Energy 68 (2014) 910–921

Contents lists available at ScienceDirect

Energy

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

The right size matters: Investigating the offshore wind turbine market equilibrium

Nikolaus Ederer*

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

ARTICLE INFO

Article history:
Received 27 November 2013
Received in revised form
2 February 2014
Accepted 16 February 2014
Available online 20 March 2014

Keywords:
Offshore wind energy
Offshore wind turbine
Upscaling
Market equilibrium

ABSTRACT

Although early experiences indicate that the maturity of deployed technology might not be sufficient for operating wind farms in large scale far away from shore, the rapid development of offshore wind energy is in full progress. Driven by the demand of customers and the pressure to keep pace with competitors, offshore wind turbine manufacturers continuously develop larger wind turbines instead of improving the present ones which would ensure reliability in harsh offshore environment. Pursuing the logic of larger turbines generating higher energy yield and therefore achieving higher efficiency, this trend is also supported by governmental subsidies under the expectation to bring down the cost of electricity from offshore wind. The aim of this article is to demonstrate that primarily due to the limited wind resource upscaling offshore wind turbines beyond the size of 10 MW (megawatt) is not reasonable. Applying the planning methodology of an offshore wind project developer to a case study wind farm in the German North Sea and assessing energy yield, lifetime project profitability and levelized cost of electricity substantiate this thesis. This is highly interesting for all stakeholders in the offshore wind industry and questions current subsidy policies supporting projects for developing turbines up to 20 MW.

1. Introduction

The EWEA (European Wind Energy Association) reveals in their annual report about key trends and statistics in the European offshore wind industry 2012 [1], that the average size of wind turbines installed in European waters has continuously increased. During 2012, the average capacity of new wind turbines installed was 4 MW (megawatt) and it is very likely that this trend continues, since EWEA also reports that by the end of 2012 76% of the announced new OWTGs (offshore wind turbine generators) have a rated capacity of over 5 MW. Under the expectation of concomitant cost reductions [2,3], this trend is also fostered by governmental subsidy programs such as the European Wind Initiative [4], which is a ten years research and development programme of the European Union, that grants subsidies for developing and testing large-scale wind turbines (10–20 MW). For example the AZIMUT Offshore Wind Energy 2020 project [5], which has the objective to develop a 15 MW OWTG, and the already completed UpWind project [6] is supported by this European initiative. The latter investigated design limits and solutions for very large wind turbines and showed that even 20 MW wind turbines are feasible from a technical point of view.

As a consequence, upscaling of wind turbines is a research topic with increasing popularity. For example Ref. [7], where this trend is investigated with the aim to provide recommendations for optimal design of large wind turbines [8], where a detailed analysis of costs in relation to upscaling is presented or [9] where an overview of upscaling trends for wind turbine gearboxes is given. This field of study is also related to the problem of finding optimal dimensions for wind turbines, e.g. in Ref. [10] it is argued why wind turbines with a low specific capacity are beneficial, in Ref. [11] an optimizer routine is presented which allows to determine the optimal rotor size for a given wind turbine rating, in Ref. [12] the optimal hub height for onshore wind turbines is investigated and in Ref. [13] the size of rotor/generator is site specific optimized. However, all these publications are written from the turbine designer point of view, whereas this article questions if larger OWTGs can ever be a competitive product assuming reasonable market conditions.

Therefore this article investigates the trend of growing OWTGs from the market point of view and answers the question if 20 MW OWTGs are ever reasonable or if there exists a market equilibrium that lies below this size. This market equilibrium would be of significant interest for stakeholders in the offshore wind industry. Early experiences revealed that the technology has not yet the

* 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.energy.2014.02.060
0360-5442/

maturity to sustain the harsh offshore environment [14]. Due to the rapid development of this industry, wind turbine manufacturers are faced with tight market conditions and are forced to continuously bring larger turbines onto the market. Supported by the prevailing tendering system of their customers, i.e. offshore wind project developers, where OWTG purchase decisions are mainly based on purchase price rather than future operating costs, improving the technology regarding reliability is therefore often missed out. In addition to that, gaining efficiency and profitability through economies of scale is hard to realize when customers already purchase larger turbines while production of the current generation has started only recently. The intention of this article is to show that there is a market equilibrium that might be reached soon. Hence the focus should be on improving the technology at this level instead of investing in the development of larger turbines. This might also give advice to political decision makers, who intend to bring the cost of electricity from offshore wind to a competitive level, how to optimally design support schemes for offshore wind. A first indication for the actual presence of a market equilibrium is the fact that this seems to be already reached for onshore wind turbines. Since a few years manufacturers have focused on offering a size between 2 and 3 MW for the onshore market [15,16].

This investigation requires the consideration of both economic and technical aspects. Considering offshore wind industry solely from an economic point of view an increasing size of wind turbines seems reasonable. Although larger turbines cost more in terms of acquisition and operation, they generate more energy and consequently also gain more revenues. Hence the growth of turbines would only stop if costs increase disproportional with size or the additional gain in revenues is too little. But physics reveals some additional limitations apart from the engineering challenges that come along with the design of larger turbines. Firstly, a wind turbine transforms the kinetic energy content of the wind into electrical energy, which results in less kinetic energy and reduced wind speed downwind. Hence if a wake intersects with the rotor of a downwind turbine in the plant it is said to be shadowed by the turbine producing the wake and results in less energy output of the downwind turbine. [17] The larger the turbines the larger the wakes and this in turn means that the spacing between the turbines within the farm has to be increased in order to obtain the same energy yield. Based on a predefined planning area this would result in fewer turbines to be optimal within the farm. Secondly, the wind resource, which is the actual long-term kinetic energy content of the wind at a specific location and height, is limited [18]. Thus the size of wind turbines will only grow until the wind resource is not sufficient to efficiently operate the large turbines.

OWF (offshore wind farm) project developers, who determine the demand for OWTGs, are faced with exactly these contrary economic and technical relations when planning a plant. Hence the idea was to use the planning methodology of an OWF project developer and assuming that the only decision criteria for selecting a wind turbine is the profitability of the plant over its whole life cycle. Applying this methodology with different sizes of OWTGs reveals a market equilibrium for OWTGs in terms of size, where OWF developers do not have an incentive to purchase larger wind turbines as this would not increase profitability. In addition to this analysis investigating the demand side, also the optimal size of OWTGs from the view of energy policy planners was analysed assuming that their objective is to exploit sea areas as efficiently as possible. Thus also the LCOE (levelized cost of electricity) for different OWTG sizes was assessed.

In order to generate reasonable and significant results with the developed model the methodology had to be applied to real data. This is why it was assumed to plan an OWF in the EEZ (Exclusive Economic Zone) of the German North Sea. Since Germany has envisaged installing 20–25 GW offshore wind capacity until 2030, the German offshore wind industry is one of the most promising markets for OWTGs in Europe [19]. There was taken particular care about the selection of data, the design of the methodology and assumptions in the sense being as close as possible to reality.

After a short clarification what is exactly understood by wind turbine size and the state of the art OWTG selection process, Section 2 describes the methodology used to identify the market equilibrium and the selected case study data. Section 3 provides the results of the analysis and in Section 4 a critical reflection based on a sensitivity analysis verifies the robustness of the results and individual conclusions for stakeholders in the offshore wind industry are discussed.

