Applied Energy 154 (2015) 805–814

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The market value and impact of offshore wind on the electricity spot market: Evidence from Germany

Nikolaus Ederer *

Vienna University of Technology, Faculty of Electrical Engineering and Information Technology, Gußhausstr. 25-29, 1040 Vienna, Austria

HIGHLIGHTS

- Market value of offshore wind based on feed-in and weather data is assessed.
- Merit order effect caused by wind energy is simulated for 2006–2014.
- Results indicate same impact of on- and offshore wind on market price and value.
- Steadier wind resource offshore imposes less variability on market price.
- Characteristic of variable wind feed-in cannot be blamed for price deterioration.

ARTICLE INFO

Article history:
Received 22 March 2015
Received in revised form 25 April 2015
Accepted 13 May 2015

Keywords:
Offshore wind
Merit order effect
Market value
Electricity market
Price deterioration
Variability

ABSTRACT

Although the expansion of offshore wind has recently increased in Germany, as in other countries, it is still forced to defend its role in long-term energy policy plans, particularly against its onshore counterpart, to secure future expansion targets and financial support. The objective of this article is to investigate the economic effects of offshore wind on the electricity spot market and thus open up another perspective that has not been part of the debate about offshore vs. onshore wind thus far. A comprehensive assessment based on a large amount of market, feed-in and weather data in Germany revealed that the market value of offshore wind is generally higher than that of onshore wind. Simulating the merit order effect on the German day-ahead electricity market for the short term and long term in the years 2006–2014 aimed to identify the reason for this observation and show whether it is also an indication of a lower impact on the electricity spot market due to a steadier wind resource prevailing offshore. Although the results suggest no difference regarding the impact on market price and value, they indeed reveal that offshore wind imposes less variability on the spot market price than onshore wind. In addition, the long-term simulation proved that the ongoing price deterioration cannot be blamed on the characteristic of variable wind production.

1. Introduction

Even prior to the disaster at the nuclear power plant in Fukushima, Germany's long-term energy strategy was dedicated to sustainable development of its energy supply and a reduction of its economic costs that also took into consideration long-term external effects and a conservation of fossil resources [1]. However, the energy turnaround ("Energiewende") that was enacted as a consequence, which designates a change of the energy mix towards a domination of renewable energy sources [2], and the nuclear phase-out in 2011 generated more emphasis and determination for this intention [3]. Wind energy is one of the key technologies that should ensure the success of the energy turnaround and is thus endowed with a benevolent subsidy scheme. Fig. 1 shows the expansion of wind energy in Germany during the past several years and a medium-term prognosis until 2019. According to the current German Renewable Energies Act (Erneuerbare-Energien-Gesetz (EEG)) [7], the expansion target for onshore wind is defined to be a net (difference between addition and decommissioning) annual increase in installed capacity of 2.5 GW and a total offshore wind capacity of 6.5 GW in 2020 and 15 GW in 2030. This would lead to an electricity generation market share of at least 18% in 2020, which reflects the increasing importance of wind energy in the German electricity industry [4].

Abbreviations: German Renewable Energies Act (Erneuerbare-Energien-Gesetz), EEG; transmission system operators, TSOs; average, AV; coefficient of variation, CV.

* Permanent address: Bandwirkerstraße 13, 22041 Hamburg, Germany. Tel.: +43 664 41 899 48.

E-mail address: nikolaus.ederer@gmail.com

http://dx.doi.org/10.1016/j.apenergy.2015.05.033

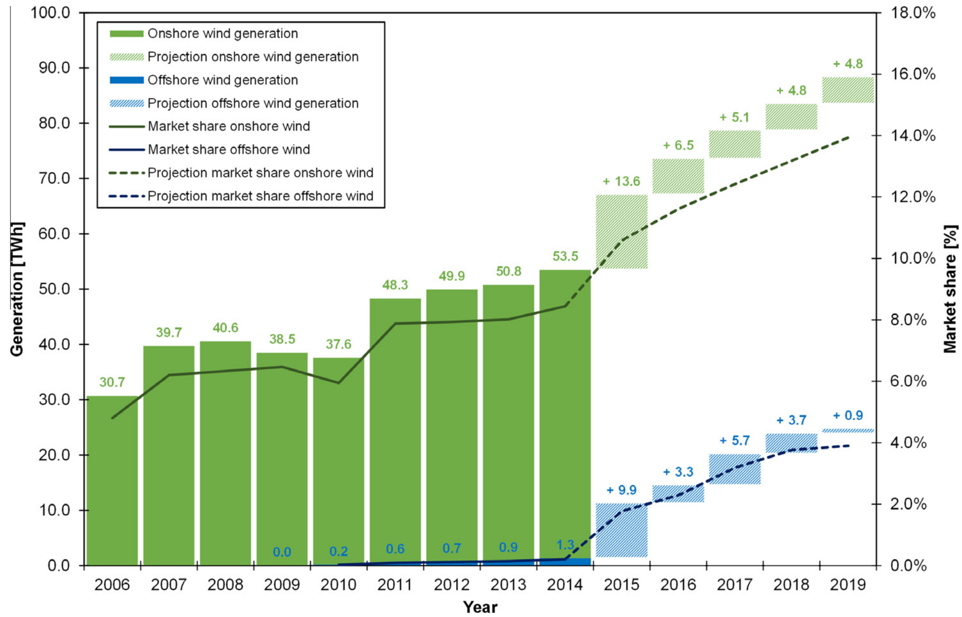

Fig. 1. Increasing importance of wind energy in the German electricity market [4–6].

Onshore wind in particular seems to have demonstrated that it is a key pillar of the German energy turnaround. By contrast, offshore wind is still in its nascent stage. There might be several reasons for this, such as the great distance to shore and water depth at the planning sites, which imply considerable effort. Another possible reason could be that the German state may have underestimated the burden that is coupled with the responsibility of ensuring grid connection for all wind farms far away from shore. These circumstances consistently promote discussion on the future role of offshore wind in the German energy turnaround, especially compared with its onshore counterpart in the battle for subsidies. The reviews [8,9] show that many pros and cons should be considered in this discussion. However, the economic effects occurring when onshore and offshore wind production is traded on the electricity spot market have not been part of these comparisons so far although they might be of significant importance in changing the energy mix. This article thus analyses the marketing of wind energy and its impact on the electricity spot market in detail with the objective of quantifying the difference between onshore and offshore wind and investigating whether offshore wind offers a benefit due to the steadier wind resource prevailing offshore.

