ON THE RELATION BETWEEN WIND POWER GENERATION, ELECTRICITY PRICES AND THE MARKET VALUE OF WIND POWER

Carlo OBERSTEINER[a,*], Marcelo SAGUAN[b,c], Hans AUER[a], Céline HIROUX[c]

[a]*Energy Economics Group (EEG), Vienna University of Technology*
Gusshausstrasse 25-29/373-2, 1040 Vienna, Austria

[b]*Department of Power and Energy Systems, SUPELEC*
3 rue Joliot Curie, 91192 Gif sur Yvette, France

[c]*GRJM, Faculté Jean Monnet, University of Paris XI*
27 avenue Lombart, 92260 Fontenay aux Roses, France

Abstract

Empirical analyses indicate that the market value of wind power is lower than the baseload price even if wind power generation shows baseload characteristics on average. In order to explain this effect we investigate the relation between wind power generation and electricity wholesale prices and identify key parameters that are affecting the market value of wind power based on simulations for a stylised system. Results indicate that the wind share, the supply characteristics, the variance of wind power and the correlation between wind power and demand influence the market value of wind power generation significantly. In power markets with significant wind power shares the baseload prices turns out to be no proper indicator for the market value of wind power. For current wind power and system characteristics instead we might expect the market value of to be significantly lower than the baseload price. When estimating the future need for supporting wind power it is crucial to take this effect into account.

Introduction

In the last decade selected European electricity markets have faced a significant increase of wind power. Given the ambitious 2020 targets of the European Commission for Renewable Energies we can expect the historic trend to continue in the short to medium term.

As marginal cost of wind power is almost zero, rising amounts of wind power ceteris paribus have a dampening effect on electricity prices for a given power system. Even if wind power today in most power systems is not sold directly on the power market this so called merit order effect can already be observed and has been studied for Germany in Neubarth et al. (2006) and Bode (2006). It is important to note that this effect is not wind power specific but might be observed for any power generation technology with low marginal cost of generation that is pushed into the market.

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[*] Corresponding author. Tel.: +43 1 58801 37367; fax: +43 1 58801 37397.
E-mail address: obersteiner@eeg.tuwien.ac.at

In the long-term however increasing wind shares will influence the investment decision for conventional power plants which has to be taken into account to get a complete picture of the influence of wind power on power prices.

From the power producers point of view the merit order effect lowers the market value of power generation i.e. the average price for selling power on the wholesale power market. In contrast to a base load generation technology i.e. a technology that produces a fixed quantity constantly, for a variable generation technology like wind power there is a correlation between power generation and electricity prices which is inherent to the system. For a power system that is specified by a certain supply structure and a fixed demand we might observe "low" electricity prices when wind power generation is high because the residual demand can be met with less costly conventional generation and vice versa. The question arises, in which direction and to which extent this relation influences the market value of wind power.

To understand principles and parameters that are affecting the market value of wind power is crucial for a number of stakeholders. Policy makers have to take the (economic) performance of generation technologies into account within their strategic decisions. Regulators base the design of support schemes on expectations on the market value of RES-E technologies that determines the cost of support. Finally depending on the support mechanism the market value of wind power may also influence the investment decision of potential investors.

Within an investigation of the long-term system value of intermittent power generation technologies Lamont (2008) finds, that the market value of wind power decreases with increasing wind shares while the average system price remains stable. He identifies the decrease in covariance between wind power generation and power prices to be the reason for this effect.

Based on this finding we aim to investigate in more detail the impact of fundamental wind and system related parameters on the market value of wind power. We therefore carry out both empirical analyses and simulations for a stylised system based on historical data for Germany and Austria.

Both the Austrian and the German power system are part of the Central European electricity market which covers besides these two countries also France and Switzerland[2]. The major power exchange in this area is the European Electricity Exchange (EEX) which offers auctions for the market areas Austria/Germany and Switzerland. Therefore prices at the EEX seem to be well suited to assess the market value of wind power for Austria and Germany.

Our stylised system allows as to simulate the wind power market value for a range of key parameters (system demand, supply curve, wind power share, wind power generation pattern, etc.). Note that, in contrast to Lamont's work, we don't model optimal supply portfolios for given wind shares but focus on sensitivities for given system configurations. Our simulations are "static" meaning that changes in parameters are not endogenous. However, results developed here may be extrapolated in dynamic (or long term) uses, just assuming a certain evolution of key parameters in the dynamic horizon.