1.1. Clarification of wind turbine size and selection process

1.1.1. Wind turbine size

First of all it has to be defined how the size of a wind turbine is specified. As indicated earlier, the size of a wind turbine is usually determined by its rated power (also referred to as installed capacity) specified in kW (kilowatt) or MW. This defines the level of power the turbine and its components is designed for and thus is also the nameplate capacity of the generator. Therefore it is the maximum power a wind turbine is able to produce. The basic equation for power generation P from wind

$$P = \frac{1}{2} \cdot A \cdot \rho \cdot v^3 \cdot C_p \tag{1}$$

where A designates the swept area of the rotor, v the wind speed, ρ the air density and C_p the rotor power coefficient, reveals that the installed capacity also determines the geometric proportions. In order to ensure efficiency of the turbine the rotor area has to be increased with rated power. In addition to that, also the hub height, which is the distance between ground and rotor centre, has to be raised, because on the one hand a certain distance between rotor tip and ground has to be adhered and on the other hand increasing wind speed with height ensures sufficient power input [20].

1.1.2. OWTG selection process

Prior to developing a research methodology for the OWTG market equilibrium, it is important to understand how a purchase decision concerning the selection of an OWTG type is usually made. Fig. 1 provides a visualisation of the selection process using IDEF0 modelling technique[1] [21] assuming that the main decision criterion is the overall project profitability. For this process basically two models are needed: a spatial planning model and an economic model. The spatial planning model calculates the optimal energy yield based on OWTG data, provided by turbine vendors, wind data of the site and an initial number of turbines. Hence this model uses an optimization algorithm in order to determine the ideal layout of the farm with regards to maximum energy output while observing the constraints of the project area. The optimal energy yield is used as an input for the economic model. This model calculates the profitability of the project using cost and remuneration data. In order to find the most profitable layout of the plant the economic model varies the number of turbines and feeds back the information to the spatial planning model. After some iterations the maximum profitability including

[1] This function modelling language is capable of graphically representing enterprise operations and has the main advantage that additional to input/output relations it is also possible to depict controls, which specify conditions required for the function to produce correct outputs, and mechanisms, which supports the execution of the function such as resources.

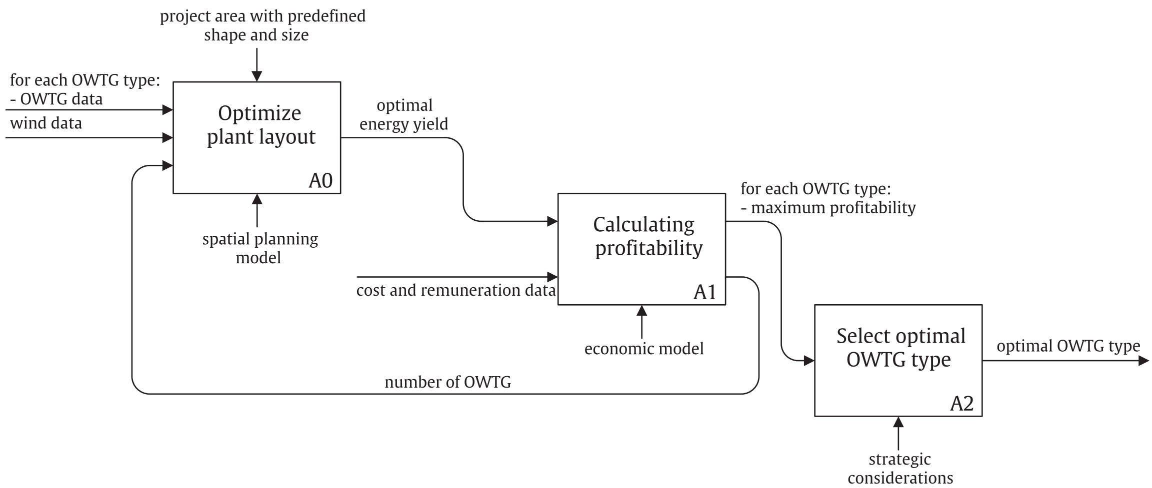

Fig. 1. OWTG selection process.

optimal number and positioning of turbines for each OWTG type is calculated. Usually also strategic considerations as for example financial standing and quality ratings of the potential suppliers are contributing to the decision, but this was not considered in the model developed in the following [22].

2. Methodology

The OWTG selection process served as a reference for developing the research methodology of this article, which is shown in Fig. 2. Instead of comparing different types of OWTGs from different vendors, the process was applied to OWTGs of different sizes. In order to obtain a clear picture and not being misled to jump to conclusions, the optimization loop was omitted. Instead of that the number of turbines was continuously increased within a range of installed capacity, which made it possible to trace the relations conditional on installed capacity. The methodology was also expanded by the LCOE model in order to evaluate the preferences of an energy policy planner. In the following sections spatial planning, profitability and LCOE model is described in detail.

2.1. Spatial planning model

An essential assumption for the spatial planning model was that the turbines are placed within an area of predefined shape and size. This is a reasonable approach, because the BSH (Federal Maritime and Hydrographic Agency) [23], which is the main authority for approving OWFs in the German seas, gives in the first instance (1st release) only a basic permission to build a wind farm within a specified project area and guarantees that no other project will be approved within this area for a given period of time. Type, number and arrangement of turbines are allowed to be modified later on (2nd release), but the boundaries of the planning area are fixed. Hence the approach, which is similar to other countries, is to first do a general planning in order to secure the site and afterwards determine details such as the selection of an OWTG type.

Due to the wake effects and their significant impact on energy yield an algorithm was needed in order to find the optimal layout. Considering the number of academic literature that addresses this particular issue, whereof Ref. [22] provides an excellent and comprehensive review, reveals that this is currently a popular research topic. But this is already not only an issue on academic

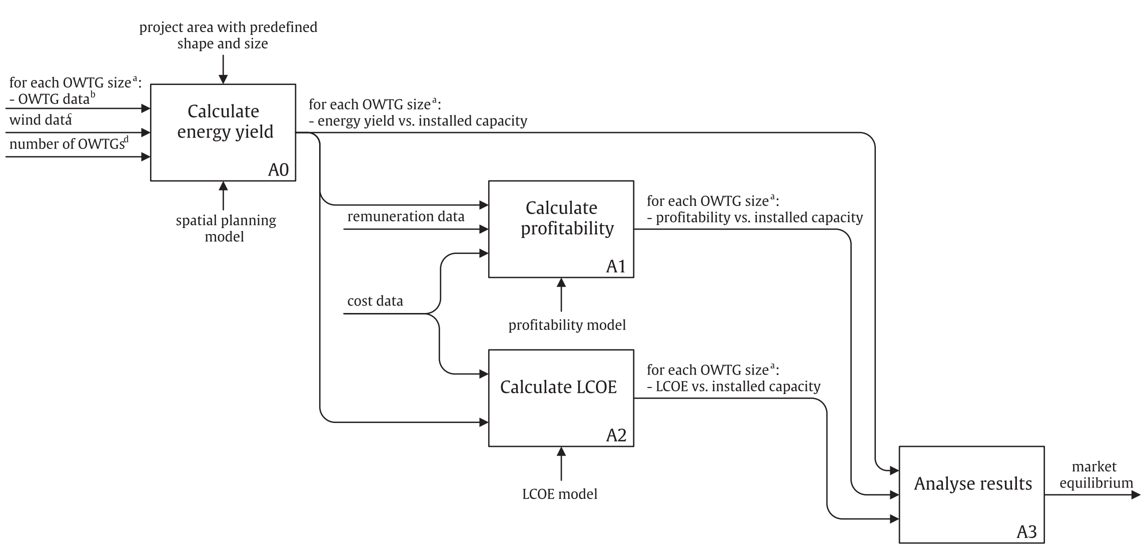

Fig. 2. Methodology. [a]OWTG sizes under investigation: 3 MW, 5 MW, 8 MW, 10 MW, 15 MW and 20 MW. [b]OWTG data: power curve, thrust curve, rated power, rotor diameter and hub height. [c]Wind data: Weibull distribution and probability for each direction sector (30°). [d]Number of turbines: varying between 300 and 600 MW installed capacity.

level. Wind farm planning software packages already contain optimization modules, which enable the users to optimize the plant layout using regular or random pattern regarding maximum energy capture [24,25] or even return on investment [26]. Considering this fact shows that the methodology presented in this article should be already state of the art for wind farm developers.