The marketing and realised market value of wind energy is significantly affected by its property of being non-dispatchable because the operator is forced to feed-in and sell the electricity when there is wind, which is in contrast to dispatchable generators that can adjust their production in relation to the electricity market. This leads to a market value below the average market price because electricity is increasingly sold when the market price is rather low. This reduction in value is also referred to as profile costs and is the topic of several recent publications, of which [10] provides a comprehensive review. However, to the author's knowledge, the market value has so far only been analysed for onshore wind. Thus, the first aim of this article is to assess the market value of offshore wind. As investigated in [11] for onshore wind in Germany, the spatial position has an effect on wind power revenues and therefore this assessment should show whether the argument of a higher and steadier wind resource prevailing offshore has a positive effect on the marketing of its electricity in addition to the increased energy yield [12]. The reason that this article might be the first analysis could be due to the lack of data availability, which was overcome by using weather data from measurement stations located in the German North and Baltic Sea in addition to feed-in data.

The variability of wind does not only have an impact on its own economics, however. In combination with the property of near zero marginal costs and supported by a benevolent subsidy scheme wind energy has a significant impact on the electricity spot market. The so-called merit order effect causes a price deterioration with increasing feed-in capacity [13]. A considerable amount of research has been performed on this topic, whereof [14] provides an comprehensive review until the year 2013 including the assessment region and period, reported price change and a short description of the used approach. Recent publications analysing the relationship between variable wind electricity generation and electricity price behaviour in Germany confirm the decreasing effect on the spot price [14–18]. In addition to that [14], suggests that the impact of wind varies depending on the region and assessment method chosen [16], reports that wind feed-in also increases spot price volatility and [17,18] indicate the load dependence of the merit order effect. Again, none of these analyses distinguishes between onshore and offshore wind. Thus, the second objective of this article is to investigate and quantify the impact of offshore wind energy on the electricity spot market compared with its onshore counterpart, which is a novelty in this field of research. The fact that its generation is less variable might be a reason for less deterioration and less variability in the spot market price, which would again be an argument in favour of offshore wind.

Modelling this impact is challenging, especially with the aim of generating reliable and significant results. In the literature this problem is generally solved by employing empirical analyses, simulation-based approaches or a combination of both. Most common when aiming for quantifying the merit order effect applying empirical analyses is the design of a regression model and applying it to historical data as, for example, done in [19] for the Spanish, in [20] for the Italian and in the before mentioned [14–17] for the German electricity market. Furthermore [21], investigated the impact of weather conditions in the Netherlands and Germany on the Dutch electricity market and [22] the effect of wind feed-in on the level of spot prices and spot-price variance in Texas using also regression analysis. In contrast to that, simulation-based approaches require the design of an electricity market model that enables to simulate the impact of increasing variable generation on the market price. For example, the authors of [23] examined the price effect on the Iberian day-ahead market by applying a long-term system dynamics based model. In [24] a agent-based simulation platform enabled a detailed analysis of the price change caused by renewable energy in Germany and the authors of [25] developed a price demand dispatch model for the Australian National Electricity Market. Another interesting methodology is described in [26,27], where an artificial intelligence-based technique (M5P algorithm) was employed in order to quantify the merit order effect in Spain. Finally, a combination of simulation and empirical analyses was used for example in [18] for the German and in [28] for the Italian electricity market. However, it is remarkable that all these approaches require a considerable amount of market data and several assumptions and simplifications, which cause significant uncertainties, in order to gain a complete picture of the market at a specific moment or within a specific period that enables to correctly evaluate the impact of an additional amount of variable generation capacity. The difference between onshore and offshore might be rather small, which thus required a different approach.

The idea for the methodology presented in this article is derived from the intention to simulate exactly the cause of the price reduction, i.e., the merit order effect, and the understanding that the original ask and bid curve, which are the basis for price setting, reflect the required complete picture of the market at a specific moment. Thus, using the original ask curve, shifting the original bid curve dependent on the increasing wind feed-in and computing the market clearing again made it possible to simulate the impact of wind electricity exactly as it would be in reality. Although this approach seems to be quite obvious, it has, to the author's knowledge, only been applied once in [29] for the Spanish electricity market. The reason might be that the design and implementation of an algorithm that reliably and precisely determines the market clearing for every hour of the years under consideration is quite sophisticated and computationally intensive. However, this seemed to be the best approach in order to generate significant results that enable factual conclusions to be derived and thus was used in this article to quantify the impact of onshore and offshore wind on the German day-ahead electricity market for the years 2006–2014. Furthermore, a differentiation was made between short-term and long-term effects because in the discussion of a decreasing market price caused by large amounts of variable renewable energy it is sometimes forgotten that the main objective of this expansion is to substitute carbon intensive energy resources and nuclear power plants. Thus, this article also investigates what happens in the long term when wind energy substitutes these base load power plants (see [30] for a complete discussion regarding short-term and long-term effects of renewable energies in electricity markets).

The next section begins with a description of the market environment for wind energy in Germany from an economic perspective, which should enable comprehension of the approach and the interpretation of the results. Section 3 provides the assessment results of the market value of offshore wind. Section 4 describes the methodology and implementation of the simulation, and Section 5 presents the results. Finally, these results are used to draw an overall conclusion in Section 6.

2. Market environment for wind energy in Germany

2.1. Remuneration scheme

In general, wind energy generation in Germany is financially supported either in form of a feed-in tariff or – in case of direct marketing – a market premium [7]. Until recently, wind farm operators were allowed to choose between the two remuneration options, but to constrain them to compete on the electricity market a revised EEG took effect in 08/2014, which allows a feed-in tariff only in exceptional cases (e.g., small power plants). Thus, now wind farm operators are obliged to trade their production themselves, and the feed-in tariff defined in the actual EEG represents a target value for the financial support. A wind energy producer in Germany therefore has two sources of revenue. On the one hand, the revenues obtained from trading electricity on the wholesale market, and on the other hand, the subsidy granted in the form of the market premium, which is defined to be

$$p_m = tv - mv \tag{1}$$

where tv is the target value and mv the market value. The latter is calculated as follows:

$$mv = \frac{\sum_{h=1}^{H} p_h^{mc} \cdot q_h}{\sum_{h=1}^{H} q_h} \tag{2}$$

where p_h^{mc} is the market clearing price at the EPEX Spot SE Day-Ahead Auction for the German/Austrian market area for an individual hour h, q_h the cumulative onshore and offshore wind feed-in capacity for this hour in Germany, respectively, and H the number of hours within the respective period. Table 1 provides the basic target values for the remuneration of wind energy before a degression is applied in subsequent years.

2.2. Marketing

Information on how traders market wind energy on short-term electricity spot markets can be found in German energy laws [7,31,32], where it is stipulated that transmission system operators (TSOs) must ensure the optimal marketing of renewable energy remunerated in the form of a feed-in tariff with the diligence of a prudent electricity trader. It is also specified that the forecasted feed-in capacity of renewable energy for every hour of the next day must be offered price-independent at the day-ahead market. Furthermore, deviations between the forecasted feed-in capacity during the day and the amount of capacity already sold must be offered or purchased on the intraday market. Considering the fact that marginal costs for wind farm operators are almost zero, it is reasonable to assume that traders market wind electricity in a similar way because as long as the resulting subsidised remuneration per electricity unit sold is positive, the wind farm operators will continue trading the forecasted amount of electricity on the day-ahead market – even when the market price is negative – and adjust for production deviations on the intraday market. Hence, the main short-term trading floor for wind energy and thus

Table 1
Target value for the remuneration of wind energy according to EEG.

