

# Deep offshore wind farm planning and cost calculation tools

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## INTRODUCTION

In planning the installation and operation of wind turbines in the offshore environment, finding new technological solutions is a key element for the economic success of offshore wind projects and represents a completely new challenge compared to their onshore counterpart. The tendency is that wind turbines will continue growing larger and more powerful and will be installed further away and in deeper waters, leading to more complex infrastructures and greater challenges.

There's a proven experience in the planning and front end engineering of fixed offshore wind farms. Promoters and engineering companies have tools for the costs calculation and wind farm planning, that support the decision making process for the investment. In deep offshore wind farms, there's still a lack of this type of tools due to the development stage of the technology: only two full scale prototypes installed. These tools can help in the optimization of the wind farm and costs reduction.

**KEY WORDS:** offshore wind; ocean energy; wind farm planning; economics.

## OBJECTIVES

The objective of the paper is to present four tools aimed to optimize the design and reduce the cost of deep offshore wind farms, by analysing key aspects in the planning stage.

**Wind Farm Layout Tool** is based on computing the total power output generated by a generic Wind Power Plant (WPP) considering any wind farm layout, any wind condition (wind direction and average wind speed) and taking into account wake effect among wind turbines, and to optimize the inter-array connection of wind turbines in order to minimize the power losses within the wind farm. The scope of this tool covers the wind farm and collecting point, but it does not take into account neither the transmission system, nor the grid interface.

**Grid Connection: Offshore Transmission Optimization Tool** is a rule based genetic algorithm which takes investment, installation and maintenance costs into account. To determine the transmission system with least life cycle costs, the costs for losses and not harvested energy are

taken into account as well.

The optimization tool takes radial and meshed grid configurations into account. As transmission technologies, AC technology and VSC HVDC are considered. The optimization tool delivers as output the optimal topology and the optimal technology, power rating and voltage level of each transmission path. The user friendly software is developed in Matlab.

**Cost Model Tool** is based on the classical distinction between capital costs, operational costs and the estimation of the economic indicator based on the revenue due to power absorption over a certain lifetime – inputs from the other tools developed in the project.

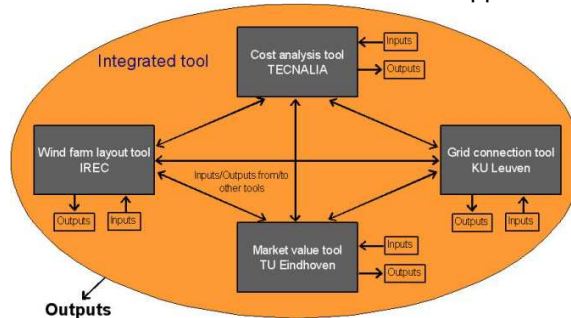
It is a fully parametric model developed using Ms Excel: the formulae used depend on the inputs, selected technology and location of the wind farm. The focus is CAPEX/OPEX assessment and main parameters influences to help the decision making about the floating structure and means required for the different stages of the wind farm development. The whole analysis is based on the estimation of the Net Present Value.

Results: CAPEX and OPEX cost breakdown for each floating technology and for a given wind farm input data. Economic analysis and comparison between different technologies: expenses, incomes, annual net cash flow, discount cash flow, profitability for a given electricity price...

The **Market Value of Wind Power Tool** assesses as the name says, the market value of wind power, here including revenues in different markets, imbalance costs and generated energy.

This tool can be used by providing a certain portfolio of wind turbines or wind farms and the wind characteristics of that location. Then, the user selects in which power market the wind energy should be integrated. The tool enables the user to optimize conditions of the market for the study, allowing thus the analysis of many different scenarios. Furthermore, it enables to perform simplified research on the market value of wind power in general, or to perform a more precise, detailed analysis.

In the next figure the relation between the different tools can be appreciated:



In addition to the integrated tool outputs, the user will have specific outputs from each tool.

