and Johnsson [19]). In the present work, we exclude the electrically isolated islands of Cyprus and Malta. The investigated area is divided into 50 regions based on transmission bottlenecks identified by ENTSO-E [20] (for more information, see Göransson et al. [17]). A map of the model regions and their names is provided in Appendix C.

To study possible investment trends in the electricity supply the ELIN model takes into account a detailed description of the current power plant structure, which is taken as an input from the Chalmers Power Plant Database [21] and includes location, technical specification, and age of existing power generation units in Europe (EU-27 plus Norway and Switzerland). While the time horizon in ELIN is flexible, we model a time period from Year 2010 to Year 2050, in order to encompass approximately one technical lifetime of the available power plants. Another reason for this choice of time span is that there are clearly specified emission reduction targets within the EU for Year 2050 [22].

The objective in the ELIN model is to minimise total cost of generating electricity for the entire period studied, with the aid of a wide range of current and forthcoming technologies (e.g., wind, solar, carbon capture and storage). The temporal resolution of investment decisions is on an annual basis, whereas the power balances include 16 intra-year time-steps to reflect variations in load as well as in intermittent supply profiles. Thus, the time-steps differentiate between seasonal averages for day-time and night-time hours, but also between weekdays and weekends.

2.2. The EPOD dispatch model

For the dispatch analysis, we use the EPOD model, which derives the cost-minimal dispatch of power plants and trade flows in the transmission system over a period of one year. EPOD uses the same geographical scope and resolution as ELIN and is formulated as a linear optimisation problem, minimising the cost of operation. The time resolution selected for the dispatch analysis in this work is 3 h. To model the power flows in the transmission system, EPOD uses DC load flow constraints, which are linearised versions of the full power flow equations. Each of the 50 regions is used as a node in the transmission system description. More details as to the formulations and assumptions made in the EPOD model are provided by Göransson et al. [17]. In the EPOD setup applied in this work, we do not include load shifting. Start-up and part-load costs are taken into account for thermal power plants by treating each technology as an aggregate and the active (started) capacity as a continuous variable, following the approach described by Göransson [23]. A mathematical formulation of the dispatch model is given in Appendix A.

2.3. Scenarios, input data, and assumptions

All the assumptions made regarding technologies, with the exception of carbon capture and storage (CCS), include the development over time of investment costs taken from the World Energy Outlook assumptions of the IEA from the 2011–2014 editions [24–27], extrapolated for Year 2035 to Year 2050. Costs for CCS technologies are obtained from the Zero Emission Platform [28], where the costs for coal and lignite CCS are based on the oxyfuel technology, and costs for natural gas CCS are based on the post-combustion capture technology. The investment costs, operational and maintenance costs, as well as the technical life-times and maximum annual load factors for the key

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[1] The EU-27 does not include the latest EU member state, Croatia.