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Spatial dependencies of wind power and interrelations with spot price dynamics

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ABSTRACT

Wind power has seen strong growth over the last decade and increasingly affects electricity spot prices. In particular, prices are more volatile due to the stochastic nature of wind, such that more generation of wind energy yields lower prices. Therefore, it is important to assess the value of wind power at different locations not only for an investor but for the electricity system as a whole. In this paper, we develop a stochastic simulation model that captures the full spatial dependence structure of wind power by using copulas, incorporated into a supply and demand based model for the electricity spot price. This model is calibrated with German data. We find that the specific location of a turbine – i.e., its spatial dependence with respect to the aggregated wind power in the system – is of high relevance for its value. Many of the locations analyzed show an upper tail dependence that adversely impacts the market value. Therefore, a model that assumes a linear dependence structure would systematically overestimate the market value of wind power in many cases. This effect becomes more important for increasing levels of wind power penetration and may render the large-scale integration into markets more difficult.

1. Introduction

The amount of electricity generated by wind power plants has increased significantly during recent years. Due to the fact that wind power is stochastic, its introduction into power systems caused changes in electricity spot price dynamics: Prices have become more volatile and exhibit a correlated behavior with wind power fed into the system. In times of high wind, spot prices are observed to be generally lower than in times with low production of wind power plants. Empirical evidence of this effect has been demonstrated for different markets characterized by high wind power penetration, e.g., by Jónsson, Pinson, and Madsen (2010) for Denmark, Gelabert, Labandeira, and Linares (2011) for Spain, Woo, Horowitz, Moore, and Pacheco (2011) for Texas or Cutler, Boerema, MacGill, and Outhred (2011) for the Australian market. Due to the cost-free availability of wind energy, wind power plants are characterized by marginal costs of generation that are close to zero and therefore lower than those for other types of power plants such as coal or gas. Hence – if the wind blows – wind power replaces other types of generation and thus leads to lower spot market prices in such hours. As a consequence, power plants are faced with increasingly difficult conditions and an additional source of price risk when participating in the market. Until now, fluctuating renewable energy technologies (including wind power itself) have often been exempted from this price risk by support mechanisms (e.g., by fixed feed-in-tariff systems) in order to incentivize investments. However, their price risk draws more and more attention as they make up an increasing share of the generation mix and may at some point be fully integrated in the liberalized power market. Therefore, for an individual investor as well as for a social planner it becomes increasingly important to understand the value of wind generation and how it depends on the location of the wind turbine.

The purpose of this paper is to derive revenue distributions and the market value of wind power, i.e., the weighted average spot price wind power is able to achieve when selling its electricity on the spot market, at specific locations. It is clear that the value of a wind turbine at a specific location depends on whether it tends to produce when many other wind turbines at other locations can also produce, or whether it is one out of few producers at a given time. To capture the full stochastic dependence structure of wind power, we use copulas and incorporate the stochastic wind generation in a supply and demand based model for electricity prices. More precisely, we take the following two steps. At first, we develop a stochastic simulation model for electricity spot prices that incorporates the market's aggregated wind power as one of

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the determinants. We use the residual demand, given by the difference of total demand and aggregated wind power, to establish the relationship between wind power and spot prices. Secondly, we link the market's aggregated wind power to the wind power of single turbines in order to quantify their market value and the revenues depending on their specific location. We use copulas to model this interrelation. The model is calibrated with German data, since Germany already has a high share of wind power.

We find that taking into account the entire spatial dependence structure is indeed necessary, and that considering only correlations between a specific turbine and the aggregate wind power would be misleading. Even if the correlation of a specific turbine is lower compared to another, the resulting market value may be lower due to a non-linear, asymmetric dependence structure. In fact, we find a pronounced upper tail dependence that adversely impacts the market value for many of the locations analyzed. Therefore, a model solely based on linear dependence measures would systematically overestimate the market value of wind power in many cases. Moreover, it is shown that this effect becomes increasingly important for higher levels of wind power penetration.

Our paper contributes to three lines of literature. First, we complement the literature on supply and demand based models. Within this class of models, Bessembinder and Lemmon (2002) were among the first to study the importance of demand and production costs for electricity prices. The model developed by Burger, Klar, Müller, and Schindlmayr (2006) follows a similar conceptual approach by including a non-linear functional dependence of the electricity spot price on a stochastic demand process as well as a long-term non-stationarity. Howison and Coulon (2009) further extend the number of state variables explaining the electricity spot price by including fuel prices. With our paper, we contribute to this line of literature by including stochastic production quantities of wind power that may impact the supply side and hence electricity prices.