Although most papers propose algorithms using random patterns, the reality shows that symmetrical wind farm layouts are preferred especially in case of OWFs [22]. Since requirements concerning the safety and efficiency of vessel traffic in the German EEZ require that at least the outer line of turbines surrounding the OWF is placed in regular distance, it seemed to be obvious to place the turbines in a regular pattern for the whole OWF [27]. However, taking into account that this approach was applied to every OWTG size it seemed to be a minor issue.

The spatial planning model determined the layout using the number of horizontal and vertical turbines as an input. Fig. 3 shows as an example how 12 turbines were placed. P_{wr} designates the point that has been chosen for the case study within the German North Sea and where wind resource data was available. This is also the centre of the planning area with a horizontal length l_h and a vertical length l_v. Since the horizontal distance d_h respectively vertical distance d_v between turbines must always be equal they result from dividing the corresponding length by the number of turbines minus one. In case of different array combinations (4×3, 3×4, etc.) which result in the same number of overall turbines, the one that generated the highest energy yield was used for the result analysis. As mentioned before the overall number of turbines was varied in a predefined interval of installed capacity. Finally, turbines were placed with a minimum distance of four rotor diameters, which is the limit of the wake model applied and beyond that commonly recommended due to high mechanical loads caused by turbulence effects [28].

The output of the spatial planning model is the annual energy yield which can be obtained with the chosen wind farm pattern. The energy yield of one turbine Y_{WTG} within the farm per annum can be calculated using following equation:

$$Y_{WTG} = 8766 \cdot \sum_{\varphi} \rho(\varphi) \cdot \sum_{v_{hub}=v_{in}+0.5}^{v_{out}-0.5} f(v_{hwr}(v_{hub}), \varphi) \cdot P\left(v_{hub} - v_{def}(v_{hub}, \varphi)\right) \tag{2}$$

where 8766 is the number of hours per year, φ the wind direction, $\rho(\varphi)$ the probability of occurrence for a specific wind direction, v_{hub} the wind speed at hub height, v_{in} the cut-in and v_{out} the cut-out wind speed of the wind turbine, $f(v_{hwr}(v_{hub}),\varphi)$ the probability of occurrence for a specific wind speed at a specific height $v_{hwr}(v_{hub})$ in a specific direction, $P(v_{hub})$ the power output for different wind speeds of the turbine and $v_{def}(v_{hub},\varphi)$ the wind speed deficit caused by wake effects for a specific wind speed and direction. The formula is based on a methodology using wind speed bins recommended in the international standard IEC (International Electrotechnical Commission) 61400-12-1 [29].

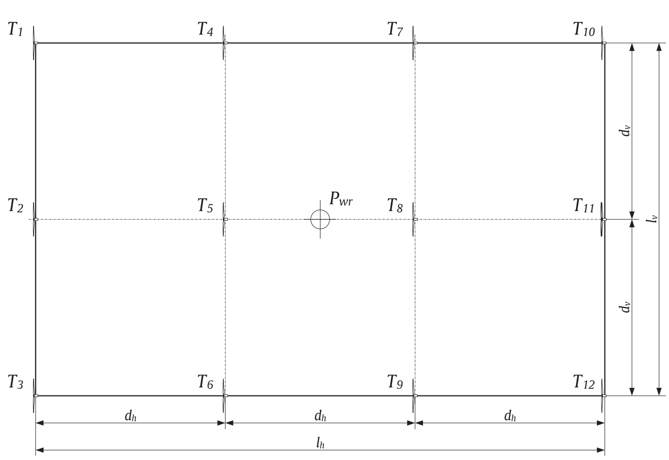

Fig. 3. Example for placement of 12 (4×3 array) turbines.

Due to the fact that the hub height of turbines increases with their size, the variability of the wind resource with height had to be included in this model. As stated in Ref. [30], using the power law instead of the stability dependent logarithmic law is suitable for a vertical extrapolation of the wind profiles for this application. The reason for that is that hub heights of OWTGs are in the Ekmand sublayer of the marine atmospheric boundary layer, which begins about 100 m above sea level, and there only a slight wind speed increase occurs. According to the international standard IEC 61400-3 [31], the height adaption using the power law can be calculated using following formula:

$$v_{hwr}(v_{hub}) = v_{hub} \cdot \left(\frac{z_{hwr}}{z_{hub}}\right)^{\alpha} \tag{3}$$

where v_{hwr} designates the wind speed at the height where the wind resource is given, v_{hub} the wind speed at hub height of the turbine, z_{hwr} the height where the wind resource is given, z_{hub} the hub height of the turbine and α the power law exponent. This standard also recommends to use 0.14 for latter which should be suitable for offshore conditions. Considering the fact of only a slight wind speed increase in this heights and the results of measurement campaigns in this area (e.g. Ref. [32] claims an α of 0.10) this value seemed to be a quite conservative assumption.

For determining the wind speed deficit the wake model proposed by Ref. [33] and further developed by Ref. [34] was used, which is according to Ref. [22] the most widely accepted model by the wind industry and with regard to the objective of this article it seemed to be the right balance between computational effort and accuracy. For a single wake the wind speed deficit caused by a turbine in a distance x, can be calculate using the following equation:

$$v_{def\_single}(v_{hub}, \varphi) = v_{hub} \cdot \left(1 - \sqrt{1 - C_T(v_{hub})}\right) \cdot \left(\frac{d_R}{d_R + 2 \cdot k \cdot x}\right)^2 \cdot \frac{A_{shadow}}{A_R} \tag{4}$$

where $C_T(v_{hub})$ is the thrust coefficient, d_R the rotor diameter, k the wake decay constant, x the distance between the turbines, A_{shadow} the shadowed area by the wake and A_R the rotor swept area. The wake decay constant k was assumed to be 0.04 which is a reasonable assumption for offshore wind farms [35]. In case of multiple interacting wakes Ref. [34] proposes to use following equation in order to calculate the resulting velocity deficit:

$$v_{def}(v_{hub}, \varphi) = \sqrt{\sum_{i=1}^{n} \left(v_{def\_single}(v_{hub}, \varphi)_i\right)^2} \tag{5}$$

Hence for every wind turbine the energy yield was calculated including the wake effects of all other turbines. This required the consideration of geometric relations between the turbines subject to the wind direction. Refs. [17,36,37] provide good guidance how to calculate them.