Figure 1: Relation between the different tools

## WORK DESCRIPTION

General description of the four tools:

### 1. Wind Farm Layout Tool

The aims of this tool are to compute the total energy yield by a generic Wind Power Plant (WPP) during its lifetime considering any wind farm layout, any wind condition (wind direction and average wind speed) and taking into account wake effect among wind turbines, and to optimize the inter-array connection of wind turbines in order to minimize the power losses within the wind farm.

The scope of this tool covers the wind farm and collecting point, but they do take into account neither the transmission system, nor the grid interface.

The methodology used is based on the four-step approach explained below. These four steps are repeated as many times as different offshore wind farms are being analyzed.

- Step 1: Wind Farm Layout:** In the first step, the layout of a specific wind farm has to be defined. Thus, a completely generic WPP layout is defined so that it can be determined not only considering a matrix rectangle, but also specifying the coordinates of each wind turbine. If the WPP layout is defined by a matrix rectangle, five parameters are required: the number of rows and columns of the WPP, the distance between nearby wind turbines in the prevailing wind direction, the crosswind spacing among wind turbines within a same row and the rotor diameter of each turbine. Otherwise, if the WPP layout is defined by coordinates, the input data required are the rotor diameter of each wind turbine and its position (x,y) in meters.
- Step 2: Wind speed calculation of each wind turbine:** Once the wind farm layout is known, the next step consists of computing the wind speeds of each turbine for the entire wind farm. As it can be seen from Figure 1 this process is repeated  $N_{Nvg}$  times (index  $i$ ) in order to assess more accurate results. Thereby,  $N_{Nvg}$  sets of wind speeds are generated, taking into account both different wind directions and average wind speeds throughout the wind farm. In addition, with the aim of analyzing the influence of wind speed variability in wind farms, another loop is considered, increasing the standard deviation (index  $k$ ) from 0.5 to  $N_{std}/2$ .

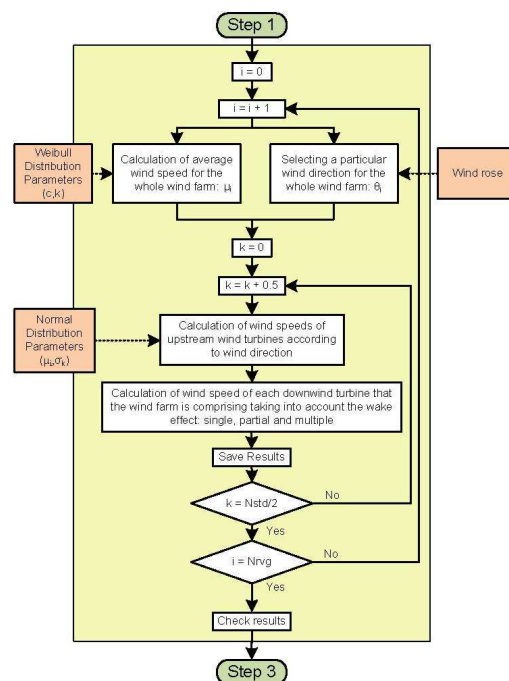


Figure 2: Wind speed calculation of each wind turbine (Step 2).

According to Figure 2, for a specific  $i$  case, two parameters have to be selected at the beginning: the average wind speed for the entire wind farm,  $\mu_i$ , and a certain wind direction,  $\theta_i$  (it is assumed that all wind turbines have the same wind direction). The former,  $\mu_i$ , is randomly generated by means of the Weibull distribution function whose dimensionless shape ( $k$ ) and scale ( $c$ ) parameters are inputs dependent on the wind farm analyzed. The latter,  $\theta_i$ , is calculated at random according to different wind roses depending on the specific wind farm location.

Once the average wind speed for an entire wind farm is known, and taking into account an incoming wind direction, the wind speeds of upstream turbines are computed. In order to do so, a standard deviation value,  $\sigma_k$ , is defined and random wind speeds are generated according to the normal distribution function,  $N(\mu_i, \sigma_k^2)$ . Then, the wind speeds from the rest of the turbines are calculated, taking into consideration the wake effect. As mentioned above, in order to analyze the influence of wind speed variability in wind farms, this process is repeated a total of  $N_{std}$  times increasing the standard deviation from 0.5 to  $N_{std}/2$ . Finally, the entire process of wind speeds calculation is executed  $N_{avg}$  times. Therefore, the total number of sets generated is  $N_{avg} \times N_{std}$  for a particular wind farm with  $N_{wt}$  wind turbines.