Secondly, we extend the literature employing copulas, especially in the context of wind power applications. Copulas have first been identified by Papaefthymiou (2006) to be a suitable tool for modeling multivariate dependencies of wind speeds. Subsequently, copulas have been employed in different studies to model spatial and temporal dependencies of wind speeds or wind power. Spatial dependencies have been modeled with the help of copulas by Haghi, Bina, Golkar, and Moghaddas-Tafreshi (2010) for PV and wind power as well as system load in an Iranian case study, by Grothe and Schnieders (2011) for wind speeds in an optimization problem minimizing aggregated wind power fluctuations in Germany, by Hagspiel, Papaemannouil, Schmid, and Andersson (2012) for wind speeds in a European probabilistic load flow analysis, and by Louie (2014) for power generation from a multitude of pairs of wind turbines in order to identify the best-suited bivariate copula models. In contrast, copulas are used for temporal dependence structures in Pinson and Girard (2012) to model the multivariate stochastic process of short-term wind power trajectories (based on a methodology developed in Pinson, Madsen, Nielsen, Papaefthymiou, & Klöckl (2009)) and in Zhou et al. (2013) to investigate wind power forecasting based on probabilistic kernel densities. We contribute to this second line of literature by applying conditional copulas to model the dependence structure between specific turbines and the aggregated wind power. This approach allows us to specify and investigate interrelations between the physical characteristics of a wind turbine and electricity spot prices, and hence to value wind power assets more appropriately.

In fact, the valuation of power generation assets is the third line of literature our paper complements. So far, research on the valuation of power generation assets has mainly focused on conventional power (e.g., Thompson, Davison, & Rasmussen (2004), Porchet, Touzi, & Warin (2009) or Falbo, Felletti, & Stefani (2010)) and the optimization of hydro power schedules (e.g., Garcfa-González, Parrilla, & Mateo (2007) or Densing (2013)). The relatively few papers that deal with the valuation of wind power is primarily based on historical data of wind power and day-ahead market prices (e.g., Green & Vasilakos (2012)). In a recent study presented by Girard, Laquaine, and Kariniotakis (2013), wind power predictability is assessed as a decision factor during the planning phase of a wind power project, showing that the financial loss due to imbalance costs induced by imperfect predictions only represents a low share of revenue in the day-ahead market. Even though they find that the aggregation of wind farms over large distances has an impact on the market value, they do not further elaborate on spatial dependencies. Our paper concentrates on this particular issue and shows that spatial dependencies are indeed crucial for the market value of wind power projects, especially for increasing penetration levels.

The remainder of this article is organized as follows: Section 2 provides a short introduction to copula modeling with a particular focus on conditional copula sampling which we apply in our model. The model itself is presented in Section 3. Section 4 reports the results of the methodology applied to the case of wind power in Germany, namely the revenues and the market value of specific wind turbines. Section 5 concludes.

2. Stochastic dependence modeling using copulas

In this section, we briefly discuss the modeling of stochastic dependencies with the help of copulas. A more detailed introduction is provided e.g., in Joe (1997), Nelsen (2006) or Alexander (2008). For a comprehensive literature review of the current status and applications of copula models, the interested reader is referred to Genest, Gendron, and Bourdeau-Brien (2009), Durante and Sempi (2010) and Patton (2012).

2.1. Copulas and copula models

A copula is a cumulative distribution function with uniformly distributed marginals on $[0,1]$. Sklar's theorem is the main theorem for most applications of copulas, stating that any joint distribution of some random variables is determined by their marginal distributions and the copula (Sklar, 1959). The bivariate form of Sklar's theorem is as follows: For the cumulative distribution function $F: \mathbb{R}^2 \to [0,1]$ of any random variables X, W, with marginal distribution functions F_X, F_W, there exists a copula $C: [0,1]^2 \to [0,1]$ such that

$$F(x,w) = C(F_X(x), F_W(w)). \tag{1}$$

Sklar's theorem also holds for the multivariate case of $n > 2$ dimensions. The copula function is unique if the marginals are continuous. Conversely, if C is a copula and F_X and F_W are continuous distribution functions of the random variables X, W, then (1) defines the bivariate joint distribution function. From Sklar's theorem, it follows that copulas can be applied with any marginal distributions. Particularly, marginal distributions may differ for each of the random variables considered.

In our application we are interested in the dependence structure of the market's aggregated wind power W and a single turbine wind power X. The copula captures the complete dependence structure of X and W. The selection of an appropriate copula model can be made independent from the choice of the marginal distribution functions. Taking advantage of this, the joint distribution of W and X is determined in a two stage process: First, the marginal