Finally, the annual energy yield of the whole wind power plant can be calculated using

$$Y_{\text{farm}} = \eta \cdot \sum_{j=1}^{\text{TN}} Y_{\text{WTG},j} \tag{6}$$

where η is the efficiency of the plant and TN the number of turbines within the farm. A plant efficiency of 95% was assumed, which includes losses due to unavailability, electrical transmission, power curve degradation, wind hysteresis, etc.

2.2. Economic models

2.2.1. Profitability model

As described before, it was assumed that OWF project developers try to maximize their profit and thus their only decision criteria for selecting an OWTG of a specific size is the resulting profitability of the project. As an indicator for profitability of the OWF the IRR (internal rate of return) was used, as it does not require assumptions on discount rates and it incorporates both costs and revenues [38]. This profitability parameter is calculated with a standard discounted cash flow model, which means that all cash flows – costs and revenues – are discounted over the lifetime of the plant to a base year. Using similar cash flow models of wind power plants (e.g. Refs. [37,39,40]) as basis the IRR can be derived by solving following equation:

$$0 = -C_{\text{Dev}} - P_{\text{R}} \cdot \text{TN} \cdot (c_{\text{Inv}} + c_{\text{Dis}}) + \sum_{t=1}^{T} \frac{Y_{\text{farm}} \cdot \left(r_{\text{t}} - c_{\text{Op}} \cdot (1 + i_{\text{Op}})^{t-1}\right)}{(1 + \text{IRR})^{t}} \tag{8}$$

where C_{Dev} designates the onetime development costs, c_{Inv} the specific investment costs, c_{Dis} the specific dismantling costs, T the lifetime of the wind farm, r_{t} the remuneration per unit of energy for the respective year, c_{Op} the specific operation costs and i_{Op} the annual increase of the operation costs. Considering the facts that current offshore turbines are designed for a lifetime of 20–25 years, wind farm approvals in Germany expire after 25 years [41] and a construction and dismantling period of a few years, the assumption of 20 years for the lifetime T of the plant seemed reasonable and is also conform with literature [38]. For the sake of simplicity, it was assumed that all turbines are fully commissioned respectively dismantled at the same point in time.

The development costs comprise all expenditures for developing an OWF from scratch such as soil examination, environmental assessments and appraisals that have to be provided to the authorities during the approval process. All expenditures incurred during the construction and commissioning of the power plant are the investment costs, which are typically standardized to the base of kW or MW. Thus included are all costs for plant components (OWTG, foundation, offshore substation, inner-array cabling), project management, logistics and others until the OWF is commissioned. Costs arising during operation such as maintenance, insurance and administrative costs are operation costs and are usually standardized to the unit of produced energy. Due to decreasing reliability of technical machines, it is reasonable to include an annual increase of operational expenditures. After the lifetime the plant has to be dismantled. All costs that arise in this phase are dismantling costs and are reduced by the residual value of the components [42].

For the economic model it was assumed that the investment costs increase linearly with the installed capacity respectively operation costs with the energy produced, which influences the numerical results significantly. Therefore Section 4.1 provides a critical reflection based on a comprehensive sensitivity analysis where the impacts of total cost variations and effects on costs such as economies of scale, cost development subject to upscaling, etc. are discussed in detail.

2.2.2. LCOE model

In order to be able to analyse the market equilibrium also from the perspective of an energy policy planner, the average lifetime LCOE was calculated. Adapting the formula defined by Ref. [43] to wind energy, LCOE can be calculated using following equation:

$$\text{LCOE} = \frac{C_{\text{Dev}} + P_{\text{R}} \cdot \text{TN} \cdot (c_{\text{Inv}} + c_{\text{Dis}}) + \sum_{t=1}^{N} \frac{Y_{\text{farm}} \cdot \left(c_{\text{Op}} \cdot (1+i_{\text{Op}})^{t-1}\right)}{(1+r)^{t}}}{\sum_{t=1}^{N} \frac{Y_{\text{farm}}}{(1+r)^{t}}} \tag{9}$$

where r is the discount rate, which was assumed to be 10% [44].

2.3. Case study

2.3.1. Position and area

The position P_{wr} within the German EEZ for implementing the case study was chosen taking into account the areas that are approved for OWF projects by BSH and the availability of wind resource data. Fig. 4 shows the chosen $P_{\text{wr}} = 54^{\circ}\ 28'\ 42.44''$ N/$6^{\circ}\ 19'\ 56.30''$ E, which lies in an area with a water depth of 30–40 m and is about 100 km away from shore. Considering the 25 wind farm projects in the North Sea that have been approved so far (status April 2013) by the BSH [41], an ordinary project area has a size of about 40 km^2, a shape with straight borders and comprises 80 wind turbines.[2] Hence a planning area with rectangular shape, vertical length of 5 km and horizontal width of 8 km was used for the case study.

2.3.2. Wind resource data

In order to obtain reasonable results, it is important to use wind data of high quality and not limiting their significance by simplification in the model such as using an average wind speed or only one wind direction. Basically, for calculating the energy yield of the wind farm including the wake effects a probability of occurrence for different wind speeds in the different directions is needed. It is common to provide the wind data as Weibull distribution which is defined as follows:

$$f(v, \varphi) = \frac{k(\varphi)}{c(\varphi)} \cdot \left(\frac{v}{c(\varphi)}\right)^{k(\varphi)-1} \cdot e^{-\left(\frac{v}{c(\varphi)}\right)^{k(\varphi)}} \tag{10}$$

where $k(\varphi)$ and $c(\varphi)$ represent the shape and scale parameter. For this analysis one point of the North Sea wind atlas developed by NORSEWInD research consortium [46] was used. They acquired, collated, quality controlled and analysed wind data from different measurement stations around the North Sea using different kinds of technologies with the aim to provide a reliable data basis for the wind industry. The wind resource data for the chosen point comprise $k(\varphi)$ and $c(\varphi)$ for 12 sectors of 30° width and the probability of occurrence for each wind direction $\rho(\varphi)$. As stated in Ref. [36], this is a good data basis for energy yield estimations. In order to generate results that make it possible to draw representative conclusions, a position with a quite good wind resource for the German EEZ was chosen. Fig. 5 shows the wind rose at P_{wr}, where

[2] The reason for these characteristics of an ordinary project area might be that the BSH states that they have so far only projects approved that comprise maximally 80 wind turbines, because the impact of offshore wind farms on navigational safety and the marine environment has not yet been finally assessed.