	Onshore	Offshore
Period of entitlement	20 years	
Base value	49.5 EUR/MWh	39 EUR/MWh
Standard value	89 EUR/MWh for first 5 years	154 EUR/MWh for first 12 years
Compression value		194 EUR/MWh for first 8 years
Extension period with standard value	+1 month for every 0.36% the energy yield comes below 130% of the reference yield and 0.48% it comes below 100% of the reference yield	+0.5 months for every nautical mile beyond 12 nautical miles to shore +1.7 months for every metre beyond 20 m water depth

the market under investigation in this article is the day-ahead market.

2.3. Day-ahead market

The so-called Day-Ahead Auction for the German/Austrian market area constitutes a market segment of the European Power Exchange EPEX Spot SE. Buy and sell orders submitted on this market, which are basically price/quantity combinations of exchange members seeking to make a transaction in a contract, are traded daily via auction trading either in the form of single-contract orders (one expiry) for one hour of the day or a pre-defined block orders (several expiries). Orders are accumulated but not executed in the order book until 12.00 pm the day before delivery. Afterwards an auction takes place, which aims to optimise the total welfare, i.e., the seller and buyer surplus. The first step is that all orders are added up to obtain an aggregated ask and bid curve. Assuming that the exchange member's interest is linear between two price/quantity combinations, the market clearing price p_{mc} and quantity q_{mc}, where the bid and ask curve intersect, are found. p_{mc} is the price at which all trades will be executed and the total welfare is maximal (see Fig. 2). Negative prices were introduced at the German day-ahead market in 2008 [33–36].

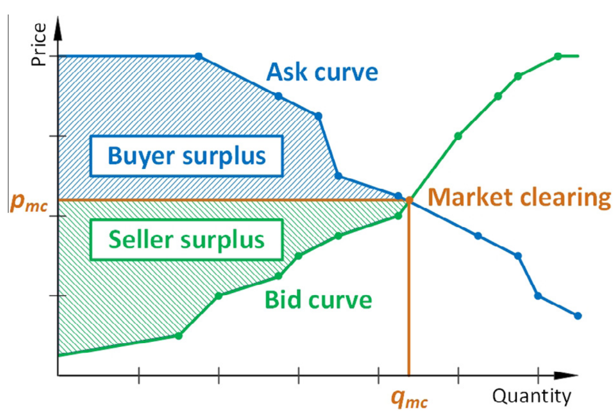

Fig. 2. Market clearing at the day-ahead market.

3. Market value of offshore wind

The main challenge in assessing the market value of offshore wind was to ensure the availability of data because on the one hand data sources that provide hourly feed-in capacities often do not distinguish between onshore and offshore wind. On the other hand, because the deployment of large-scale offshore wind farms started only a few years ago, the period of data available is often rather short. That is also the case for Germany; the first offshore wind farm, alpha ventus, was commissioned at the end of 2009 and only since 2012 have the TSOs been obliged to provide offshore wind feed-in data separately. Thus, to obtain results for a significant period of time, wind data from measurement platforms in the German North and Baltic Sea [37] were also analysed. Another benefit of using these wind data in contrast to the feed-in data is that they do not contain the effect of continuously increasing capacity during the year. Fig. 3 shows the position of the measurement platforms FINO 1 and FINO 3 in the North Sea, FINO 2 in the Baltic Sea as well as offshore wind project areas.

Wind data from these measurement masts provided by [39] at 90 m height were checked, cleaned up and used to calculate power generation for each hour based on a power curve from a generic 5 MW wind turbine with a 130 m rotor diameter. The effect of data gaps due to corrupt or missing wind data was neglected on the grounds that offshore wind turbines have availability in the same range and that the annual energy production for every year under consideration was also at a plausible level. Sources for actual onshore and offshore wind feed-in were provided by the TSOs [40–43] and a platform for market transparency [44]. Market clearing prices for the day-ahead market were provided by [45]. Only years with full data availability were considered and an hourly data resolution was chosen. This naturally required far more effort than a daily data resolution, but it ensured the highest possible quality of results. To have the ability to compare the market value of different energy technologies in different years it is common to use the market value factor, which is defined to be

$$f_{mv} = \frac{mv}{\overline{p_{mc}}} \quad (3)$$

where $\overline{p_{mc}}$ is the average market clearing price within the respective period [10].

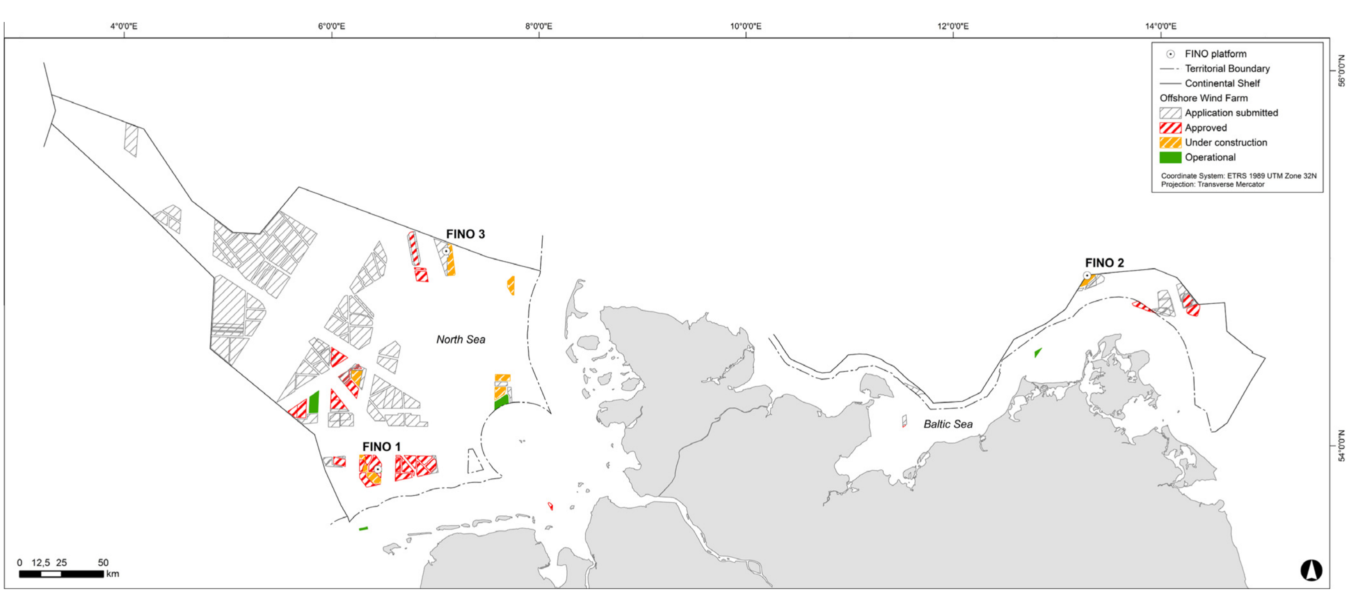

Fig. 3. Offshore wind development areas and FINO platforms in German waters (based on data provided by [38]).