- **Step 3: Calculation of energy generated by the wind farm for each topology:** In the third step, the generated energy of the whole wind farm is computed as a function of the wind turbine parameters and the incoming wind speeds previously computed. The power generation of those turbines, whose wind speeds (obtained in the step 2) are among  $V_{rated}$  and the cut-out-speed (Full load operation), is kept constant to its rated value ( $P_{rated}$ ) since, in this region II, pitch control is activated, limiting the power output. This calculation procedure is repeated as many times as wind speed sets are generated, that is,  $N_{avg} \times N_{std}$ .
- **Step 4: Inter-array cable optimization:** Finally, in this step a code is implemented in DigSilent PowerFactory, using the programming language DPL. Given the inter-array cable database and all data extracted from steps 1 to 3 (wind farm layout, wind conditions and wind turbine data) and according to a maximum admissible loading of the cable entered by the user, the program selects the most appropriate inter-array connection to minimize the losses within the wind farm. The losses will be calculated by means of the power load flow calculations (LF) and the power generated by each wind turbine is considered according to a Weibull distribution that combined with its power curve define the energy produced by the aggregated wind farm in each state per year. The solutions will be based on minimum section of cables for the inter-array connection and the calculations will take into account the efficiency losses of the components.

## 2. Grid Connection: Offshore Transmission Optimization Tool

The goal of the offshore transmission optimization tool is to determine the transmission system layout to connect multiple offshore wind farms requiring the least life cycle system costs. The life cycle system costs consist of investment cost, cost of losses, cost of maintenance and cost of non-harvested energy due to unavailability of the transmission system. The optimization tool delivers besides the optimal layout, the optimal voltage level of transmission path and the necessary cross-sections and power ratings of used equipment. The tool is developed to be used in the first stages of planning where little information is available.

The optimization tool takes radial and meshed grid layouts into account, as well as the use of HVAC and HVDC technology as possible transmission options.

As mentioned above, the tool can be used in the first planning stage of the project. Therefore the focus has been to provide a tool using as little input data as possible. The tool requires the geographic positions of wind farms and possible points of common coupling (PCCs) as input (fig. 3). Besides the locations, also the rated power of the wind farms and the maximum amount of power which can be injected in the PCCs have to be delivered as input. The tool offers the possibility of defining multiple onshore areas and prohibited areas where no cables may be installed.

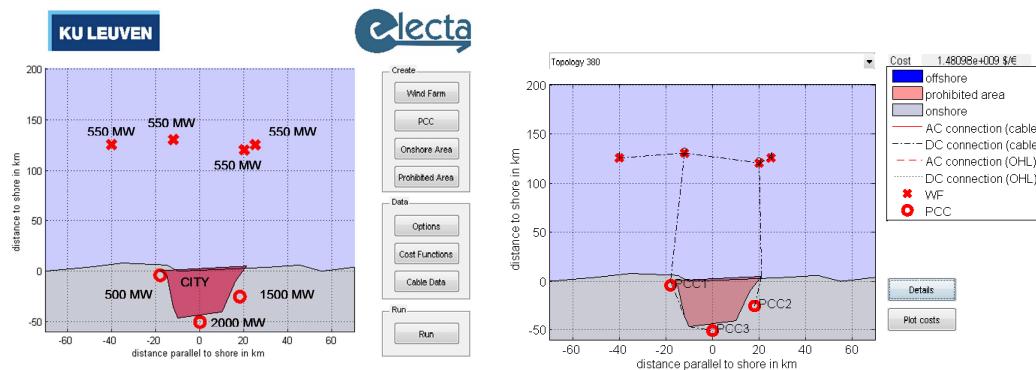


Figure 3: Input interface of transmission optimization tool, showing location of wind farms (X), points of common coupling (O), onshore areas (grey) and prohibited areas (red). Figure 4: Optimization results delivered by the developed tool

The optimization tool contains a cost database for possible technology options in form of cost functions. The used cost functions can be updated by the user. This allows a more accurate representation of costs for different geographic regions or market conditions. Some specific options, such as the energy price to calculate the value of losses, or the life time of the transmission system can be updated by the user.