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[2] After the introduction of market coupling between France, Belgium and the Netherlands wholesale power prices in the two Benelux countries tend to converge towards the price level in the Central European Electricity Market. A similar trend can be observed for the Czech Republic (see Haas et al. (2008)).

This paper is organized as follows. In section 1, main parameters influencing the market value of wind power are identified. In section 2 the modeling and simulation framework to assess the market value of wind power for different situations is explained. Section 3 presents and discusses results from simulations. Section 4 concludes.

1. Main parameters influencing the market value of wind power

The aim of this section is to identify main parameters influencing the market value of wind power. We define market value of wind power as the sum of revenues by unit of energy if all wind power production were sold in the power exchange.

When identifying the market value for a specific generation technology as interpreted within this paper it is important to note that there is no single but a broad range of market values depending on the supposed trading strategy. Wind power might e.g. be sold on the long-term market i.e. bilaterally or in form of baseload futures and additionally short-term deviations based on wind power forecasts may be settled on the day-ahead market. Finally deviations between trading schedules and actual generation are settled with imbalance clearing prices within the balancing mechanism. The market value is finally results in the sum of revenues (and cost) from several trading activities as illustrated in Obersteiner and von Bremen (2008). Within this paper we don't aim to investigate imbalance cost and trading strategies. Therefore imbalance costs are neglected when determining the market value and we define prices of day-ahead auctions at the EEX as the reference for the empirical analyses.

In order to idenfy crucial parameters influencing wind power market value, we start to analyse Lamont's findings. A key analytical finding from Lamont (2008) is that market value of wind power can be split up in two components: i) a "baseload" power price component and ii) a component related to the covariance between the power price and wind power production. This relation could be seen in (1).

$$MV_W = \frac{\sum_{h=1}^{H} \pi_{PX,h} \cdot Q_{W,h}}{\sum_{h=1}^{H} Q_{W,h}} = \overline{\pi}_{PX} + \frac{\operatorname{cov}(\pi_{PX}, Q_W)}{\overline{Q}_W} \tag{1}$$

where MV_W is the market value of wind power, $\pi_{PX,h}$ is the power price at the power exchange in hour h, $Q_{W,h}$ is the wind power generation in hour h, π_{PX} is the power price vector and Q_W is the wind power generation vector.

Empirical analyses support these analytical findings. In 2006 the average baseload price at the EEX spot market is 50.9 €/MWh. The wind power volume weighted average price i.e. the market value is 48.7 €/MWh and 45.1 €/MWh for Austrian and German wind power respectively. Results for the correlation between (hourly) wind generation and spot prices are consistent with observed market values: For both countries the correlation is negative whereas for Germany the (absolute) number is higher (-0.13) than for Austria (-0.05) which goes in line with the higher deviation from the baseload price. On a monthly basis the deviation between average market value and baseload price (market value minus baseload price) varies between 23.8 and -1.8 €/MWh for Austria and 18.4 and -0.5 €/MWh for Germany.

A further finding from Lamont (2008) is that the market value of wind power decreases with increasing wind power share and this is because increasing wind share decreases covariance between wind power and power price.

If we would like to generalise Lamont's findings, two questions arise: i) which parameters are affecting the covariance between wind power and power price and ii) how might these parameters evolve with increasing wind shares? Therefore we identify fundamental parameters determining the correlation between generation and power prices and filter out those being specific to wind power.

In a competitive power market, the wholesale price is determined by the generation costs of the marginal technology i.e. the SRMC of the most expensive plant which is needed to satisfy demand. Therefore price variations may originate from variations in generation costs of the marginal technologies, from variations in demand or from variations in the availability of power generation (determining the shape of the supply curve). In a non-competitive setting, prices may additionally be affected by strategic behaviour of market actors.

As gas and coal power plants represent the marginal technologies in the Central European power market variations in generation cost are mainly related to gas and coal and CO2-certificate price developments. Power demand is stochastic in nature but follows a typical yearly and daily pattern. Finally the availability of power generation is determined by the availability of natural resources in the case of hydro and wind power and by maintenance schedules and at a progressive rate by cooling restrictions for thermal power plants.

We assume that fuel and CO2 price shocks are not correlated with wind power generation. Therefore these shocks may determine the market value of wind power in relation to the baseload price in a specific consideration period but in the long run their impact should smooth out. However there might be a statistical relation between wind power generation, hydro power and power demand. Within this paper we investigate the relation between wind power and demand only and neglect the wind power hydro power relation.