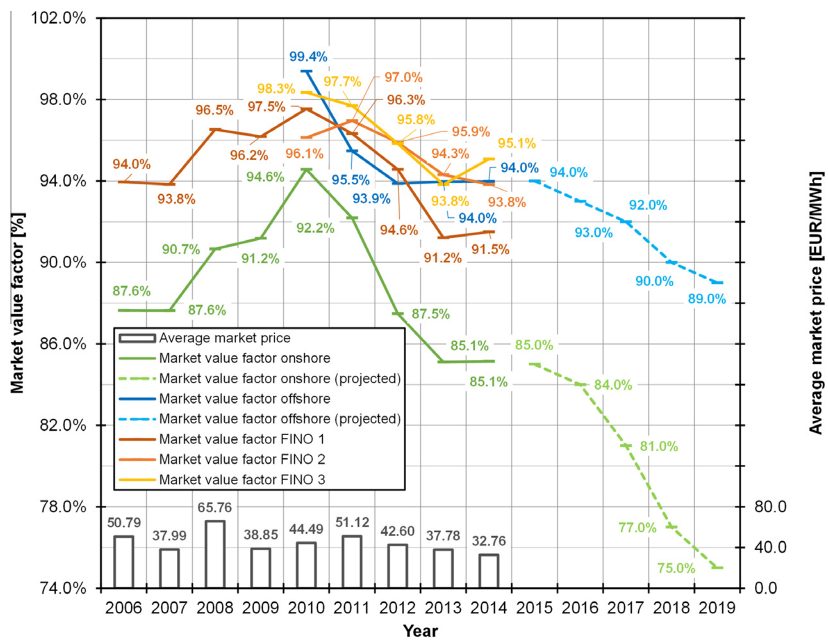

Fig. 4. Market value of offshore wind in comparison with onshore wind in Germany.

Fig. 4 provides the assessment results for the years 2006–2014 and a projection until 2019 by [46]. Although the change in the market value factor of offshore wind and the measurement masts follows the same pattern as the market value factor of onshore wind, it is generally higher. This is indeed interesting and raises the question about the reason for this observation. The most obvious explanation for it might be that there are differences in the feed-in curves. Thus, Fig. 5 shows the capacity factor curve for onshore, offshore and FINO 1 as well as its characteristic parameters for the year 2013. The average and coefficient of variation (CV) reveal the expected property of offshore wind having a higher and steadier generation profile. If this characteristic causes a higher market value it might also be an indication for offshore wind having a less negative impact on the electricity market than its onshore counterpart. However, this can only be proven by a well-designed simulation that enables this difference to be worked out and includes the fact that there is already far more operational onshore wind capacity than offshore, which could be another explanation.

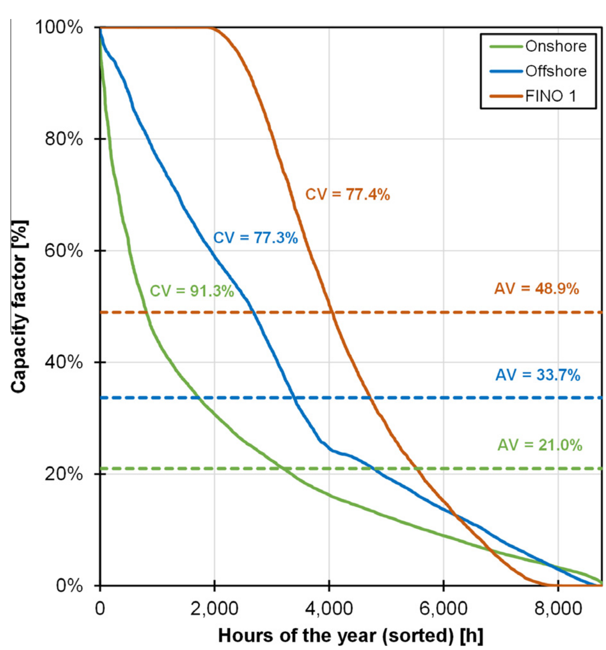

Fig. 5. Capacity factor curve for onshore and offshore feed-in as well as an assumed 5 MW wind turbine at FINO 1 position incl. average (AV) and coefficient of variation (CV) in the year 2013.

4. Simulation

4.1. Methodology

The merit order effect (see Fig. 6 (top)), which was simulated in the following, is based on the assumption that the demand curve is independent of the supply curve, which means that regardless of how much wind generation is traded on the day-ahead market the ask curve stays the same. This is in contrast to the bid curve. Due to the property of wind energy having near zero marginal costs and the support through subsidies, wind energy is offered at a low price. This results in a shift of the bid curve by the additional wind capacity q_{wind}, which in turn causes a shift of the market clearing and thus leads to a lower market clearing price p_{mc}^{wind}. The extent of this effect depends on the additional wind capacity and the shape and position of the bid and ask curve. Considering the fact that all of these influencing parameters vary for each hour of a year, it is obvious that the impact of wind feed-in cannot be assessed precisely by applying statistical methods to market clearing prices and quantities. It only enables a snapshot of past market conditions to be estimated, but an active projection of the impact should be interpreted with care. Hence, the results presented in the following were obtained by simulating this shift exactly using the original bid and ask curves from the day-ahead market provided by [47], feed-in curves for offshore and onshore wind and a calculated generation curve based on FINO 1 measurements for the years 2006–2014. The market impact was simulated for three levels of additional energy generation per year q_{add} – 5 TWh, 10 TWh and 15 TWh – from onshore and offshore wind, respectively. Applying the simulation to original data from the past ensured that the analysis is not falsified by a projection of input parameters. Thus the results reflect what would have happened if in the respective year a specific amount of

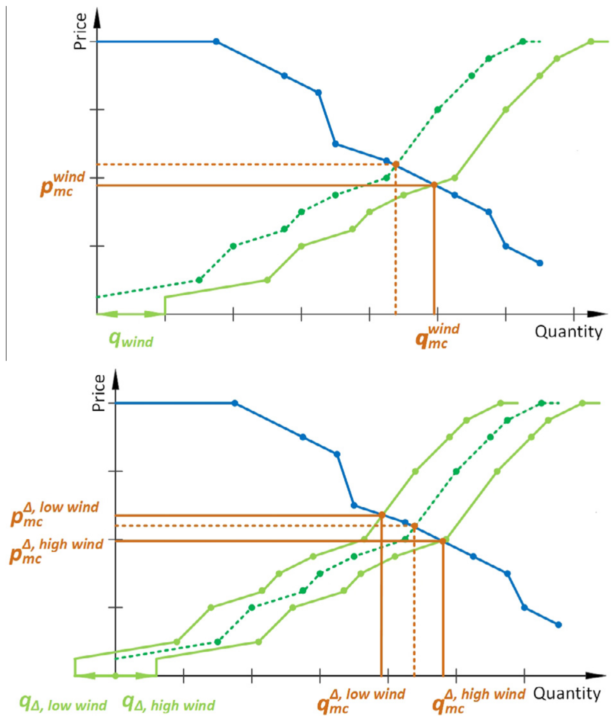

Fig. 6. Simulating the merit order effect in the short term (top) and in the long term (bottom).

onshore/offshore wind energy would have been added to the day-ahead market. The reason for using only FINO 1 data is that most offshore wind capacity will become operational in its region in the next years (see Fig. 3) and the difference compared with FINO 2 and FINO 3 is rather small.