The optimization tool uses a rule based heuristic algorithm to create transmission system topologies. For each created topology, the voltage level and the used technologies are optimized using a deterministic approach (Figure 5). A detailed description of the optimization algorithm can be found in [1].

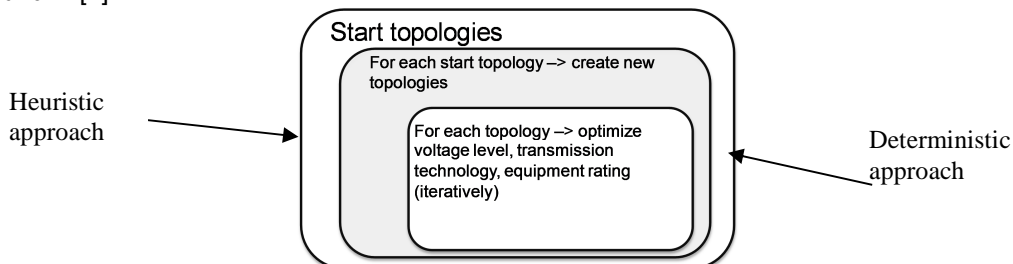


Figure 5: General structure of the optimization algorithm

The optimization tool delivers the optimal transmission technology of each transmission path. All feasible transmission topologies are stored and provided to the user so that further technical analysis can be performed on these topologies. The obtained topologies are ranked, based on their total lifecycle costs. Beside the optimal topology, also the optimal voltage level of used equipment such as cables, transformers, compensation equipment or HVDC converters, is determined. For transmission cables, the required number of cables as well as their cross sections are provided in the output interface.

### 3. Cost Model Tool

Cost analysis tool provide CAPEX and OPEX costs calculation for a deep offshore wind farm, taking into account all the cost contributors: floating structure type, wind turbine, electric infrastructure, energy production... NPV is calculated for different types of floating structures in order to compare different alternatives. With the calculated costs, a model to evaluate the market value of wind power located at a certain site, integrated in a certain electricity supply system, is carried out with the

objective to develop a simple and effective tool to demonstrate the value of wind-based generated energy.

The main objective of the tool is the comparison through technical-economic aspects different floating structures of offshore wind in deep water. Nowadays there are mainly three floating concepts.

An economic assessment has been done with the different incomes and expenses along the project life. CAPEX and OPEX costs calculation are described taking into account all the cost contributors: floating structure type, material, wind turbine, electric infrastructure (submarine cable, offshore substation), energy production... The outputs of the economic study are economic indicators used to determine the profitability of the project such as Net Present Value (NPV) which is calculated for each type of floating structure in order to compare different technologies.

With the objective to bear in mind the electrical losses, a preliminary electrical model has been developed, where distributed parameter models of submarine cable and losses of the offshore substation are described. Currently no differences of energy production have been considered between the three different technologies. The main differences between them are structural, manufacturing and installation costs for the floating structures and moorings.

In the next figure there is a diagram with the different parts that is divided the model. There are some general inputs valid for the three types of structures and specific inputs only valid for specific technology cost estimation. For the economic assessment the incomes had been estimated taking into account a unique capacity factor for the three technologies, so that the incomes are the same for the economic balance. Depending on the objective this tool gives the possibility to make optimization of the different parameters.

