WEATHER CONDITIONS AS CHALLENGE FOR THE ELECTRICITY SYSTEMS OF THE FUTURE

Marius Goerge, Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation, Forschungszentrum Jülich, D-52425 Jülich, Germany, +49 2461/614151, m.goerge@fz-juelich.de
Stefan Vögele, Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation, Forschungszentrum Jülich, D-52425 Jülich, Germany, +49 2461/613393, s.voegele@fz-juelich.de
Andrew Ross, Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation, Forschungszentrum Jülich, D-52425 Jülich, Germany, +49 2461/ 611798, a.ross@fz-juelich.de

Overview

The electricity sector faces many challenges, such as fluctuating fuel prices, market liberalization, implementing emission trading systems, and new/emerging technologies. Changes in technology prioritization by policy makers, in particular climate change policies, are a major challenge for the electricity sector. The large-scale transformation of the electricity sector towards green energy presents a huge challenge in the future. In addition, increasing renewable energy capacities poses challenges to energy supply security. For example, solar and wind power generation is heavily influenced by weather conditions like wind speed, solar irradiation, and air temperature. While many studies have shown that an increase in solar and wind electricity production reduces wholesale electricity prices (known as the merit order effect), only a few studies have explored the weather's impact on the electricity system and its key metrics, like prices, supply, trade, and demand [1-3]. There is currently limited knowledge on how (future) weather conditions might impact the (future) distribution of electricity among producers and consumers, such as how they are affected by power shortages during lulls or cold, dark doldrums. To address this, our study aims to identify how continual fluctuations in weather conditions might impact the European electricity system in the future. Specifically, we investigate how changes in wind speed and solar irradiation will impact renewable energy generation, wholesale electricity prices, electricity exchange, and producer surplus in Germany and other European countries by 2030. We use a bottom-up electricity dispatch model for Europe to conduct our analysis. It is important to note that we use historical weather data to analyse how the future electricity system would cope with weather conditions already experienced.

Methods

To assess the impact of weather conditions on the electricity system, we employ a bottom-up electricity dispatch model for Europe called EMME [3-5]. This model is based on two assumptions. First, power plant operators aim to minimize running costs. Second, at any given point in time, electricity supply must meet electricity demand. Electricity can be supplied through domestic power plants or by importing electricity from a foreign country. The import/export capacities are constrained by existing infrastructure. The EMME model is outlined mathematically as follows:

Objective function:

$$\min Z = \sum_{h,i,d} [Pr(h,i,d) \cdot Cst(i,d)] + \sum_{h,d,k} Im(h,d,k) \cdot T \qquad (1)$$

Constraint 1: Demand has to be fulfilled

$$\sum_{h,i,d} Pr(h,i,d) + \sum_{h,d,k} Im(h,d,k) = Dm(h,d) \qquad (2)$$

Constraint 2: Only existing capacity can be used

$$\mathrm{Pr}(h,i,d) \leq \mathrm{Cp}(h,i,d) \qquad (3)$$

Constraint 3: Limited exchange capacity is available

$$Im(h,d,k) \leq NTC(d,k) \qquad (4)$$

with:

i:	generation technology type	Cp:	generation capacity [MW]
h:	specific hour of the year [-]	Im:	electricity imports from country k to country d [MWh]
T:	transport costs for imports and exports [€/MWh]	Dm:	electricity demand [MWh]
d and k:	country indexes [-]	NTC:	net transfer capacity between two markets [MW]
Cst:	variable generation costs [€/MWh]	Pr:	electricity production [MWh]