The first step was to determine the additional wind capacity for every hour of the year $q_{\text{wind},h}$, which was obtained by calculating a multiplication factor α with which the wind feed-in of every hour of the year under consideration $q_{\text{feed\_in},h}$ was multiplied aiming at an adjusted feed-in curve with a cumulative generation amount of the chosen level of additional energy per year:

$$\alpha = \frac{q_{\text{add}}}{\sum_{h=1}^{H} q_{\text{feed\_in},h}} \tag{4}$$

$$q_{\text{wind},h} = \alpha \cdot q_{\text{feed\_in},h}, \quad \forall h \tag{5}$$

Afterwards, the bid curve was simply shifted based on the additional wind capacity of the respective hour or, in other words, for every point on the aggregated bid curve the original price remained the same but the associated capacity was increased. Calculating the intersection with the original ask curve results in the simulated market clearing price p_{mc}^{wind}, which in turn enabled calculation of the market value. This methodology applied for every hour of the years under consideration ensured that the results represent an exact projection of reality without any simplification and generalisation. In contrast to the procedure for assessing the short-term impact described up to now, the long-term impact, i.e., wind replacing base load capacity (see Fig. 6 (bottom)), was simulated by shifting the bid curve for a capacity $q_{\Delta,h}$, which is the difference between $q_{\text{wind},h}$ and the base load generation capacity per hour $q_{\text{base\_load}}$ that is replaced:

$$q_{\Delta,h} = q_{\text{wind},h} - q_{\text{base\_load}}, \quad \forall h \tag{6}$$

The latter was calculated for each hour by simply dividing the level of additional energy generation per year by the number of hours of the year under consideration:

$$q_{\text{base\_load}} = \frac{q_{\text{add}}}{H} \tag{7}$$

Hence, in the long-term simulation the market clearing was shifted to higher (lower) capacities $q_{mc}^{\Delta,\text{high wind}}$ ($q_{mc}^{\Delta,\text{low wind}}$) in hours of high (low) wind generation $q_{\Delta,\text{high wind}}$ ($q_{\Delta,\text{low wind}}$) resulting in a lower (higher) market clearing price $p_{mc}^{\Delta,\text{high wind}}$ ($p_{mc}^{\Delta,\text{low wind}}$). This opens up another perspective of the issue of decreasing electricity market prices due to a rapid expansion of non-dispatchable renewable energy generation units because it enables to distinguish between the effect caused by the variable characteristic of the renewable energy source (long-term simulation) and, on the other hand, the effect of excess supply (difference between short-term and long-term simulation).

It is obvious that adding energy to this extent to the market will have a significant impact. Thus, to ensure the plausibility of the results a limit for negative prices was needed because the whole model is based on the assumption that wind power traders always bid the whole production price-independent or at a low price that does not influence the market clearing price. As discussed in Section 2.2, this is plausible in general, but if the market clearing price decreases to a level where a profit would not remain even with subsidised remuneration, it is not reasonable that traders would continue to bid the whole production. Thus, it was assumed that wind generation is only put on the market up to a threshold of −76 EUR/MWh (onshore) and −157 EUR/MWh (offshore), which represents their levelised cost of electricity according to [48]. In the end, this constitutes the limit which should at least be covered by subsidies to ensure profitability. These figures might be a point of criticism, but it should be noted that the reasonable range of this trading threshold is rather small and a sensitivity analysis revealed that the impact on the results is negligible. Moreover, the results also cover an analysis of the number of hours with negative prices.

4.2. Implementation

In the literature, whereof [49–52] provide an excellent overview, the bid and ask curves are often simplified using blocks, and the market clearing is determined using optimisation models. Unfortunately, these methods do not seem to apply to real market data, and the actual algorithm used to determine the market clearing at the EPEX Spot is unknown. Therefore, a custom algorithm was developed, which basically works in two steps and aims to determine the point of intersection between the aggregated bid and ask curve. Starting at a quantity of zero and continuously increasing it, the ask and bid price/quantity combination (p_a/q_a and p_b/q_b) where the bid price exceeds the ask price ($p_b \geqslant p_a$) is found (see Fig. 7). Thereafter, the linear equation of a straight line

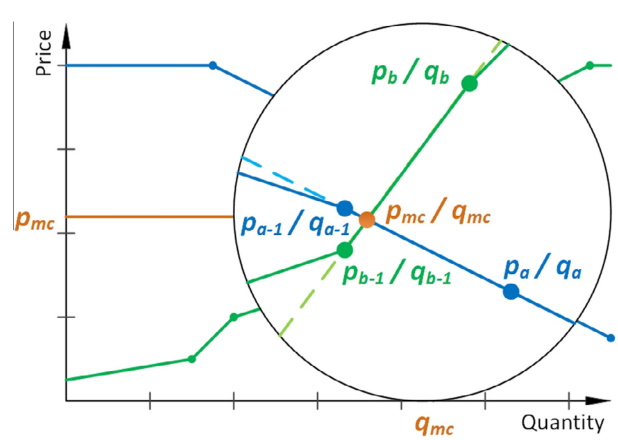

Fig. 7. Visualisation of the algorithm for determining the market clearing.

passing through the price/quantity combination found and the one with less accumulated quantity (p_{a-1}/q_{a-1} and p_{b-1}/q_{b-1}) is calculated for both ask and bid. In case the intersection of these two lines (p_{mc}/q_{mc}) lies between the two price/quantity combinations used to determine their linear equation ($p_{a-1} \geqslant p_{mc} \geqslant p_a \wedge p_{b-1} \leqslant p_{mc} \leqslant p_b \wedge q_{a-1} \leqslant q_{mc} \leqslant q_a \wedge q_{b-1} \leqslant q_{mc} \leqslant q_b$), the market clearing point is found. Otherwise, the position of the intersection relative to the price/quantity combinations determined before reveal which adjustments are needed to find the correct market clearing price/quantity combination. This might not be the optimum approach to determine the market clearing and perhaps also not the fastest, but it turned out that it was the most stable and reliable in terms of computing absolute correct results. The algorithm was validated by simulating the actual market clearing, i.e., computing p_{mc} and q_{mc} assuming $q_{\text{wind}} = 0$ and comparing them with the real figures for every hour of every year under consideration.