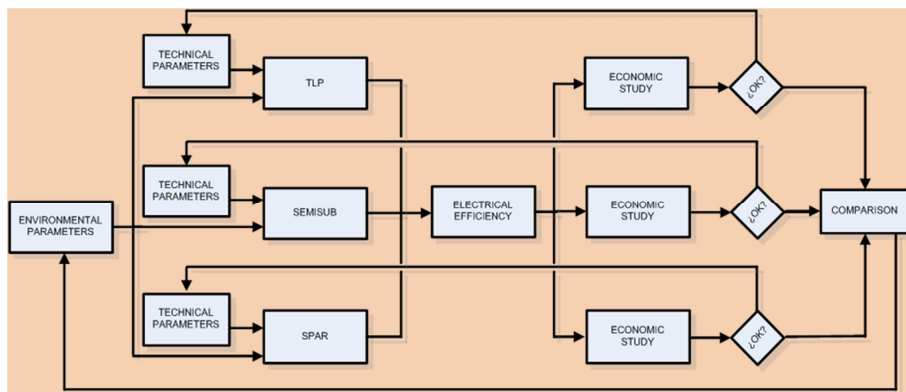


Figure 6: Scheme of the 3 concepts comparison

The tool has been developed is divided in 8 different parts.

Table 1 Different parts of the economic tool

NAME	DESCRIPTION
INPUTS	General inputs of wind farm
DATA	Internal parameters (can be modified – might be acceptable with default values)
TLP	Definition of TLP structure
SEMI-SUBMERSIBLE	Definition of semi-submersible
SPAR	Definition of SPAR structure
EFFICIENCY	Offshore substation and transmission efficiency is calculated
ECONOMIC	Economic balance of wind farm
RESULTS	Diagrams of the results

The outputs of the model are economic parameters: NVP, COE and B / C.

**NPV** (Net Present Value): is defined as the sum of the present values (PVs) of the individual cash flows of the same entity. NPV can be described as the “difference amount” between the sums of discounted: cash inflows and cash outflows. It compares the present value of money today to the present value of money in future, taking inflation and returns into account

$$NPV = \sum_{t=1}^n \frac{C_e * \text{energy}}{(1+k)^t} - CAPEX - \sum_{t=1}^n \frac{OPEX}{(1+k)^t}$$

Where:  $C_e$  Cost of energy (€/kW),  $n$ ; Life of the project, energy: Energy produced per year  
 CAPEX; Capital expenditure costs (initial investment); OPEX: Operation and maintenance costs.

Depending on the value of the NPV the decision of the investors must change:

Table 2 NPV description

VALUE	MEANING	DECISSION
NPV > 0	The investment produces more incomes than the required profitability (k)	The project can be accepted
NPV < 0	The investment produces less incomes than the required profitability (k)	The project can't be accepted
NPV = 0	The investment doesn't produce incomes and losses	The project doesn't produce incomes, so that the decision is made taking into account different aspects.

**COE** and **Benefit-Cost (B/C)**: The real cost of the energy produced and balance between benefit and costs can be obtained with the equation below:

$$COE = \frac{CAPEX + \sum_{t=1}^n \frac{OPEX}{(1+k)^t}}{\sum_{t=1}^n \frac{\text{energy}}{(1+k)^t}}, \quad \frac{B}{C} = \frac{\sum_{t=1}^n \frac{\text{benefits}}{(1+k)^t}}{\sum_{t=1}^n \frac{\text{costs}}{(1+k)^t}}$$

In the next figure there is an example of cost distribution of a semi-sub and total CAPEX (Pn:250 MW , Ds=50 km, Wd= 100m):

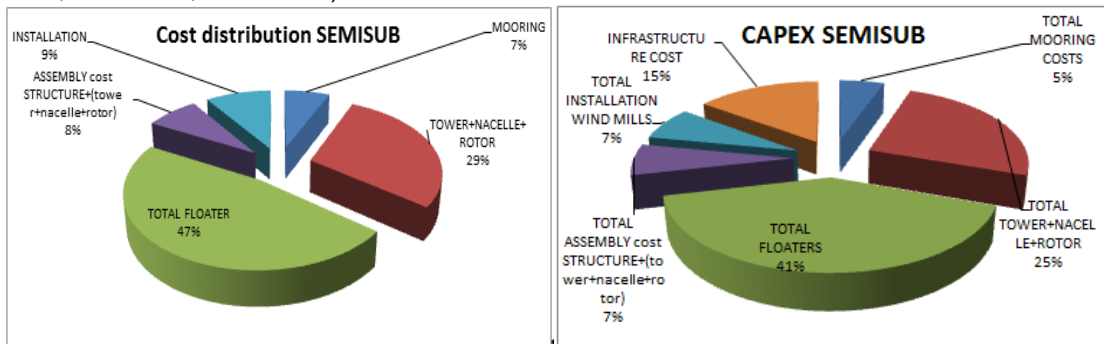


Figure 7: Case study example (Pn:250 MW , Ds=50 km, Wd= 100m): Cost distribution SEMISUB and CAPEX

