

## Market value of wind power

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# Market Value of Wind Power

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**Abstract**—Variability and predictability constraints of wind hinder the cost-efficient integration of wind power generation into power markets. Within the framework of EIT KIC INNOENERGY Offwindtech project, a ‘Market Value’ tool is developed. Here, the market value of wind power generation can be assessed with respect to its wind site and the respective power market it is integrated in. A case study is introduced to compare the potential market value of different wind sites (offshore/onshore) and of different power market concepts (day ahead/intra-day). It is found that the relative market value of wind power does not significantly differ between its diverse conditions. Nevertheless, when considering the costs of wind power generation, coastal wind power generation, to be sold in intra-day markets, has the largest potential to be cost-efficient. Future reduction of offshore installation and maintenance cost could further increase the market value/competition of offshore wind power. The difference of predictability accuracy between onshore and offshore wind power generation has negligible impact on the results.

*Keywords*—day ahead market; intra-day market; wind forecast; wind power generation

## I. INTRODUCTION

The integration of wind power generation into power markets requires a different approach with respect to energy trading. Due to variability and predictability constraints of wind power generation, Balance Responsible Parties experience difficulties to meet their energy schedules. Due to the inaccurate prediction and the rather negative correlation between system load and wind power generation, challenges are faced. As a result, the generation portfolio of market parties still relies mainly on conventional generation. Nonetheless, several new market arrangements have been introduced, to enable a more cost-efficiently integration of wind power generation into power markets. Two main examples are trading across borders and trading closer to real-time, at intra-day. Several studies have investigated the financial impact and the costs of integrating wind power generation e.g. [1]. This work aims at assessing the value, rather than the costs of wind power.

It is somehow self-evident that the forecast of wind power generation closer to real time is more accurate. This logical reasoning is followed by the hypothesis that wind power should always be sold in intra-day markets. Though, market prices differ between day ahead and intra-day. It is

certainly not evident that market prices at intra-day stage are equal or larger compared to prices at day ahead stage. Therefore, the actual market value of wind power depends on the related market prices at day ahead and intra-day and is determined by the accuracy of forecast techniques at day ahead and intra-day.

Supported with a case study, the market value of wind power is determined, based on geographical conditions of exemplarily chosen wind power plants and based on specific power market concepts it will be integrated in.

The paper is structured as follows: the project of EIT KIC INNOENERGY Offwindtech and the applied algorithm for the ‘market value’ tool are introduced in section II. The case study is introduced in section III in combination with a data analysis of wind power generation and market prices of the year 2011. The algorithm of the tool is used to acquire results, presented in section IV. Finally, conclusions are drawn in section V.

## II. KIC INNOENERGY

### A. KIC Offwindtech

Within the EIT KIC INNOENERGY Offwindtech project, four tools are developed. Their inter-relation is schematically shown in Fig. 1.

The peculiar concept of the project is characterized by the possible interconnection of all 4 separate tools. This enables an overall assessment of specific wind power plants, with detailed results. However, all tools can be used independently.

### B. ‘Market value’ tool

The ‘market value’ tool is developed for, e.g., policy makers, regulators, wind power plants operators, investors,

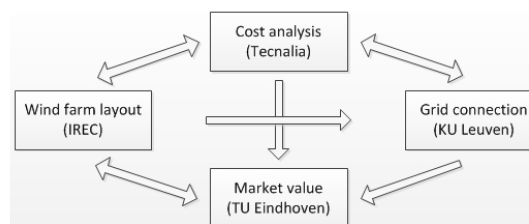


Figure 1. Relation of the four tools within the Offwindtech WP1 framework.

market parties and academics. Besides, the versatility of the tool enables to perform simulations with a diversity of objectives. Policy makers could determine the requested subsidy or feed in tariff for wind power generation. Investors can trace optimal locations of their planned wind power plants. Market parties use the tool to calculate their optimal market integration of wind power. The tool can also be used to investigate the effect, impact or performance of different forecast techniques.

The ‘market value’ tool is developed in Matlab environment. Its inputs are schematically depicted in Fig. 2.

### C. Algorithm

The algorithm of the market value tool is comprehensively explained in [2]. Here, wind speeds on sensor height are converted to wind speeds experienced at the related hub-height of wind turbines [3]. The wind speed time series is converted into wind power generation time series representing a wind power plant. Therefore, a multi turbine power curve approach of [4] is applied based on wind turbines with a power–wind speed characteristic of [5] and [6].