5. Results

The three parameters of average market price factor, market value factor and number of extreme events were identified to give an indication of the impact on the electricity spot market and therefore were determined for the short term and long term. In general, the simulation that was developed generated reasonable and expected results, i.e., a decreasing market price and value as well as an increasing volatility subject to an increased wind energy feed-in. The applied approach of simulating the merit order effect for past years entirely based on real data (ask and bid curves, feed-in capacities and wind measurement data) ensured that as few assumptions as possible were required and thus neither errors (validation executed) nor significant uncertainties were imposed on the results. Nevertheless, it should be noted that the used feed-in capacities increased as a whole during a year due to a continuous expansion of wind power. This effect is not contained in the FINO measurement data; instead, it should be considered that the results based on these data reflect the production of a single wind turbine at one specific location and that there generally occurs a smoothing effect due to the spatial spread as more capacity is in operation. Lastly, secondary effects, such as a change in the generation mix, and strategic behaviour of market players are not included in the analysis. However, it is not expected that these effects have an impact on the overall conclusions drawn based on the results.

5.1. Market price

Fig. 8 shows a visualisation of the resulting average market price factor, which is the simulated average market price related to the original average market price (=100%), in the case of adding 5/10/15 TWh in the short term and long term. The short-term results reveal the expected impact of a decreasing market price as more wind energy is added. In contrast, the long-term results of the simulation suggest that the substitution of base load by wind energy tends to increase the average market price. This is remarkable because this would mean that the sole reason for the actual price deterioration on the spot market is not the property of wind energy being non-dispatchable but rather the general excess supply. The reasons for the tendency to increase the market price might on the one hand be that there are more hours with less wind and on the other hand that there is a higher price sensitivity for a lower market clearing quantity. Similar to other publications in this field, Table 2 provides the average deviation of the market

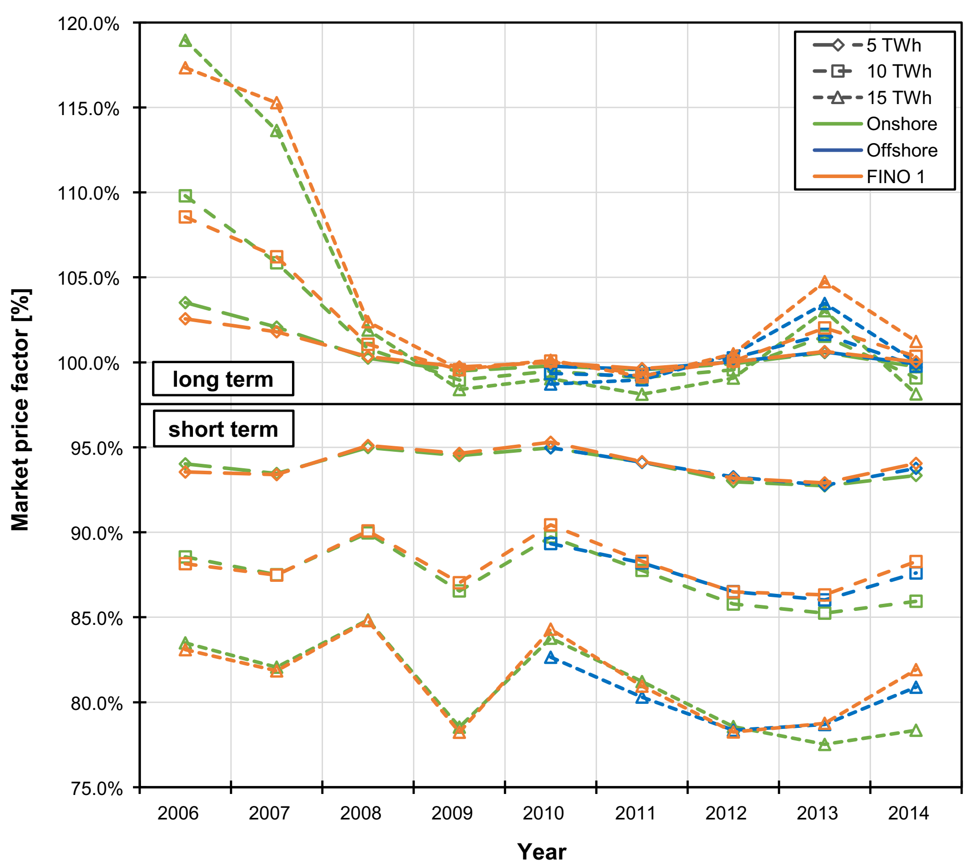

Fig. 8. Market price factor in case of adding 5/10/15 TWh in the short term (bottom) and long term (top).

Table 2
Average deviation of the market price (factor) per additional TWh wind energy in EUR/MWh (%).

		Short term	Long term
Market price (factor)	Onshore	−0.56 (−1.27%)	0.11 (0.22%)
	Offshore	−0.75 (−1.32%)	−0.19 (0.02%)
	FINO 1	−0.55 (−1.24%)	0.13 (0.30%)

price (factor) per additional TWh of wind energy. The presented values and the graph show that a clear difference between the impact of onshore and offshore wind on the market price cannot be determined.

5.2. Market value

As expected, the simulations reveal a decreasing market value caused by an increasing amount of additional wind energy. The results provided by Table 3 indicate a considerable difference between the short-term and long-term case. The values for the long term can be interpreted as the impact caused solely by the variability of the wind feed-in whereas the difference between the short-term and the long-term results represent the effect of general supply excess. However, the results again do not suggest lower impact of offshore wind compared with onshore wind.

5.3. Extreme events

Finally, the impact of variability that is induced by the feed-in of wind energy on the electricity spot market was determined. In general, a volatile market price implies aggravated predictability and thus increased risk in market operations for market participants (see [53] for further information regarding risk management in energy production and trading). More specifically, the excess of electricity supply generates negative price spikes, which can result in forced shutdowns and thus efficiency losses as well as financial losses with the consequence of an unprofitable operation in the long term. On the contrary, the occurrence of major electricity shortages generates positive price spikes and increases the necessity of reserve capacity to prevent blackouts. In this case, gas-fired power plants are placed in operation because they offer high operational flexibility and short ramp-up times (see [17] for a complete discussion on the role of different forms of energy within the electricity market). However, this in turn contradicts energy policy targets to decrease dependency on gas and the electricity supply by CO_2 intensive power plants. All in all, increasing volatility imposes significant challenges on the electricity market environment.

Table 3
Average deviation of the market value (factor) per additional TWh wind energy in EUR/MWh (%).

