The economics of wind & solar variability - How the variability of wind and solar power affect their marginal value, optimal deployment, and integration costs

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Non-technical summary

Variable renewable energy sources (VRE) for electricity generation, such as wind and solar power, are subject to inherent output fluctuations. This variability has significant impacts on power system and electricity markets if VRE are deployed at large scale. While on global average, wind and solar power currently supply only a minor share of electricity, they are expected to play a much larger role in the future – such that variability will become a major issue (which it already is in some regions). This thesis contributes to the literature that assesses these impacts the "system and market integration" literature.

This thesis aims at answering the question: What is the impact of wind and solar power variability on the economics of these technologies? It will be laid out that the impact can be expressed in (at least) three ways: as reduction of value, as increase of cost, or as decrease of optimal deployment. Translating between these perspectives is not trivial, as evidenced by the confusion around the concept of 'integration costs'. Hence, more specifically: How does variability impact the marginal economic value of these power sources, their optimal deployment, and their integration costs? This is the question that this thesis addresses.

This study comprises six papers, of which two develop a valuation framework that accounts for the specific characteristics of the good electricity, and the specific properties of wind and solar power versus "dispatchable" power plants. Three articles then assess quantitative questions and estimate marginal value, optimal deployment, and integration costs. These estimates stem from a newly developed numerical power market model, EMMA, market data, and quantitative literature reviews. The final paper addresses market design.

In short, the principal findings of this thesis are as follows. Electricity is a peculiar economic good, being at the same time perfectly homogenous and heterogeneous along three dimensions - time, space, and lead-time. Electricity's heterogeneity is rooted in its physics, notably the fact it cannot be stored. (Only) because of heterogeneity, the economics of wind and solar power are affected by their variability. The impact of variability, expressed in terms of marginal value, can be quite significant: for example, at 30% wind market share, electricity from wind power is worth 30-50% less than electricity from a constant source, as this study estimates. This value drop stems mainly from the fact that the capital embodied in thermal plants is utilized less in power systems with high VRE shares. Any welfare analysis of VRE needs to take electricity's heterogeneity into account. The impact of variability on VRE cannot only be expressed in terms of marginal value, but also in terms of costs, or in terms of optimal deployment. The mentioned value drop corresponds to an increase of costs by 30-50%, or a reduction of the optimal share by two thirds.

These findings lead to seven policy conclusions:

1. Wind power will play a significant role (compared to today).
2. Wind power will play a limited role (compared to some political ambitions).
3. There are many effective options to integrate wind power into power systems, including transmission investments, flexibilizing thermal generators, and advancing wind turbine design. Electricity storage, in contrast, plays a limited role (however, it can play a larger role for integrating solar).
4. For these integration measures to materialize, it is important to get both prices and policies right. Prices need to reflect marginal costs, entry barriers should be tiered down, and policy must not shield agents from incentives.
5. VRE capacity should be brought to the system at a moderate pace.
6. VRE do not go well together with nuclear power or carbon capture and storage – these technologies are too capital intensive.
7. Large-scale VRE deployment is not only an efficiency issue, but has also distributional consequences. Re-distribution can be large and might an important policy driver.