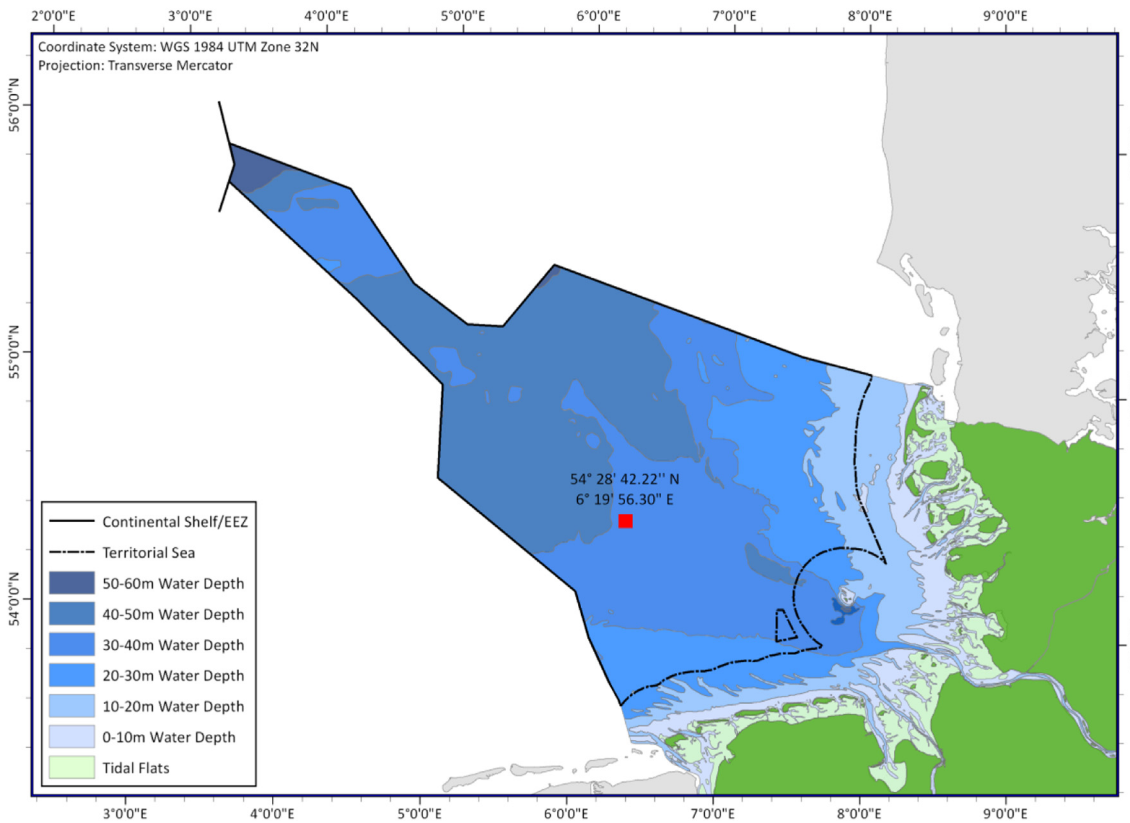

Fig. 4. Position for case study (based on data provided by Ref. [45]).

the total distribution parameters equal $c_{total} = 11.7$ m/s and $k_{total} = 2.12$.

2.3.3. Wind turbine data

The methodology described above reveals that following data of every OWTG is needed: rated power, hub height, rotor diameter, power curve (power output vs. wind speed) and thrust curve (thrust coefficient vs. wind speed). This input data was defined based on specifications of current commercially available OWTGs ([47] provides a good overview), projections of the upscaling trend [48] and scientific concepts (e.g. Refs. [5–7]). Furthermore wind turbine data was determined very carefully in order to be as close as possible to reality, but also to have a clear difference between the different sizes. Table 1 provides the chosen dimensions of the different OWTG sizes.[3]

The smallest size that was included in the analysis is 3 MW. As a reference for the data the Vestas V90-3.0 MW [49] was used. This OWTG belongs to the last generation and has been deployed for example for the UK round 1 OWF projects at Kentish Flats and Barrow [14]. The data of the largest wind turbine were used from the UpWind project [6]. As a reference for OWTGs of the near future, data of the Vestas V164-8.0 MW [50] and SeaTitan 10 MW [51] wind turbines were used. The dimensions of the 5 MW size, which is the current generation, and the 15 MW size were calculated using the others as basis and trendlines provided by Ref. [48]. The power curves were defined using the data of the turbines mentioned above and harmonizing them with each other to ensure that manufacturer specific deviations do not falsify the analysis. Ref. [52] presents a fast and efficient method of how rescaling of power curves can be done based on equation (1). Fig. 6 shows the applied power curves. The same thrust curve, cut-in wind speed (4 m/s) and cut-out wind speed (25 m/s) were used for all turbines.

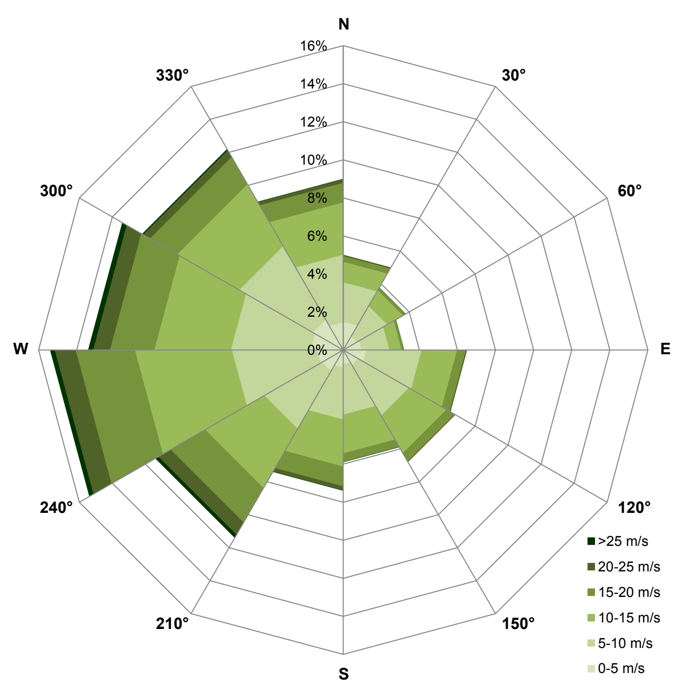

Fig. 5. Wind rose at position 54° 28′ 42.44″ N/6° 19′ 56.30″ E.

[3] It has to be commented that the results of this analysis do not reflect the relative performance of the turbines used as a reference, because the power curves and thrust curve were significantly modified.

Table 1
OWTG dimensions.

Rated power	3 MW	5 MW	8 MW	10 MW	15 MW	20 MW
Hub height	80 m	90 m	105 m	125 m	140 m	153 m
Rotor diameter	90 m	130 m	164 m	190 m	222 m	252 m

2.3.4. Cost assumptions

There are several sources available where the cost components of OWFs are assessed and analysed (e.g. Refs. [39,53]). For the model developed in this paper it was more important that the relation of the cost components relative to each other is reasonable than their individual level. This is why all values were used from one source, because cost data vary significantly between different projects and in that way the same data basis is ensured. Hence cost data of the German offshore market provided by Ref. [42] were used for the analysis (see Table 2).

2.3.5. Remuneration assumptions

According to the renewable energy law (EEG (Erneuerbare-Energien-Gesetz)) in Germany [54], an operator of an OWF can choose between three remuneration options (see Table 3). For this model it was assumed that 16 years after commissioning the energy is remunerated with a tariff of 150 EUR/MWh, which corresponds to the standard option plus an extension period of four years (36 m water depth and 100 km distance to shore). Subsequently it was assumed that the energy is traded for the remaining four years. The average market price in this period was calculated using 50 EUR/MWh as basis for the year of commissioning and adding an escalation of 2% every year.

3. Results

The model was evaluated for an OWF with an installed capacity between 300 and 600 MW, which seemed to be reasonable for the selected case study parameters. In addition to the economic parameters IRR and LCOE the energy yield was calculated in order to determine also the behaviour of the physical basis. Placing turbines with a reasonable proportion between horizontal and vertical quantity and within the installed capacity limits revealed an almost linear relationship between installed capacity and energy yield (see Fig. 7).