Given the principle of price formation there is an inherent relation between wind power generation and power prices as described above. Parameters that determine the extent of this relation include the share of wind power on system demand, the characteristics (form) of the supply curve and the characteristics of wind power (variance, probability distribution). The impact of these parameters on the market value of wind power is investigated within this paper for a stylised system.

2. Modelling the interaction between wind power and power prices

The characteristics of the stylised power system are represented by a continuous function – the supply curve – which describes the relation between the quantity of supply Q_S and the marginal cost MC at which this quantity may be produced:

$$MC = a + Q_S{}^b \tag{2}$$

with a and b being constants greater than zero. The supply curve represents several generation technologies except from wind power and is assumed to be fixed. Wind power generation $Q_{W,h}$ in time step h is reflected within the residual system demand $Q_{D,res,h}$ which has to be met by the remaining power generation technologies in the form

$$Q_{D,res,h} = Q_{D,h} - Q_{W,h} \tag{3}$$

where $Q_{D,h}$ represents system gross demand in time step h i.e. electricity demand including power losses. If we assume perfect competition, the power price π_h in the stylised system results as

$$\pi_h = a + Q_{D,res,h}{}^{b}\,. \tag{4}$$

To simulate the interaction between wind power generation and power prices we apply vectors of wind power generation and gross demand (representing hourly values of those parameters for the considered period) to the described model. The baseload price[3] π_{base} is calculated as the average of elements π_h of the resulting price vector

$$\pi_{base} = \frac{1}{H}\sum_{h=1}^{H}\pi_h \tag{5}$$

while the market value of wind power[4] MV_W is calculated as the volume weighted average price

$$MV_W = \frac{\sum_{h=1}^{H} Q_{W,h}\cdot\pi_h}{\sum_{h=1}^{H} Q_{W,h}} \tag{6}$$

Finally we compare the baseload price with the market value of wind power.

Historical (2006) hourly wind power generation and gross demand data for Germany and Austria are used to simulate the price effect. In order to ease the calibration of the supply function real data is normalised with residual demand. Figure 1 exemplarily illustrates how the distribution of the residual demand is translated into a distribution of the power prices given a certain degree of convexity for the supply curve (a = 0, b = 4) for German wind and demand data. This deformation is also reflected in the average power system price: even though average residual demand is 1 the average price is 1.20. The market value of wind power at the same time is 1.11.

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[3] Base load price represents the revenue per unit of energy if power is produced in a constant manner over the studied period.

[4] It is important to note that the market value is defined for total wind power generation and therefore represents the revenue for a single actor managing the whole portfolio. A particular wind farm however will have a specific market value that will depend on the specific correlation between its production and market price.

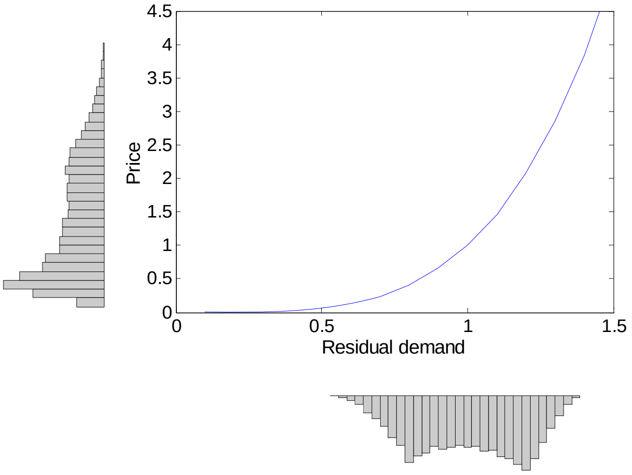

Figure 1. Illustration of the relation between residual demand and power price for convex supply curve. Assumptions: German wind power and demand, a=0, b=4

In order to derive the sensitivity of above mentioned parameters on the market value of wind power their value is varied within simulations while several other parameters a kept constant. Characteristics of historical data for Germany and Austria define the reference values respectively. Table 1 summarises key original data and reference values of investigated parameters for both Austria and Germany.