The calculated wind power generation time series in [MWh/h] is multiplied with market prices [EUR/MWh] to calculate the revenue of wind power generation [EUR/h].

$$\begin{aligned} \text{Revenue of wind generation [EUR/h]} & \quad (1) \\ &= \text{wind power generation [MWh/h]} \\ & \quad * \text{market prices [EUR/MWh]} \end{aligned}$$

To determine the financial yield of wind power generation, the time series imbalance costs [EUR/h] are deducted from the wind revenue [EUR/h].

$$\begin{aligned} \text{Yield of wind power generation [EUR/h]} & \quad (2) \\ &= \text{revenue of wind power generation [EUR/h]} \\ & \quad - \text{wind imbalance costs [EUR/h]} \end{aligned}$$

Here the wind imbalance costs are a result of the multiplication of expected wind power generation – actual wind power generation in [MWh/h] with imbalance costs in [EUR/MWh].

$$\begin{aligned} \text{Wind imbalance costs [EUR/h]} & \quad (3) \\ &= \left[ \begin{array}{l} \text{expected wind power generation [MWh/h]} \\ - \text{actual wind power generation [MWh/h]} \end{array} \right] \\ & \quad * \text{imbalance costs [EUR/MWh]} \end{aligned}$$

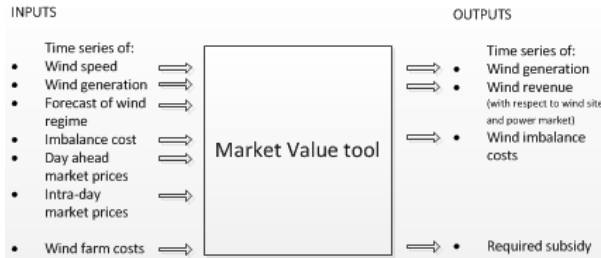


Figure 2. Schematic overview of the inputs and outputs of the ‘Market Value’ tool.

## III. CASE STUDY

In this section, a case study is introduced to assess the market value of wind power located in the Netherlands for a reference year 2011. The geographical distinction of wind sites will be made between offshore, coastal, and inland onshore wind power generation. These three locations differ based on the combination of wind regime and costs of wind power plant installation. The assessment will elaborate on the hypothesis that coastal wind power, traded closer to real time is most cost-efficient.

The generated power is fictively sold in the Dutch power market, the energy exchange platform of APX-Exend, operating spot and futures markets for electricity. APX-Exend made data available [7], and in [2] it is elaborated how this data was used. With respect to the full integration of large scale wind power into spot markets, it must be clarified that day ahead and intra-day markets are not (yet) mature and liquid to support this integration. It is expected that market prices would significantly be affected.

The wind data set with its associated forecast data set was made available based on work of [8]. The related power imbalance costs in [EUR/MWh] were acquired from the Dutch Transmission System Operator TenneT TSO B.V. [9].

### A. Cases

The distinction is made between 6 different concepts as depicted in Fig.3.

### B. Wind site

Three different wind sites have been chosen based on their characteristic wind site experience. Offshore wind power generation represents high wind speeds, however, its installation and maintenance costs are significant larger compared to onshore with smaller energy yield. Nevertheless, the main property of the coastal location is its wind regime with approximately offshore conditions, but with low installation costs. The statement that coastal installation, especially in the Dutch west coastline, has offshore wind conditions is deduced from the fact that in the Netherlands, wind flows on annual basis mainly directed from south-west towards north-east. This is geographically depicted in Fig. 4, with a reference to the three wind sites assessed in this work. The analysis is based on data from [10].

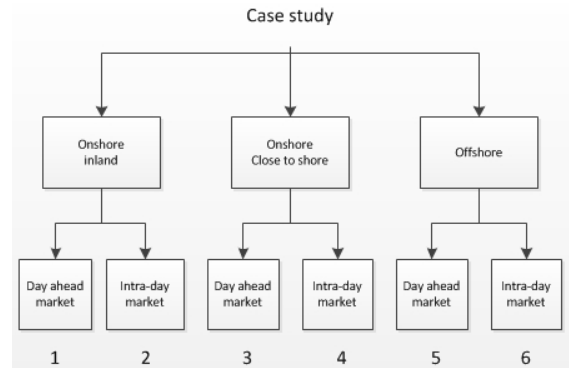


Figure 3. Schematic depiction of the 6 concepts of wind power plants within the case study.