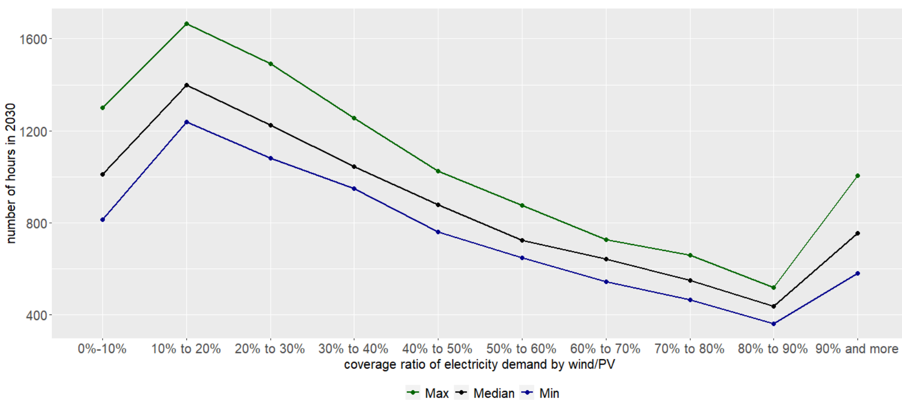
Using the EMME model, we investigate the effects of weather conditions on the European electricity system in the year 2030. We use data from the Distributed Generation (DG) scenario from ENTSO-E [6] to obtain information on how the European electricity system might look in 2030. This scenario was published in 2018 as part of the 10-year network development plan (TYNDP). Specifically, we use information on installed capacity, energy prices, and expected electricity demand in 2030 based on the DG scenario. To take variations in weather conditions into account, we use data from the open data platform Renewables.ninja [7] on the capacity factors of wind (onshore/offshore) and PV as indicators of wind availability and solar irradiation, respectively. Capacity factor is defined as the average power generated by turbines relative to their peak capacity. We use hourly data on capacity factors for each year between 1980 and 2019 on a national level for all European countries.

By implementing this data into the EMME model in combination with the DG 2030 scenario, we can simulate the electricity production, power trading, wholesale market prices, and the producer surplus in the European electricity market in 2030, assuming the past weather conditions in the period 1980-2019.

Results

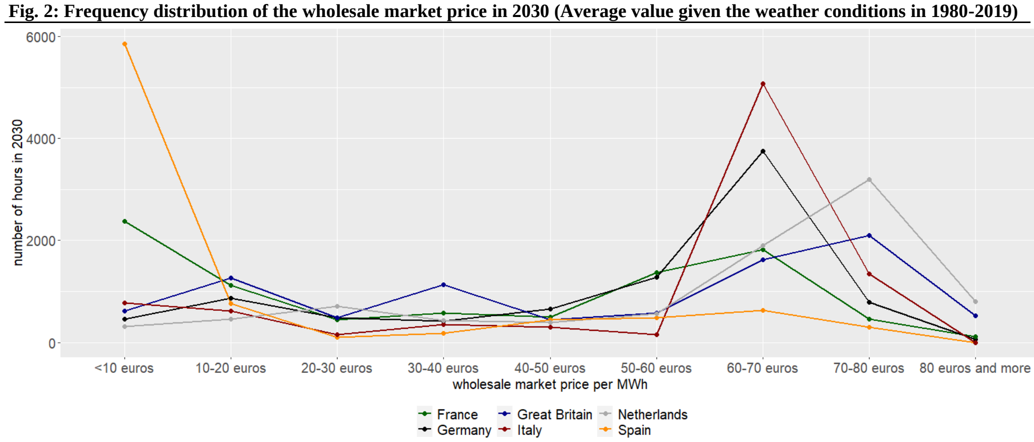
Preliminary results are shown in Fig. 1, showing the frequency distribution of covering electricity demand by renewables production in 2030 in Germany. The graph expresses the average distribution based on 40 different frequency distributions of the demand coverage ratio, given the weather conditions of each year in 1980-2019. The figure can be read as follows: Given the average weather conditions in the period 1980-2019, it is expected that in about 2,410 hours in 2030, the renewables wind and PV will only be able to cover total electricity demand in Germany by at most 20%. In other words, this accounts for more than one quarter of overall time in 2030. Otherwise, electricity production of these renewables will be enough to capture 90% and more of electricity load in Germany in only 760 hours, i.e., 9% of overall time in 2030. Therefore, Fig. 1 illustrates significant fluctuations and uncertainties regarding the future potential of renewables in Germany in satisfying the domestic demand for electricity, even if we neglect potential extreme weather events, but focusing on average weather conditions.