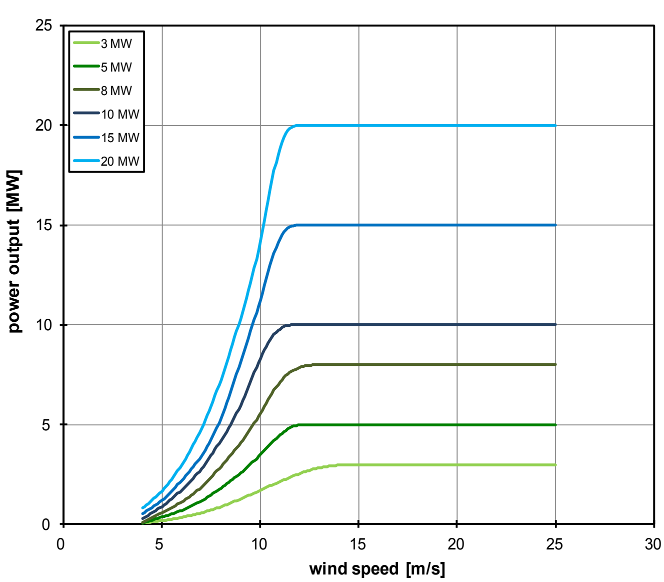

Fig. 6. Power curves.

Table 2
Overview of cost assumptions.

C_{Dev}	35 EUR million
c_{Inv}	3.6 EUR million per MW
c_{Op}	25.5 EUR/MWh
i_{Op}	2.0% per year
c_{Dis}	0.2 EUR million per MW

Table 3
Remuneration scheme (commissioning before 1.1.2018 assumed).

	Initial period	Extension period	Remaining period
Trading		Market price	
Standard	150 EUR/MWh 12 years	150 EUR/MWh +0.5 months for every nautical mile beyond 12 nautical miles to shore	35 EUR/MWh
Compression	190 EUR/MWh 8 years	+1.7 months for every meter beyond 20 m water depth	

Since the economic parameters highly depend on the energy yield they also follow an almost linear trend conditional on the installed capacity. Therefore Table 4 provides the results in the form of linear regression factors including the coefficient of determination.

In order to be able to derive conclusions Fig. 8 shows the mean relative deviations subject to the OWTG size using the 10 MW turbine as a benchmark.

4. Discussion and analysis of results

The results apparently indicate a market equilibrium for OWTGs with a size of 10 MW. The fact that doubling the size from 10 MW to 20 MW, which entails substantial technical challenges, gains only a minor increase in energy yield and thus also in IRR, which is the customers' key figure for a purchase decision, suggests that the incentive for wind turbine manufacturers to invest in the development of 20 MW turbines at least for the German offshore wind

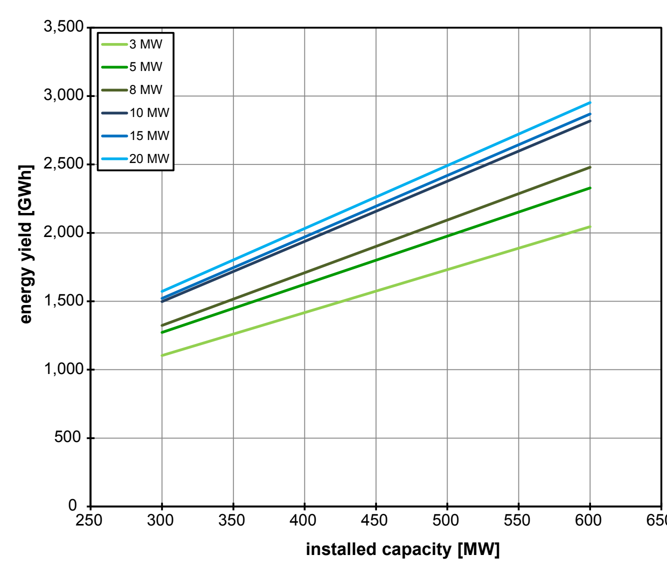

Fig. 7. Energy yield vs. installed capacity.

Table 4
Relationship between energy yield/IRR/LCOE and OWTG size specified in form of linear regression factors.

OWTG size, MW	Energy yield			IRR			LCOE		
	MWh		R^2	%		R^2	EUR/MWh		R^2
	m	*b*		*m*	*b*		*m*	*b*	
3	3139.50	161,281	0.9967	−2.73E-05	9.28%	0.8219	2.37E-02	148.23	0.7722
5	3523.19	214,794	0.9987	−3.77E-05	11.87%	0.9343	2.61E-02	130.80	0.9344
8	3854.41	166,978	0.9978	−2.67E-05	12.27%	0.7890	1.70E-02	128.92	0.7887
10	4403.55	176,287	0.9990	−2.75E-05	14.53%	0.7997	1.40E-02	117.54	0.7809
15	4489.80	174,544	0.9996	−2.72E-05	14.84%	0.8422	1.35E-02	116.17	0.8354
20	4536.84	217,894	0.9995	−2.48E-05	15.32%	0.9080	1.19E-02	114.01	0.9051

- Valid within range between 300 and 600 MW installed capacity.
- $y = m \cdot P_R \cdot TN + b$ where y is the energy yield/IRR/LCOE.
- Linear least squares regression applied.

market is insufficient. The results indicate that the potential increase of the energy yield and the significantly decreasing potential sales volume may not compensate the effort for developing larger OWTGs, setting up new manufacturing facilities and elaborating new installation and service concepts. Cost reductions that can be obtained due to increasing reliability and standardization may have a similar or even higher cost-benefit effect [44,55]. Apart from that the trend of the LCOE subject to OWTG size questions governmental subsidies, which support the development of OWTGs beyond the size of 10 MW, since this does not lead to the intended significant cost degression. The reason for a flattening of the energy yield and as a consequence also of the IRR and LCOE with increasing OWTG size is simply the limited available wind resource. Something similar was already reported in Ref. [56], where the results reveal that higher yield from larger OWTGs far away from shore do not compensate for the increased costs compared to smaller OWTGs near the coast.

4.1. Critical reflection and sensitivity analysis

Admittedly, the analysis is based on several assumptions that were needed to anticipate the future development of OWTGs. Therefore this section provides a critical reflection of the input parameters in order to prove if the methodology presented generated representative results. It has to be pointed out that the aim of this article was to show that there is an indication for a market equilibrium. Especially the analysis of the economic parameters IRR and LCOE was not aiming at providing an exact numerical projection of these parameters. The intention was to show that these key figures, which are the basis for a purchase decision of the wind turbine manufacturers' customers respectively the basis for decision-making for energy policy planners, are also flattening with increasing OWTG size similar to the energy yield. Thus the economic analysis presented before should only give evidence with regard to future market behaviour. The critical discussion in the following is based on a comprehensive sensitivity analysis (see Supplementary Notes for detailed results).

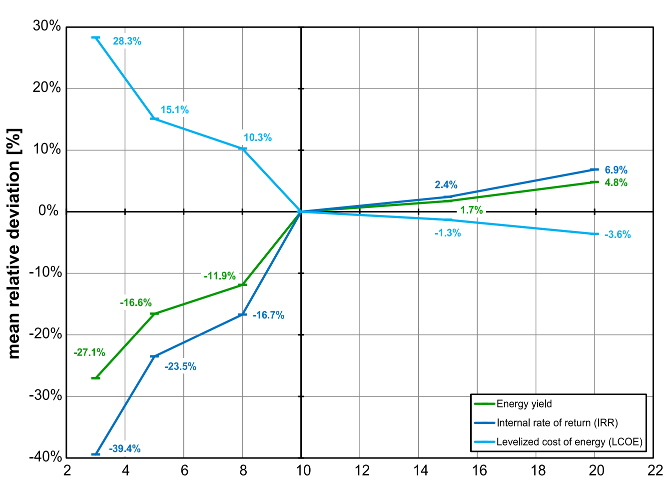

Fig. 8. Mean relative deviations of energy yield/IRR/LCOE subject to OWTG size using 10 MW as a benchmark.

