Locational (In)Efficiency of Renewable Energy Feed-In Into the Electricity Grid: A Spatial Regression Analysis

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In order to mitigate climate change, governments all over the world have started a sustainable transformation of their energy generation systems. The associated introduction of renewable energy sources (RESs) into the energy system has led to a significant transformation of the energy sector in numerous countries worldwide. While most energy systems can accommodate moderate shares of variable renewables, severe challenges, such as grid imbalances or massive curtailment of electricity generation, occur at higher shares. Germany, as one of the forerunners in transforming the energy system ("Energiewende"), has already experienced such challenges in the past. A major reason for these challenges is that variable renewables, such as solar and wind energy, are located in regions with favorable weather conditions, which, in Germany, have a quite low energy demand. This leads to an imbalance of electricity supply and demand. Further stress factors for the energy system originate from the rising share of intermittent electricity production and the direct infeed of the produced electricity into the distribution grid. These changes in the electricity generation require an expansion and reinforcement of the electricity infrastructure. However, due to public resistance, this expansion and reinforcement is lagging behind. As a result, a local overstress of the electricity infrastructure can occur in times of high renewable electricity production. In order to still balance electricity supply and demand, system operators often need to reduce the production output of renewable and conventional power plants. In 2017, the system operators reducted 5,518 gigawatt-hour (GWh) of renewable energy output—the so-called *RES curtailment*. This accounts for approximately 2.9% of the total electricity produced by renewables. The associated costs for RES curtailment totaled €610 million in 2017.

In this context, our study aims at identifying the main drivers for curtailing renewables and at explaining the regional variability of RES curtailment costs. More specifically, we analyze the RES curtailment costs of four distribution system operators (DSOs) in Germany in the period 2015–2017 by means of an econometric model. To further refine the analysis, the DSO regions are partitioned into 1,111 subregions based on substations on the high-to-medium voltage level. To this end, we apply a Voronoi tesselation, which allocates all renewables and conventional power plants to the closest substation.

In order to investigate RES curtailment costs, we apply a two-step Heckit sample selection model, which accounts for non-randomly selected variables. The selection equation is a binary choice model that estimates the probability of occurrence of curtailment in a subregion associated with different types of renewables, conventional power plants, and the prevalent load. This analysis considers all subregions of the respective DSOs. In contrast, the outcome equation considers only those subregions that experienced curtailment costs in each year of the period 2015–2017. The latter

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model aims at monetarizing the effects of different types of renewables and conventional power plants on RES curtailment. The model corrects for cross-sectional dependence by combining a spatial econometric model and a correlated common effects model. The analysis is conducted once using the installed capacities and once using the generated electricity of various types of renewables. The generation technologies considered are wind and solar power as well as biomass, hydroelectric, and conventional power plants.

The investigation of RES curtailment costs in Germany shows that only a very few subregions account for the majority of total curtailment costs. Of all subregions considered, only a quarter experienced RES curtailment in the period 2015–2017. The applied selection equation indicates that an additional megawatt (MW) of the capacity of wind energy, solar power, and biomass power plants increases the likelihood of occurrence of curtailment in a subregion by 0.3% each. When taking into account the generated electricity instead of the installed capacity, the numbers vary but also indicate a positive impact of these renewables on RES curtailment (wind energy systems and biomass power plants +0.07% per GWh and PV systems +0.5% per GWh). A further result is that higher electricity demand in a subregion decreases the probability of occurrence of RES curtailment (–0.04% per GWh). The outcome equation shows that only wind energy systems have a significant effect on RES curtailment costs in the subregions considered. In contrast, all other power plants and the prevalent load do not exert a significant effect. Increasing the installed capacity of wind energy systems by one MW raises the curtailment costs in a subregion by 0.7%. Similarly, one GWh of additional electricity produced increases the costs by 0.2%. In the most affected subregions, which are located mostly in northern and eastern Germany, this increase is associated with RES curtailment costs of approximately 28,250 €/MW and 8.10 €/MWh. In other words, in the examined period between 2015 and 2017, the yearly RES curtailment costs in the affected subregion induced by an additional MW of capacity of wind energy amounts to approximately 1.8% of the average overall costs of wind energy systems in Germany. The costs associated with the generated electricity equals approximately 9.2% of the remuneration tariff for wind turbines. These costs are passed on to the consumers in the region concerned.

The results imply that an uncontrolled deployment of renewables, especially of wind turbines, induces additional costs due to the overstress of the electricity infrastructure. These costs need to be internalized by the operator of renewable power plants in order to enable a welfare-enhancing deployment of renewables. A welfare-enhancing deployment implies that all costs associated with the electricity generation and transmission are internalized. A possible policy regime to achieve a welfare-enhancing siting of renewables would be to set regionally varying price signals that account for congestion in the transmission and distribution grid. In addition to steering the siting of renewables, a further instrument to enhance social welfare might be to promote flexibility options in regions with a high amount of curtailed electricity. Such flexibility options comprise, among other things, energy storage systems, electric vehicles, or power-to-heat and power-to-gas applications.