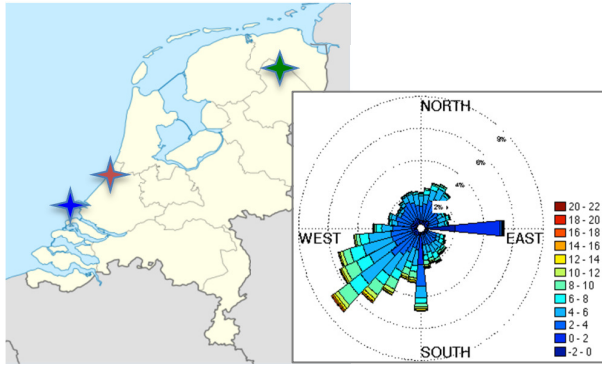


Figure 4. Geographical depiction of the three wind sites and the main wind direction over the Netherlands.

### C. Wind power generation

The wind power generation data set of the onshore site is depicted in Fig. 5. The randomly behavior is noticeable.

### D. Wind forecast and power imbalances

The wind forecast techniques used in this work become more accurate closer to real time. This effect is depicted in Fig. 6 where from day ahead (D-24h) up to one hour ahead (D-1h) the duration curves of forecast errors are shown.

The related imbalances for the case study are derived using (3) and the results show that besides wind generation, also wind power imbalances are identified with certain patterns or trends, in order to anticipate on.

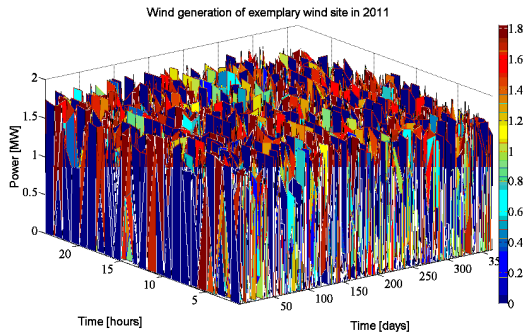


Figure 5. Exemplarily depiction of an annual profile of onshore wind power generation.

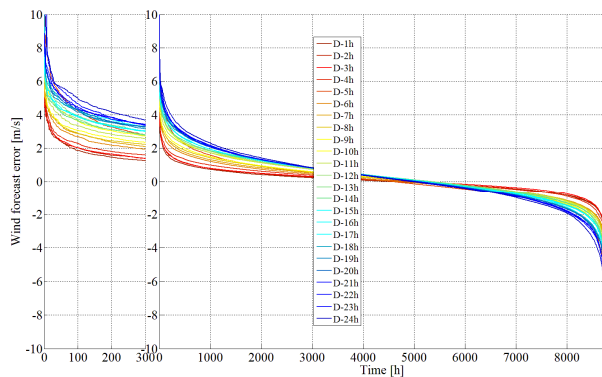


Figure 6. Duration curve of wind forecast mismatches of day-24h up to day-24h.

### E. Market prices

The APX Endex market data of day ahead is depicted in Fig. 7. Day and night patterns as well as seasonal patterns are clearly noticeable. The correlation of market prices and wind power generation is weak.

## IV. RESULTS

Based on the algorithm (section II) and the case study (section III) results are shown in Table 1. Generally, the calculated values of revenues of wind power generation are relatively high, compared to values from literature. This is caused by theoretical considerations with perfect circumstances, not considering imperfections such as turbulence of wind sites, or maintenance and failures of wind turbines, or taking into consideration other externalities.

Secondly, based on analyses of market price data, it is found that intra-day market prices are commonly larger compared to day ahead, however, this difference is relatively small. Likewise, the profile of the day ahead and of the intra-day market prices is strongly correlated. Therefore, it can be concluded that the impact of inaccuracy of wind power forecast is the main cause of dissimilar results for the resulting economic benefits of wind power in day ahead and intra-day markets.

Thirdly, the data analysis revealed that the forecast of inland onshore wind power generation is optimistic (more generation) compared to the forecast of offshore wind power generation. This will result in additional negative imbalances for onshore wind power generation which commonly come along with larger imbalance costs, due to the Dutch thermal generation oriented system. This effect has the largest impact at the day ahead market, and closer to real time at the intra-day market, this effect attenuates. Thus, the performance of a more accurate forecasting limits the expense of total imbalance costs.

In Table 1 it is listed that the wind power imbalance costs reduce significantly as expected when changing from day ahead stage towards the intra-day stage. This effect is similar for all three locations. The accuracy of wind prediction at the intra-day stage is related to the fact that wind will not vary significantly up to real time, as can be concluded from the “van der Hoven Spectrum” [3]. Therefore, forecast should become more accurate which is confirmed by the results of Table 1. The impact of wind inaccuracy is smallest for offshore wind generation.