For the sake of simplicity and considering the fact that all result parameter functions are almost linear and parallel subject to the installed capacity it is useful to discuss only the relative and absolute effect of each sensitivity case. Relative effect means that the average relative distance between the result function for a specific wind turbine size and the 10 MW benchmark either increases or decreases. Or in other words the graphs shown in Fig. 7 are either expanded or contracted. In contrast to that, absolute effect means that all result functions are shifted either to lower or higher values without changing their relative distance to the 10 MW benchmark. Fig. 9 provides a visualisation of these effects. With regard to the aim of this article only the relative effect of an increased distance (expansion) to the 10 MW benchmark would oppose the conclusion of a 10 MW market equilibrium.

The main input parameter with regard to the impact on energy yield is clearly the wind resource. Table 5 provides an overview of the effects caused by the associated sensitivity cases. For the case study only one position of the NORSEWInD atlas [46] was used, which questions how representative the selected wind resource for the German EEZ is. Analysing the NORSEWInD atlas within the German EEZ and considering only areas which are allocated for offshore wind reveals that the minimum ($c_{total} = 11.5$ m/s/$k_{total} = 2.12$) and maximum ($c_{total} = 11.8$ m/s/$k_{total} = 2.12$) wind resource do not significantly deviate from the one used for the analysis. Thus basing the analysis on these two wind resources leads subsequently only to minor deviations and mainly to a shift to lower respectively higher values.

Another critical aspect of the analysis is the height adaption using the power law with an exponent of 0.14, which is, as discussed before, a quite conservative assumption. The result using a lower power law exponent ($\alpha = 0.00$) is obvious: lowering the power law exponent leads to the relative effect of contraction, because the assumption causes that the wind resource is the same for every turbine size and thus larger turbines with higher hub height do not have a higher wind resource available. Moreover, this admittedly extreme sensitivity case exhibits that the losses due to wake effects would be also higher for larger OWTGs resulting in less energy yield for the same installed capacity compared to the 10 MW benchmark.

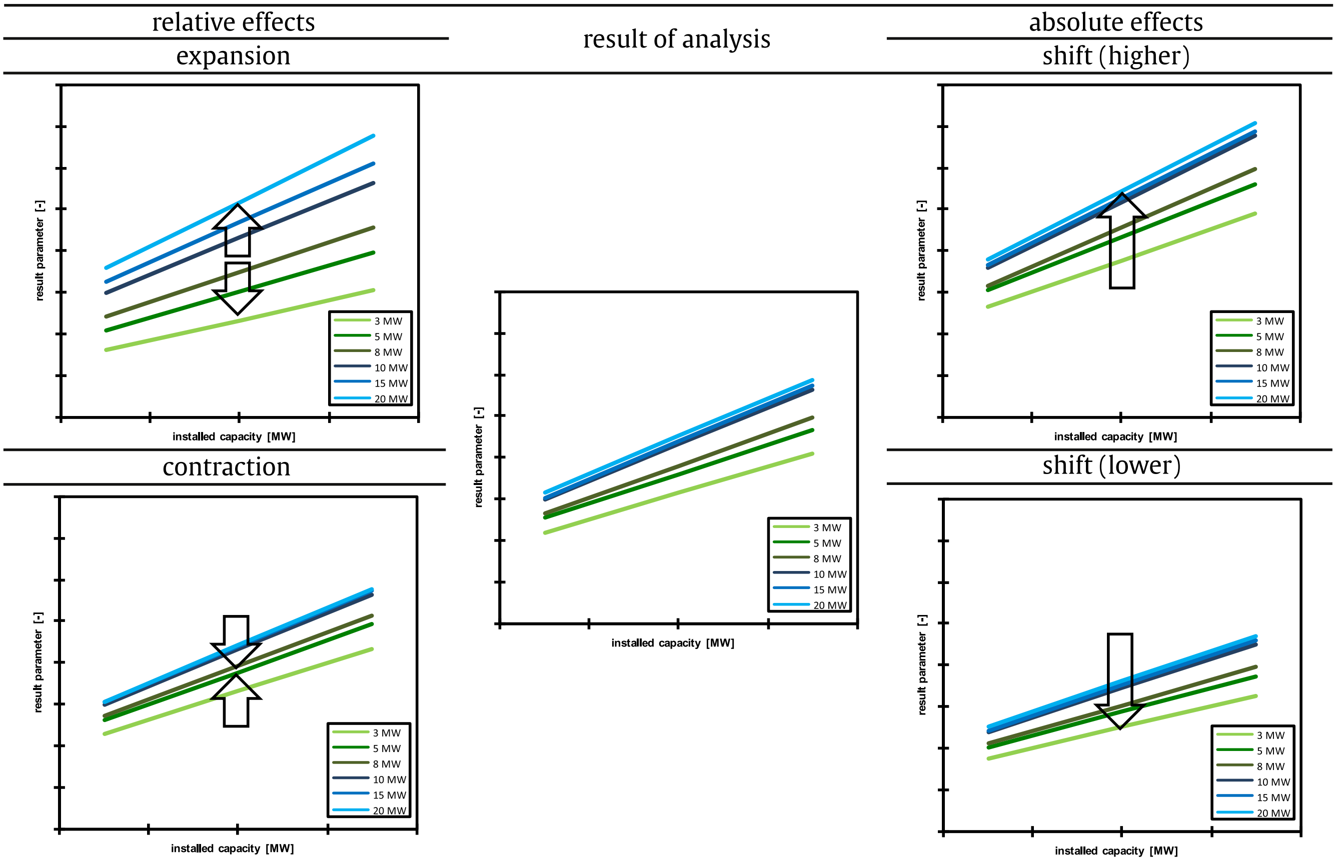

Fig. 9. Visualisation of possible relative and absolute effects caused by sensitivity investigations.

Considering these sensitivity cases investigating the effects caused by changes of the input wind resource shows that although they have an impact on the numerical result, they prove that the article's statement regarding the presence of a market equilibrium is robust. Apart from that, also wind turbine data and the wake model could have influenced the energy yield. Possible deviations caused by those inputs can be ruled out since the data for the 3 MW, 8 MW, 10 MW and 20 MW size stem from reliable sources and the wake model was verified using professional wind energy assessment software.

But apart from the assumptions used for calculating the energy yield, also the effects of varying cost inputs should be discussed in more detail (see Table 6). First of all the level of costs are worthy of discussion, because for example the specific investment costs depend significantly on distance to shore and water depth [57]. Apart from that substantial cost reductions are intended in the near future in order to make electricity from offshore wind more competitive [2,3]. However cost may develop in future, when assuming that all sizes experience the same negative or positive cost trend, the effect on IRR and LCOE is only absolute. This effect is the same for any change in feed-in remuneration scheme as long as electricity from larger OWTGs is not remunerated differently than that from smaller OWTGs. Since costs and remuneration determine profitability and therefore investment decisions any absolute change would only influence the sales volume for OWTGs, but not affect the purchase decision regarding OWTG size. Thus the conclusion of the presence of a market equilibrium is independent of the level of cost or feed-in remuneration.