#### 4. Market Value of Wind Power Tool

The ‘market value’ tool is developed for a range of stakeholders, e.g., policy makers, regulators, wind power plants operators, investors, market parties and academics. Furthermore, the versatility of the tool enables to perform simulations with a diversity of objectives. For example, policy makers could determine the requested subsidy or feed in tariff for wind power generation. Also, investors can trace optimal locations of their planned wind power plants. As well, market parties may 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 Figure 8

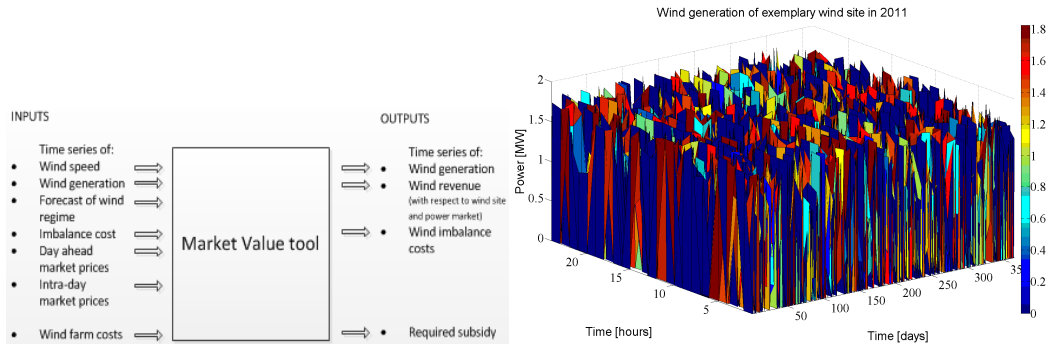


Figure 8. Schematic overview of the inputs and outputs of the 'Market Value' tool., Figure 9: Exemplarily depiction of an annual profile of wind power generation.

### Algorithm

The algorithm of the market value tool is comprehensively explained in [2]. Here, wind speeds on sensor height are up scaled to 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].

### Case study

As an application example of the software, a case study is displayed, assessing the market value of wind power located in the Netherlands for the reference year of 2011. The wind sites are geographically classified as offshore, coastal, and inland onshore. These three locations differ based on the combination of wind regime and/or on the costs of wind power plant installation. The current 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-Endex, for operating spot and futures markets for electricity, who made data available [7] [2]. Concerning the full integration of large scale wind power into spot markets, it should be highlighted that day ahead and intra-day markets are not (yet) mature and liquid enough to support it. It is expected that market prices would significantly be affected.

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

### Wind site

Three different wind sites have been chosen based on their characteristic wind site experience. Offshore wind power generation presents high wind speeds. Nonetheless, its installation and maintenance costs are significant higher when compared to onshore with smaller energy yield. However, the main property of the coastal location is its wind regime presenting approximately offshore conditions, but with low installation costs. The statement that coastal installation, especially in the west coastline, has offshore wind conditions is deduced from the fact that annually, in the Netherlands, wind flows mainly directed from south-west towards north-east. This is geographically depicted in , Figure 9, which show the location of the three wind sites assessed in this work. The analysis is based on data from [10].

### Wind power generation

The wind power generation data set of the onshore site is depicted in , Figure 9. The random behavior is noticeable.



### Wind forecast and power imbalances

The wind forecast techniques used in this work become more accurate closer to real time. This effect is shown in Figure 10 where are displayed the duration curves of forecast errors from day ahead (D-24h) up to one hour ahead (D-1h).