Table 1. Key parameters of wind power and gross demand in Austria and Germany for 2006

		Austria	**Germany**
Real data			
Installed wind capacity (end of year)	*MW*	965	20,622
Wind generation	*TWh*	1.7	30.6
Mean wind generation	*MW*	198	3,491
Standard deviation of wind power	*MW*	186	3,189
Gross demand	*TWh*	67.4	559.1
Average demand	*MW*	7,698	63,824
Standard deviation of gross demand	*MW*	1,379	11,193
Model data (normalised with residual demand)			
Mean wind generation		0.0264	0.0579
Variance of wind power		0.00062	0.0028
Average demand		1.0264	1.0579
Variance of gross demand		0.0338	0.0344
Wind share		0.0257	0.0547
Correlation wind-demand		0.0476	0.1519

The variance of wind power when related to mean generation is almost twice for Austria compared to Germany (0.048 vs. 0.023). Austrian wind power in the considered year is significantly less correlated with demand than in Germany. The German wind share (mean generation related to gross demand) is almost twice the Austrian wind share (see Table 1).

In the following we provide argumentative background for variations of investigated parameters in or among real systems and describe their implementation within the model.

Supply curve convexity

The supply curve of (competitive) power markets is defined by the SRMC of generation and the corresponding capacity sorted in the merit order and therefore shows a stepped characteristics. Furthermore it is not fixed but changes over time as a result of variations of fundamental parameters like fuel and CO2 prices and available capacities. Depending on the power generation portfolio real supply curves may have quite different characteristics. The supply curve of the Austrian hydro-thermal power system is e.g. characterised by a high share of capacity with low SRMC (hydro power). The steep part of the supply curve is determined by few hard coal units, CCGTs, gas and oil peakers. For the German thermal power system the supply curve instead shows a lower share of generation at low SRMC (hydro and nuclear) and the higher share of lignite and hard coal power plants.

For the power system model we approximate supply characteristics using the continuous function described above and assume it being time invariant for the reason of simplicity. Within simulations the supply curve parameters *a* and *b* are varied to reflect different degrees of supply curve convexity seen in real systems (see Figure 2). Except for the scenario of constant marginal cost *a* is assumed to be zero while *b* ranges from 1 to 5. Setting *a=0* and *b=4* is used as a reference for this parameter. The modelled supply curve can be either interpreted as SRMC of generation (competitive setting) or bids of generators which might include a strategic mark-up or even withhold of capacities (scenario with abuse of market power).

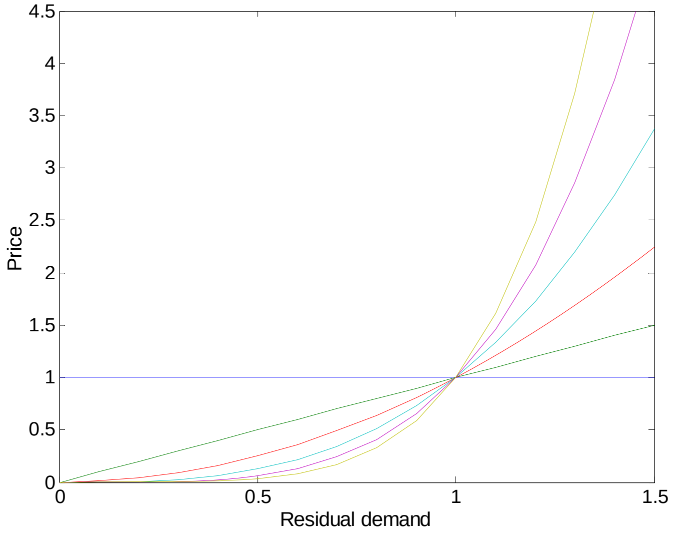

Figure 2. Degrees of supply curve convexities implemented in the power system model

Wind power share:

As indicated in the introduction given the ambitious goals for Renewable Energies of the European Commission we might expect the trend of increasing wind shares to hold on in the short to medium term. Therefore wind shares up to 30 % are reflected in simulations by scaling historical wind generation data. It is important to note that by normalising wind generation and demand with the corresponding residual demand it is guaranteed that the operating point of the system remains the same for analysed wind scenarios. This approach reflects the medium term view of the system i.e. the wind power development is taken into account for investment decision in new conventional capacity.