		Short term	Long term
Market value (factor)	Onshore	−0.78 (−0.92%)	−0.33 (−0.92%)
	Offshore	−0.81 (−1.08%)	−0.33 (−0.82%)
	FINO 1	−0.79 (−0.87%)	−0.28 (−0.84%)

The results shown in Fig. 9 are provided using the average number of negative and positive extreme events per year as a measure of variability instead of other more common key figures for price volatility (e.g., annualised volatility [53]). These were considered to be the most suitable parameters for analysing results with this specific characteristic (inter alia negative prices) and deducing factual conclusions. Negative extreme events were defined to be hours where the market clearing price is negative and positive extreme events where it is higher than twice the annual average market price. FINO data were excluded, because the missing smoothing effect would falsify the variability analysis.

In general, the results of the short-term simulation show the expected shift to lower prices, i.e., the average number of negative (positive) price events increases (decreases) as the energy amount added increases (decreases). The long-term simulation reveals that the more wind energy is added the more negative and positive extreme events occur, which implies that it induces higher variability on the electricity spot market. Both the results of the short-term and long-term simulation suggest that these effects are stronger for onshore wind than for offshore wind, which is an indication of the positive impact of a steadier offshore wind resource.

6. Conclusion

Although a comprehensive assessment has revealed that the market value of offshore wind is in general higher compared with onshore wind, the results of the simulation suggest that the impact

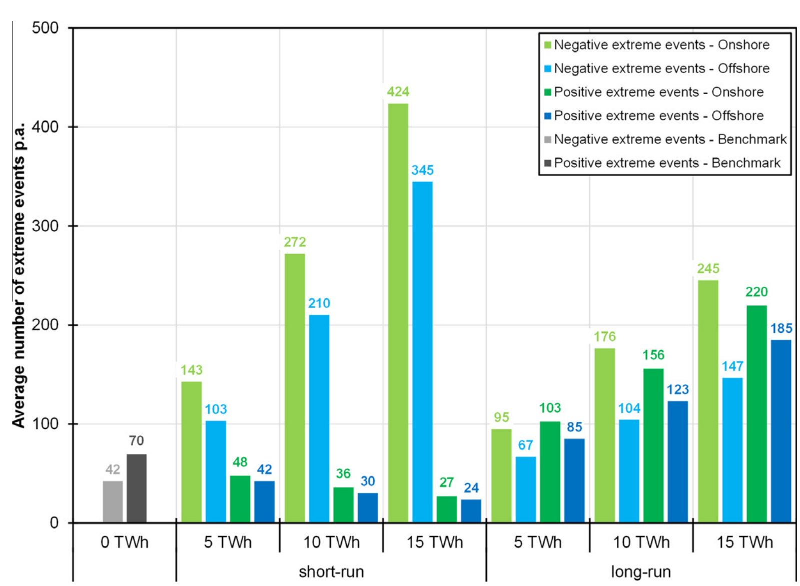

Fig. 9. Average number of negative (market price < 0) and positive (market price > 2 × average market price) extreme events p.a. in the years 2010–2014.

of additional energy amounts on the market value is rather the same. This allows to conclude that the only reason for the lower market value of onshore wind is the large amount of operational capacity already available, i.e., due to the limited spatial spread of the wind farms (most of them are located in northern Germany) the merit order effect is intensified during high wind periods. A similar conclusion can be drawn for the impact on the spot market price – there is an effect but it is very much the same for onshore and offshore wind. However, in addition to the results of the short-term analysis showing the expected decrease in the market price subject to an additional amount of energy, the simulation of the long-term impact revealed an interesting aspect beyond the evaluation of onshore vs. offshore wind electricity. The results suggest that if the additional amount of wind energy replaces the same amount of energy provided by base load power plants, the market price would not change and thus the only reason for a decreasing market price is the excess of supply. This is remarkable because publications in this field tend to link the expansion of renewable energy with a decreasing market price. Although the reason might lie in how research questions are formulated, it casts a shadow on the German energy turnaround. The simulation demonstrated that the impact on the spot market price is not related to the property of renewable energy feed-in but to the consequence of a rapid expansion of renewable electricity supply without the envisaged concomitant phase-out of coal and nuclear power plants.

Nevertheless, a difference between onshore and offshore wind in terms of variability imposed on the electricity spot market was determined. The steadier wind resource prevailing offshore seems to result in less variability induced by the feed-in on the spot market price compared with its onshore counterpart. Because increasing volatility entails significant challenges for the electricity market environment – i.e., increased risks, negative market price and its consequences, support of unwanted peak-load power plants and the necessity of increased reserve capacity – this finding is indeed an argument in favour of offshore wind. To what extent lower variability may compensate for drawbacks such as the higher levelised cost of offshore wind electricity is a question for future research.

Acknowledgements

The author would like to thank the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and Projektträger Lülich (PTJ) for permission to use wind data measured at the FINO 1, FINO 2 and FINO 3 research platform, as well as Prof. Franz Wirl for his advice.