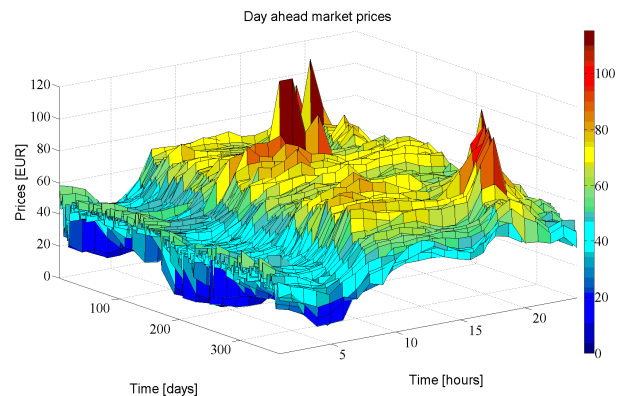


Figure 7. Exemplarily depiction of an annual profile of day ahead market prices.

Primarily, this is due to the optimistic (more generation) forecast of onshore which leads to relatively lower offshore imbalance costs. Next, this is based on the power–wind speed curve of wind turbines. Hence, at moments of higher wind speeds, wind turbines operate at rated power, where variations in wind speed (leading to forecast inaccuracy) do not lead to power deviations. At offshore wind sites the probability of higher wind speeds is larger, due to smaller roughness factors. Therefore, imperfections in wind forecast have a smaller impact on offshore wind power generation, and consequently wind imbalance costs are smaller compared to onshore wind power generation.

Even though offshore wind power generation is forecasted more accurately and therefore smaller imbalance costs are experienced, its installation and maintenance costs are higher. Therefore, in this case study, coastal wind power generation is still most cost-efficient, operating in the intra-day market.

Table 1. Results of the six concepts of wind power generation based on wind sites and power market.

	Offshore Wind	Onshore Wind	Coastal Wind
Costs [€/MWh]	80.0	60.0	48.0
Day Ahead revenue [€/MWh]	54.49	54.57	54.57
Day Ahead imbalances [€/MWh]	9.56	12.29	10.20
Day Ahead value [€/MWh]	45.00	42.28	44.57
Intra-day revenue [€/MWh]	57.74	58.46	58.16
Intra-day imbalances [€/MWh]	3.64	4.85	3.95
Intra-day value [€/MWh]	54.09	53.61	54.20

## V. CONCLUSIONS

The integration of wind energy into power markets is challenged by variability and predictability constraints of wind power generation. The variability of wind power restricts the desired sale of wind power on peak moments at rated power. Furthermore, forecast mismatches of wind induce imbalance costs. Therefore, in order to assess the actual market value of wind power, an algorithm is developed, within the framework of EIT KIC INNOENERGY Offwindtech project. This software tool “Market Value of Wind Power” determines the performance of wind power in certain power markets where the relation between energy prices, imbalance costs and wind energy yield are congregated to determine the actual value of wind power generation.

Supported with a case study, the market value of different wind sites (offshore/onshore) and of different power market concepts (day ahead/intra-day) is assessed. In our example, the results show that coastal wind power generation is indeed the most cost-efficient concept, integrated in intra-day markets. This outcome is owed to low installation and maintenance costs in combination with a high energy yield wind site.

Nevertheless, the concept of coastal wind power does not have the highest potential in the medium and long term,

as it is rather unlikely that coastlines will be equipped with large scale wind power plants. Thus, due to the residential and recreational value of coastal areas in The Netherlands, this area will most probably remain unexploited.

A significant step is already made with the integration of intra-day power markets where closer to real time wind power can be traded and, evidently, lower imbalance costs are involved. Nevertheless, these spot markets are currently not (yet) mature and liquid to support the large scale integration of wind power generation. A second adequate step to increase the cost-efficient integration of wind power is under development, where installation and maintenance costs of offshore wind power generation are reduced applying new techniques and gaining experience in this field.

Finally, this work’s approach is to display how wind power can be integrated into power markets as an independent power source. More practically, wind power is part of a generation portfolio relying on complementary assets. Therefore, wind power imbalances are respectable counterbalanced with assets within the generation portfolio of market parties. Nevertheless, with the increased share of wind power generation, it is plausible that wind power could solely be integrated into power markets as a cost-efficient, independent power source.

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