Correlation between wind power generation and demand

For meteorological reasons wind power generation shows typical (average) patterns on different time-scales. In Central Europe wind power generation is typically peaking during the winter period. The daily wind power pattern in Austria and Germany has baseload characteristics on average but may also show peak characteristics in selected month. Both annual and daily pattern are reflected in form of peaks in the wind power spectrum as shown in Olsina et al. (2007). As demand has distinct annual and daily patterns as well, the described characteristics of wind power generation results in a certain correlation between wind power and demand. We again analyse the sensitivity of this parameter on the market value of wind power in order to reflect the bandwidth of this parameter in real systems.

Mathematical tools offer functions to generate bivariate random variables for defined probability density functions (e.g. normal, lognormal, Weibull), mean, variance and covariance. As on the one hand wind power generation and demand show quite different probability distributions and on the other hand available probability distribution functions are not well suited to describe the characteristics of power demand it doesn't seem to be appropriate to use such variables for simulating different degrees of correlation for these input parameters.

Instead vectors of wind power generation and demand with defined correlation and the probability density distribution of original data are simulated using so called copulas. Therefore in a first step two vectors with uniform probability distribution and a specified correlation are generated. In a second step these vectors are applied to the inverse cumulative distribution function of historic wind power and demand data respectively. The resulting vectors show the same probability distribution, mean value and variance as historic data and the specified correlation. A detailed description of copulas including various applications is provided e.g. in Nelsen R. B. (2006).

Figure 3 illustrates exemplarily the probability density representation of real wind power generation and demand compared to simulated variables using copulas based on corresponding histograms.

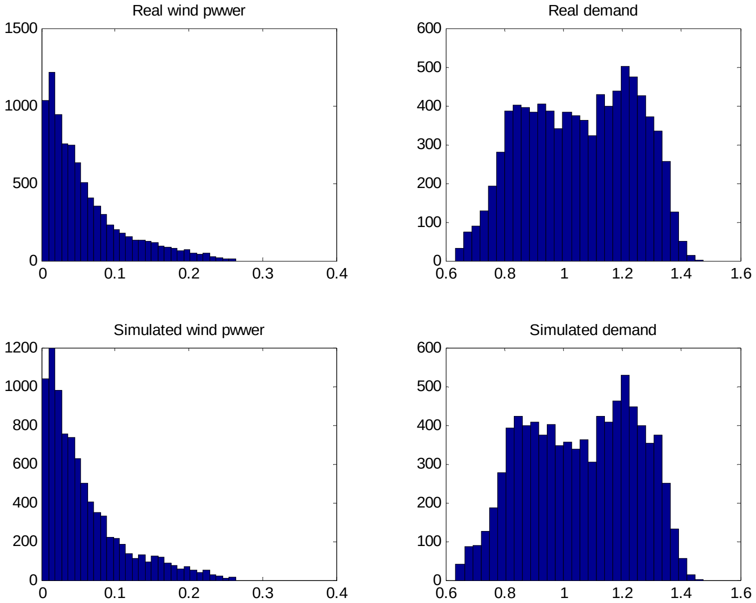

Figure 3. Probability density representation of real vs. simulated wind power generation and demand. Assumption: German data.

Wind power characteristics

Besides the mean generation the variability of wind power is the most important parameter describing its characteristics. Within this paper the variance is used to describe the variability. Main parameters that determine the variability of wind power are the spatial distribution of wind sites and meteorological characteristics. Wind power generation from spatially distributed wind sites is less variable than for geographically concentrated sites. Therefore when integrating e.g. two power markets the resulting (normalised) wind power variability will be lower than for the case of isolated power markets. In Europe an increased utilisation of offshore wind potentials may also affect the variability of wind power in the future. On the one hand wind characteristics tend to be steadier offshore which would result in lower site specific variability. If this will result in a lower variability of the overall wind power generation again depends on the geographical distribution of offshore sites in relation to those for onshore sites.

In order to simulate wind power generation vectors with varying variance we firstly generate uncorrelated Rayleigh[5] distributed wind speed vectors with defined mean value. We then apply these vectors to a normalised power curve which has been developed within the EU-project TradeWind and reflects the characteristics of regionally distributed wind farms in lowland areas (see Figure 4). For a mean wind speed of 6.5 m/s the resulting capacity factor of simulated wind power generation is about 0.21 which seems to be representative for Austrian and German wind power. By summing up different numbers of uncorrelated wind power vectors we generate resulting wind power vectors with different variance. Finally these vectors are scaled to the reference mean wind power generation. The following table summarizes variances of simulated hourly wind power time series for Austria and Germany respectively.