References

[1] Bundesministerium der Justiz. Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG); 2008.
[2] German Federal Government. Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung, Berlin; 2010.
[3] Blomberg S. The realisation of offshore wind park projects in Germany - political environment, legal framework and bankability implications. Hamburg: Anchor Academic Publishing; 2014.
[4] Prognos AG. Institute of Energy Economics at the University of Cologne (EWI), Gesellschaft für Wirtschaftliche Strukturforschung mbH (GWS). Entwicklung der Energiemärkte – Energiereferenzprognose. Basel/Cologne/Osnabrück; 2014.
[5] Leipziger Institut für Energie GmbH. Mittelfristprognose zur EEG-Stromeinspeisung bis 2019, Leipzig; 2014.
[6] Federal Ministry for Economic Affairs and Energy. Energy data and prognoses <http://www.bmwi.de/DE/Themen/Energie/Energiedaten-und-analysen/Energiedaten/energietraeger.html> [accessed 30.10.14].
[7] Bundesrepublik Deutschland. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2014), Germany; 2014.
[8] Bilgili M, Yasar A, Simsek E. Offshore wind power development in Europe and its comparison with onshore counterpart. Renew Sustain Energy Rev 2011;15:905–15.
[9] Toonen HM, Lindeboom HJ. Dark green electricity comes from the sea: capitalizing on ecological merits of offshore wind power? Renew Sustain Energy Rev 2015;42:1023–33.
[10] Hirth L. The market value of variable renewables. Energy Econ 2013;38:218–36.
[11] Grothe O, Müsgens F. The influence of spatial effects on wind power revenues under direct marketing rules. Energy Policy 2013;58:237–47.
[12] Kaldellis JK, Kapsali M. Shifting towards offshore wind energy—recent activity and future development. Energy Policy 2013;53:136–48.
[13] Ray S, Munksgaard J, Morthorst PE, Sinner A-F. Wind energy and electricity prices – exploring the "merit order effect"; 2010, http://www.ewea.org/fileadmin/files/library/publications/reports/MeritOrder.pdf [accessed 15. January 2015].
[14] Würzburg K, Labandeira X, Linares P. Renewable generation and electricity prices: taking stock and new evidence for Germany and Austria. Energy Econ 2013;40:S159–71.
[15] Cludius J, Hermann H, Matthes FC, Graichen V. The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: estimation and distributional implications. Energy Econ 2014;44:302–13.
[16] Ketterer JC. The impact of wind power generation on the electricity price in Germany. Energy Econ 2014;44:270–80.
[17] Paraschiv F, Erni D, Pietsch R. The impact of renewable energies on EEX day-ahead electricity prices. Energy Policy 2014;73:196–210.
[18] Keles D, Genoese M, Möst D, Ortlieb S, Fichtner W. A combined modeling approach for wind power feed-in and electricity spot prices. Energy Policy 2013;59:213–25.
[19] Gelabert L, Labandeira X, Linares P. An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. Energy Econ 2011;33:S59–65.
[20] Clò S, Cataldi A, Zoppoli P. The merit-order effect in the Italian power market: the impact of solar and wind generation on national wholesale electricity prices. Energy Policy 2015;77:79–88.
[21] Mulder M, Scholtens B. The impact of renewable energy on electricity prices in the Netherlands. Renew Energy 2013;57:94–100.
[22] Woo CK, Horowitz I, Moore J, Pacheco A. The impact of wind generation on the electricity spot-market price level and variance: the Texas experience. Energy Policy 2011;39:3939–44.
[23] Pereira AJC, Saraiva JT. Long term impact of wind power generation in the Iberian day-ahead electricity market price. Energy 2013;55:1159–71.
[24] Sensfuß F, Ragwitz M, Genoese M. The merit-order effect: a detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 2008;36:3076–84.
[25] McConnell D, Hearps P, Eales D, Sandiford M, Dunn R, Wright M, et al. Retrospective modeling of the merit-order effect on wholesale electricity prices from distributed photovoltaic generation in the Australian National Electricity Market. Energy Policy 2013;58:17–27.
[26] Azofra D, Jiménez E, Martínez E, Blanco J, Saenz-Díez JC. Wind power merit-order and feed-in-tariffs effect: a variability analysis of the Spanish electricity market. Energy Convers Manage 2014;83:19–27.
[27] Azofra D, Martínez E, Jiménez E, Blanco J, Azofra F, Saenz-Díez JC. Comparison of the influence of photovoltaic and wind power on the Spanish electricity prices by means of artificial intelligence techniques. Renew Sustain Energy Rev 2015;42:532–42.
[28] Gullì F, Balbo A Lo. The impact of intermittently renewable energy on Italian wholesale electricity prices: additional benefits or additional costs? Energy Policy 2015;83:123–37.
[29] Ciarreta A, Espinosa MP, Pizarro-Irizar C. Is green energy expensive? Empirical evidence from the Spanish electricity market. Energy Policy 2014;69:205–15.
[30] Wozabal D, Graf C, Hirschmann D. Renewable energy and its impact on power markets. In: Kovacevic RM, Pflug GC, Vespucci MT, editors. Handb Risk Manag Energy Prod Trading. New York: Springer Science+Business Media; 2013. p. 291–319.
[31] Bundesrepublik Deutschland. Verordnung zur Weiterentwicklung des bundesweiten (Ausgleichsmechanismus - AusglMechV), Germany; 2014.
[32] Bundesrepublik Deutschland. Verordnung zur Ausführung der Verordnung zur Weiterentwicklung des bundesweiten Ausgleichsmechanismus (Ausgleichsmechanismus-Ausführungsverordnung - AusglMechAV), Germany; 2014.
[33] EPEX SPOT SE. EPEX Spot Exchange Rules – 13/05/2014; 2014.
[34] EPEX SPOT SE. EPEX Spot Operational Rules – 13/05/2014; 2014.
[35] EPEX SPOT SE. EPEX SPOT RULES & REGULATIONS - DEFINITIONS – 16/10/2012; 2012.
[36] EPEX SPOT SE. European Power Exchange EPEX Spot Website <http://www.epexspot.com/en/> [accessed 20.1.15].
[37] Forschungs-und Entwicklungszentrum Fachhochschule Kiel GmbH. FINO - Research platforms in the North Sea and Baltic Sea <http://www.fino-offshore.de/en/> [accessed 30.11.14].
[38] Federal Maritime and Hydrographic Agency (BSH). Continental Shelf Research Information System (CONTIS) <http://www.bsh.de/en/Marine_uses/Industry/CONTIS_maps/> [accessed 30.11.14].
[39] Bundesamt für Seeschifffahrt und Hydrographie (BSH). FINO Database <http://fino.bsh.de/> [accessed 15.03.15].
[40] 50Hertz Transmission GmbH. Wind power feed-in <http://www.50hertz.com/en/Grid-Data/Wind-power> [accessed 14.01.15].
[41] Amprion GmbH. Wind power infeed <http://www.amprion.net/en/wind-feed-in> [accessed 14.01.15].

[42] TenneT TSO GmbH. Actual and forecast wind energy feed-in <http://www.tennettso.de/site/en/Transparency/publications/network-figures/actual-and-forecast-wind-energy-feed-in> [accessed 14.01.15].

[43] TransnetBW GmbH. Wind infeed <http://www.transnetbw.de/en/key-figures/renewable-energies/wind-infeed> [accessed 14.01.15].

[44] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH. Veröffentlichungen zur Marktprämie <http://www.netztransparenz.de/de/Marktprämie.htm> [accessed 20.03.15].

[45] EPEX SPOT SE. Market Data – Auction <http://www.epexspot.com/en/market-data/auction> [accessed 18.01.15].

[46] Energy Brainpool GmbH & Co. KG. Ermittlung des Marktwertes der deutschlandweiten Stromerzeugung aus regenerativen Kraftwerken, Berlin; 2014.

[47] European Energy Exchange AG. FTP-Server - Market Data <https://infoproducts.eex.com> [accessed 22.09.14].

[48] Fraunhofer Institute for Solar Energy Systems ISE. Levelized cost of electricity renewable energy technologies, Freiburg; 2013.

[49] Conejo AJ, Carrión M, Morales JM. Decision making under uncertainty in electricity markets. New York: Springer Science+Business Media, LLC; 2010.

[50] Galiana FD, Conejo AJ. Economics of electricity generation. In: Gómez-Expósito A, Conejo AJ, Cañizares C, editors. Electr Energy Syst – Anal Oper. Boca Raton, FL: Taylor & Francis Group; 2009.

[51] Morales JM, Conejo AJ, Madsen H, Pinson P, Zugno M. Integrating renewables in electricity markets; 2014, New York: Springer Science+Business Media.

[52] Gabriel SA, Conejo AJ, Fuller JD, Hobbs BF, Ruiz C. Complementarity modeling in energy markets. New York: Springer Science+Business Media; 2013.

[53] Kovacevic RM, Pflug GC, Vespucci MT. Handbook of risk management in energy production and trading; 2013, New York: Springer Science + Business Media.