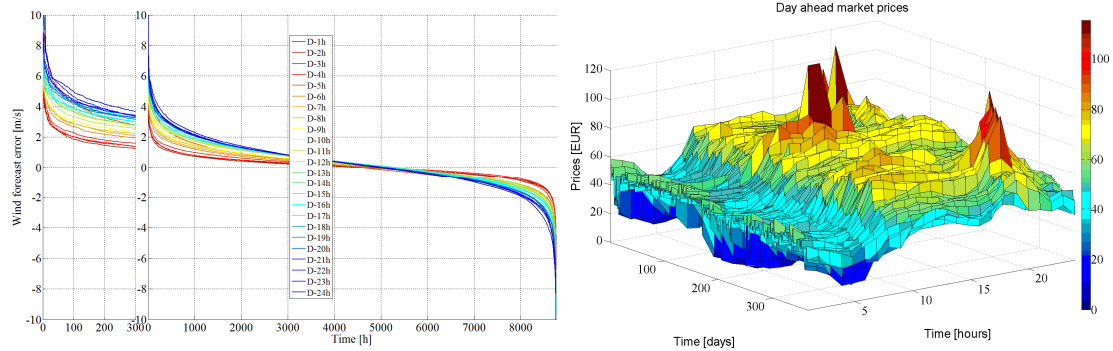


Figure 10: Duration curve of wind forecast mismatches of day-24h up to day-24h. Figure 11: Exemplarily depiction of an annual profile of day ahead market prices.

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.

### Market prices

The APX Endex market data of day ahead is depicted in Figure 11. Day and night patterns as well as seasonal patterns are clearly noticeable. The correlation between market prices and wind power generation is weak.

### Results

Based on both the algorithm and the case study, the summary of the results is shown in Table 3. There, it can be seen that, in this case study, the calculated revenues values of wind power generation are relatively high, compared to the values from the literature. This is due to theoretical considerations with perfect circumstances, not considering imperfections such as turbulence of wind sites, or maintenance and failures of wind turbines.

Furthermore, 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 the day ahead and intra-day markets.

Additionally, 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 results in further negative imbalances for onshore wind power generation which commonly come along with larger imbalance costs, due to the thermal generation oriented system of The Netherlands. This effect has the largest impact at day ahead markets, whereas at intra-day markets, closer to real time, this effect is attenuated. Therefore, the performance of a more accurate forecasting limits the expenses of the total imbalance costs.

From Table 3 it can be depicted how the imbalance costs of wind power generation reduce significantly as expected when changing from day ahead stage towards the intra-day stage for all three locations. The accuracy of wind prediction at the intra-day stage is due to the fact that wind will not vary significantly anymore, as can be concluded from the “van der Hoven Spectrum” [3]. Forecast becomes then more accurate which is confirmed by the results of Table 3. The impact of wind inaccuracy is smallest for offshore wind generation. Primarily, this is due to the optimistic forecast of onshore which leads to relatively lower offshore imbalance costs. Secondly, this is based on the power–wind speed curve of wind turbines. Thus, at moments of higher wind speeds, wind turbines operate at rated power, where variations in wind speed (forecast inaccuracy) do not lead to

power deviations. Also, the probability of higher wind speeds is larger at offshore wind sites, due to smaller roughness factors. Hence, imperfections in the wind forecast have a smaller impact on offshore wind power generation, and consequently wind imbalance costs are smaller compared to onshore wind power generation. Thus, it differs from onshore wind power generation, which does not have this attenuation of wind power imbalances.

Even though offshore wind power generation is forecasted more accurately and therefore smaller imbalance costs are noticed, its installation and maintenance costs are higher. Therefore, coastal wind power generation is still more cost-efficient, concerning the intra-day market.

Table 3 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

## CONCLUSIONS

The work carried out provide tools for the planning and economic assessment of deep offshore wind farms, to get the profitability -or not- of the wind farm. They can help in the technology selection during the FEED stage of the project based on parameters such as number of turbines, total power, water depth, wind resource, distance to shore and support the investment decision taking into account also the electricity markets. Although the tools have been designed for floating wind farms, they can also be applicable to bottom fixed wind farms, by doing some adaptations to the cost model tool.

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