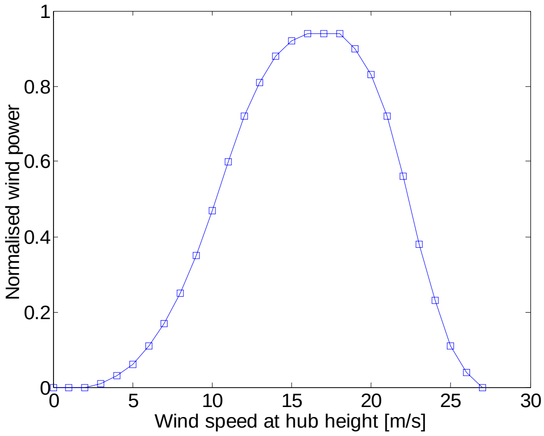

Figure 4. Power curve used to transform wind speeds into wind power. Source: McLean (2007)

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[5] The occurrence frequencies of wind speeds are usually well fitted by the Weibull distribution function. A Weibull distribution function with shape parameter equal to 2 is known as the Rayleigh distribution and often used by wind turbine manufacturers to describe the standard performance of turbines.

Table 2. Variance of simulated wind power scenarios when scaled to the reference mean values

No. of uncorrelated sites	**Variance**	
	Germany	*Austria*
Reference	2.79E-03	6.17E-04
1	4.37E-03	9.11E-04
2	2.17E-03	4.52E-04
3	1.47E-03	3.06E-04
4	1.09E-03	2.27E-04
5	8.95E-04	1.87E-04
10	4.38E-04	9.14E-05

To reflect the reference correlation between wind power generation and demand, again copulas are used to simulate corresponding vectors based on Weibull distributed wind power and historic gross demand[6].

3. Sensitivity of the market value of wind power

Detailed results presented in the following refer to German data on wind power generation and demand. Finally derived sensitivities are compared with those for the Austrian data set.

For the reference case the analysed price effect is negative from the perspective of wind power i.e. the market value is lower than the baseload price in the stylised power system. The magnitude of this effect depends on the shape of the supply curve - the price effect increases with increasing degree of convexity from 0% for the (theoretical) case of a supply curve with constant marginal cost up to 9.6 % for a supply curve polynomial of 5th order (see Figure 5).

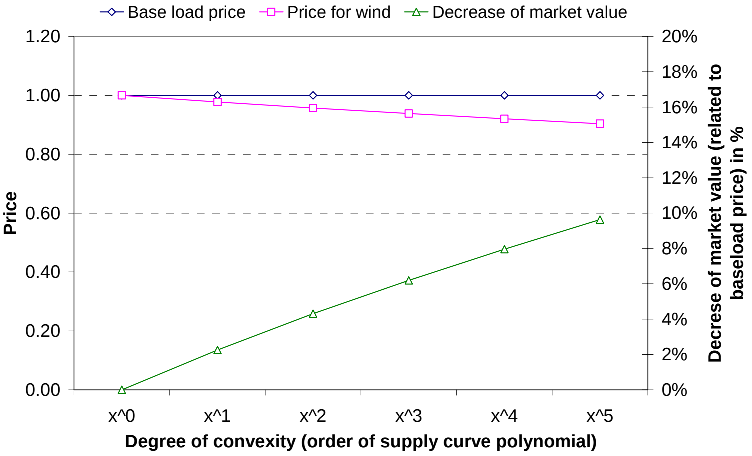

Figure 5. Comparison of wind power market value and baseload price for different degrees of supply curve convexity. Assumptions: German data, results normalized with base load price

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[6] Bivariate variables which are generated using copulas in general do not show the exact specified correlation. Therefore simulations are repeated until relative deviation stays within acceptable limits (set at 5%).

The share of wind power has a significant influence on the wind power market value (see Figure 6). When increasing the wind share from 5 to 30 % in the investigated isolated system the normalized wind power market value decreases from 0.93 to 0.45 given a supply curve polynomial of 4th order. The decrease of the market value is progressive for b=0 and b=1 and declining for b>1. The fact that for the case of a constant supply curve the market value decreases compared to the baseload price for wind shares > 20 % indicates that wind power generation exceeds system demand in selected hours.