Fig. 1: Frequency distribution of the coverage ratio of electricity demand by renewables in 2030 (Average value given the weather conditions in 1980-2019)



Our findings have several implications for the electricity market in Germany and Europe. The merit-order effect suggests that low values of electricity generation by renewables and low demand coverage ratios will also influence electricity market prices in Germany. With the EMME model, we can simulate the effect of fluctuations in wind and solar availability on both electricity production and wholesale market price. As shown in Fig. 2, we expect high electricity market prices for most hours in Germany in 2030 compared to France, Great Britain, and Spain. Specifically, we find that in 53% of total time in 2030, the average wholesale market price will be at least 60 euros per MWh in Germany, while electricity prices in Spain will mostly be below 10 euros per MWh due to favourable weather conditions, especially in terms of solar irradiation. France is less likely to experience significant peaks in electricity market prices due to the high relevance of electricity generation by nuclear energy, which equalizes potential renewables shortages during dark doldrums. Using the EMME model, we also calculated the producer surplus of electricity suppliers. With higher prices, the producer surplus per MWh will increase. Therefore, we expect renewables energy suppliers in Germany to be the main beneficiaries compared to Spanish, French, and British producers.

Fig. 2: Frequency distribution of the wholesale market price in 2030 (Average value given the weather conditions in 1980-2019)



Going forward, we intend to improve the analysis by investigating the volatility of electricity generation, wholesale market prices, and producer surplus in Germany in terms of fluctuations in weather conditions in 2030. We will then compare it with the resilience of other European countries' electricity systems. Additionally, we will conduct a sensitivity analysis by running the EMME model with other ENTSO-E scenario data.

Conclusions

Our preliminary results indicate that assuming the weather conditions observed during the period 1980-2019, Germany is likely to face insufficient electricity supply from renewables to cover domestic demand in 2030. This is due to fluctuations in wind availability and solar irradiation across different daytimes and seasons, resulting in low demand coverage ratios and periods of low-capacity utilization of wind and solar power plants. The unavailability of renewables capacities will lead to higher prices on the wholesale market and higher producer surpluses. Our EMME model shows that Germany, with power plant stocks dominated by renewables, will be more affected by higher prices than other countries like Spain and France in 2030. These higher prices will also lead to higher expenditures on electricity, disadvantaging the end consumer. Therefore, changes in weather conditions have economic distribution effects between producers of renewables and end consumers of electricity. From a policy perspective, given the political commitments to reach climate targets and the need to transform the electricity system towards renewable energy capacities, weather conditions are expected to play a more crucial role in ensuring energy security in the future than in the past. As such, large investments in new wind and solar power plants are necessary to minimize shortages in electricity generation. Additionally, electricity storage capacities are vital to increase the probability of continuous electricity supply throughout the day and year. Conventional power plant capacities also play a relevant role in counteracting shortages in renewables electricity generation due to their flexible usability in the short-term. Finally, a large-scale and efficient electricity transfer system between European countries can guarantee power system stability and security of energy supplies during periods of dark doldrums.

References

1. Tanaka, K., et al., *The impact of weather changes on the supply and demand of electric power and wholesale prices of electricity in Germany.* Sustainability Science, 2022. **17**(5): p. 1813-1825.
2. Staffell, I. and S. Pfenninger, *The increasing impact of weather on electricity supply and demand.* Energy, 2018. **145**: p. 65-78.
3. Pittel, K., et al., *International Climate Policy and Economic Perspectives*, in *Handbook of Climate Change Mitigation and Adaptation*, W.-Y. Chen, T. Suzuki, and M. Lackner, Editors. 2021, Springer: Heidelberg and Berlin.
4. Mayer, P., et al., *Analyzing Brexit: Implications for the Electricity System of Great Britain.* Energies, 2019. **12**: p. 1-27.
5. van Vliet, M.T.H., S. Vögele, and D. Rübbelke, *Water constraints on European power supply under climate change: impacts on electricity prices.* Environmental Research Letters, 2013. **8**: p. 1-11.
6. ENTSO-E, *TYNDP 2018 Scenario Report - Main Report*. 2018.
7. Pfenninger, S. and I. Staffell, *Renewables.ninja*. https://www.renewables.ninja/.