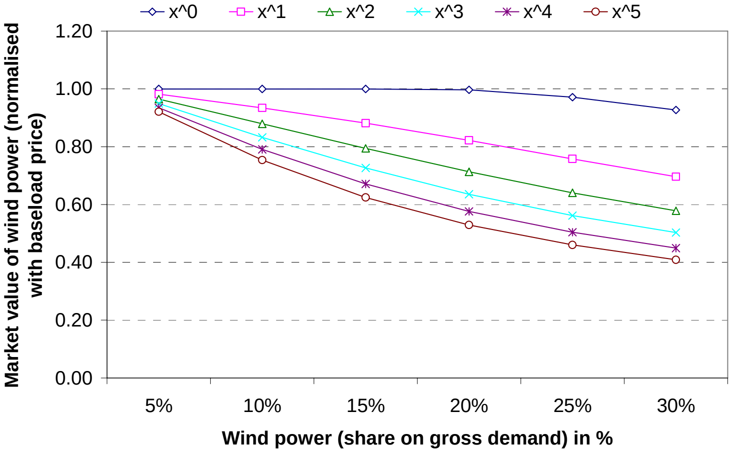

Figure 6. Market value of wind power depending on the wind share in the stylized system for different supply curve representations. Assumptions: German data, market value normalized with base load price

Wind power-demand correlation and wind power market value are positively correlated (see Figure 7). For analyzed supply curve representations the relation between these two parameters is found to be linear. When lowering the correlation from 0.15 (reference value) to 0.05 the market value decreases from 0.93 to 0.85 for the reference supply curve representation (x^4). At a correlation of about 0.3 the price effect diminishes for all investigated supply curve scenarios. For higher correlations the price effect becomes positive.

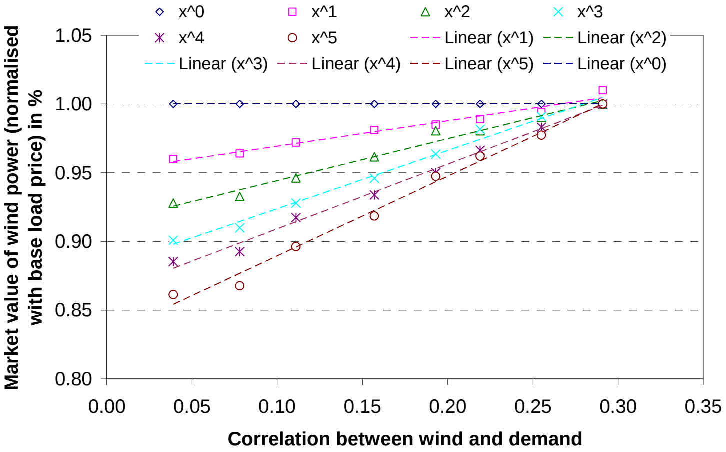

Figure 7. Market value of wind power depending on the correlation between wind power generation and demand for different supply curve representations. Assumptions: German data, market value normalized with base load price

The market value of wind power decreases with increasing variance of wind power generation. A doubling of the reference wind power variance (0.0028) results in a decrease of market value from 0.93 to 0.81 for the reference supply curve. For variances < 0.001 the observed price effect diminishes (see Figure 8).

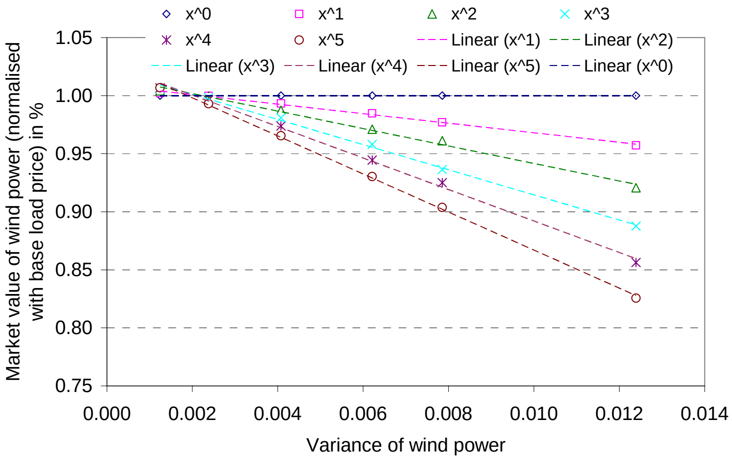

Figure 8. Market value of wind power depending on the variance of wind power generation for different supply curve representations. Assumptions: German data, market value normalized with base load price

Figure 9 summarizes the sensitivities of investigated parameters on the normalized market value of wind power for the reference supply curve representation. The market value of wind power is most sensitive with respect to the wind power share. An increase of this parameter of 10 % results in a market value decrease of 17 %. Wind-demand correlation and wind power variance show comparable sensitivities with converse signs. When increasing the correlation by 10 % the market value increases by 8 %. The same relative increase of wind power variance leads to a decrease of the market value of 12 %.

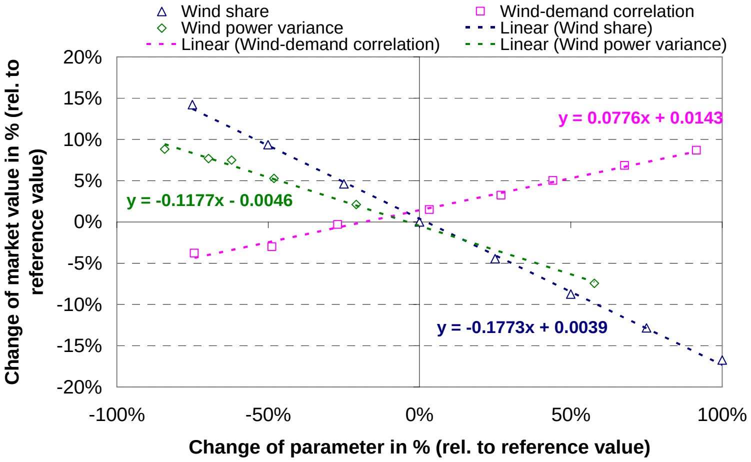

Figure 9. Sensitivity of the wind power market value on investigated parameters. Assumptions: German data, supply curve representation: a=0, b=4, market value normalized with base load price

Corresponding results for simulations with the Austrian data set are illustrated in Figure 10. Sensitivities show the same qualitative trend, the order of magnitude is for all parameters about half of corresponding values for the system based on German data.

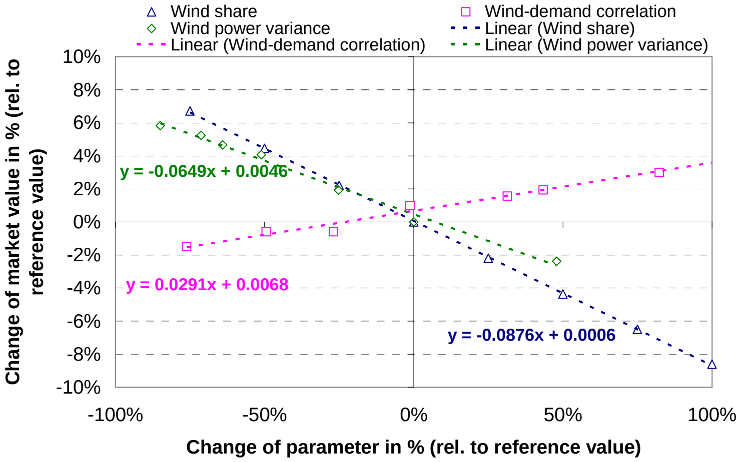

Figure 10. Sensitivity of the wind power market value on investigated parameters. Assumptions: Austrian data, supply curve representation: a=0, b=4, market value normalized with base load price

4. Conclusions

The paper discusses the relation between wind power generation and electricity wholesale prices and identifies key parameters that are affecting the market value of wind power based on simulations for a stylised power system modelled for this purpose.

Results of simulations indicate that the wind share, the supply characteristics, the variance of wind power and the correlation between wind power and demand influence the market value of wind power generation significantly.

In power markets with significant wind power shares the baseload prices turns out to be no proper indicator for the market value of wind power. For current wind power and system characteristics instead we might expect the market value of to be lower than the baseload price.

The sensitivity of the market value on the wind power variance implies that geographically extended power markets are beneficial from the perspective of wind power given the relation between spatial distribution and wind power variability.

When estimating the future need for supporting wind power it is crucial to take into account the relations between wind power generation and wholesale electricity prices as illustrated in this paper.

At this stage results for the German and Austrian system respectively have to be interpreted with care as we model systems as if they would be isolated and not integrated in the Central European Electricity market. Future work may include the extension and application of the model to regional power markets with realistic supply curve representation and an assessment of the empirical bandwidth of analysed influence parameters.

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