Another point of criticism might be the assumption that no economies of scale occur, which seems to be unrealistic and the resulting linear functions for IRR and LCOE implausible. First of all, it has to be commented that the survey done by Ref. [58] clearly shows that economies of scale for OWFs do not occur so far. However, the presence of economies of scale may again have an impact on the numerical results of this analysis, but it is not reasonable that this would change the conclusion. The reason for that is the simple fact that economies of scale for smaller OWTGs will always occur before they do for larger ones, because for an OWF with the same installed capacity always less larger than smaller turbines are needed. Hence considering this effect in a chronological view, it rather promotes the theory of a market equilibrium, because wind turbine manufacturers, who are facing the decision of either developing a larger OWTG or continuing to exploit economies of scale with the current generation, are aware that economies of scale for the larger OWTGs take only effect again after selling large quantities, which is more difficult since they can only sell less OWTGs for the same OWF size [59]. Even it is assumed that economies of scale become effective in the same quantity range this would only change the shape of the graph, but not have a relative effect on IRR or LCOE.

Table 5
Sensitivity effects due to changes in wind resource assumptions.

Sensitivity case	Energy yield	
	Relative effect	Absolute effect
Higher wind resource	Slight contraction	Shift (higher)
Lower wind resource	Slight expansion	Shift (lower)
Lower power law exponent	Contraction	–

Table 6
Sensitivity effects due to changes in cost assumptions.

Sensitivity case	Internal rate of return		Levelized cost of energy	
	Relative effect	Absolute effect	Relative effect	Absolute effect
Cost reduction	Slight concentration	Shift (higher)	–	Shift (lower)
Cost increase	Slight expansion	Shift (lower)	–	Shift (higher)
Larger comparatively less expensive than smaller	Expansion	–	Expansion	–
Smaller comparatively less expensive than larger	Concentration	–	Concentration	–

More interesting is the question how cost will develop with increasing size. Would larger wind turbines be comparatively less (more) expensive than smaller, an expansion (contraction) of the graphs would be the consequence, which would disprove the statement of this article. But investigations about costs in relation to upscaling clearly reveal a disproportional increase of costs with size due to the impact on weight and loads [7]. A good example is Ref. [8], where after a comprehensive analysis is concluded that turbine sizes lower than 10 MW will be optimal due to the exponential increase of cost subject to size. In conclusion, although the analysis presented in this article is based on several assumptions, the sensitivity analysis showed that the theory of a market equilibrium for 10 MW OWTGs is robust.

4.2. Managerial implications

In case of the presence of a market equilibrium for OWTGs the conclusion for stakeholders in the offshore wind industry is obvious. Focussing instantaneously on developing 10 MW OWTGs and placing them onto the German offshore wind market, would promise wind turbine manufacturers a sustainable competitiveness. This would be also applicable for the supplying industry as for example foundation and ship vendors that are forced to adapt their products to the size of OWTGs. Interestingly, the analysis also revealed a significant increase in efficiency for installing 5 MW turbines instead of 3 MW respectively 10 MW instead of 8 MW and only a minor increase between 5 MW and 8 MW OWTGs. This would be an indication for the 8 MW size being only an intermediate technology level.

For energy policy planners and governmental decision makers the market equilibrium would suggest that it should be preferred to grant subsidies to research projects that investigate how it is possible to improve the maturity of the technology instead of investing in projects that investigate OWTGs of a size that might be never reasonable. For example fostering technology transfer from other successful industries such as oil & gas, which have considerable experience in offshore operations, might gain more efficiency in order to significantly reduce the cost of electricity generation from offshore wind [60]. It has to be mentioned that the cumulative discounted operating costs over the whole life cycle account for 35–45% of the overall project costs. Considering also the cost reduction potentials for operation & maintenance costs of about 12% [61] resp. 14% [62], which could decrease the overall OWF costs of up to 7.8% [2], suggests that supporting a reduction of operating costs is as important as research projects that aim for lowering the initial investment costs.

Moreover, the results presented in this article also enable to estimate average installed capacity respectively annual energy yield per unit area and their relation to OWTG size (see Table 7). Applying the common recommendation for wind farm layout design presented in Ref. [28] to all OWTG sizes reveals that the average installed capacity per unit area remains nearly constant, which does not surprise considering the geometric relations. Although an average value of 12.5 MW/km^2 seems to be quite high (Ref. [63] reports 9 MW/km^2 respectively 7 MW/km^2 for UK round 1 resp. 2 OWFs), the fact that it is independent of the OWTG size contradicts investigations about the future trend (e.g. Ref. [64]) that claim an increase of this value with technological development. Apart from that, this information is of particular interest for transmission system operators and offshore substation suppliers since it enables to estimate the maximum capacities expected from sea areas. It also allows the conclusion that the development of standard sizes is reasonable, which would help to reduce costs. Finally the annual energy yield per unit area gives advice to energy policy planners since it answers the question what maximum energy extraction can be expected from sea areas in the German EEZ.

5. Conclusion

This article refers to the current issues of the offshore wind industry with the tight market conditions due to the pressure to continuously place larger OWTGs onto the market. A model was developed with the objective to identify a market equilibrium for OWTGs. This was identified investigating the trend of growing OWTGs from an OWF project developer's point of view, which reflects the demand side of the market, and from the point of view of an energy policy planner. In order to be able to generate reasonable conclusions, the model was applied to a case study wind farm in the German EEZ. Finally, a sensitivity analysis verified the robustness of the article's statement.

The results indicate a market equilibrium for 10 MW OWTGs due to the limited available wind resource. This is highly interesting for stakeholders in the offshore wind industry and allows individual conclusions. The strategic focus on this size might promise

Table 7
Average installed capacity and energy yield per unit area.

OWTG size, MW	Maximum number of turbines[a], –	Maximum installed capacity[a], MW	Average installed capacity per unit area, MW/km^2	Average annual energy yield per unit area, MWh/km^2
3	182	546	13.7	46.9
5	90	450	11.3	45.0
8	64	512	12.8	53.5
10	49	490	12.3	58.4
15	36	540	13.5	65.0
20	25	500	12.5	62.3

[a] Within 40 km^2 assuming minimum horizontal distance of seven and vertical four rotor diameters.

OWTG manufacturers and the supplying industry a sustainable competitiveness. A governmental planner might be better advised to support research projects with funding that aim for improving the 10 MW range instead of the development of OWTGs that do not gain a significant yield and efficiency increase. Finally, the analysis gives information about how much energy yield and installed capacity can be expected from German North Sea areas.

Although the German EEZ is one of the most promising markets for offshore wind in Europe, it would be interesting to investigate the OWTG market equilibrium also for other regions in the world. This could be done using the methodology presented in this article, if necessary adapting it to the legal framework for OWFs in the respective country and applying the respective local wind resource. However, the wind resource used is quite good and experiences reveal that already these conditions are challenging the reliability of currently used technology far away from shore.

Acknowledgements

I would like to thank Strabag OWEVS GmbH for their permission to use data and software tools, Prof. Andreas J. Novak and Prof. Franz Wirl for their advice and several colleagues within the offshore wind industry as well as three independent reviewers for their constructive comments.

Abbreviations

BSH	Federal Maritime and Hydrographic Agency
EEZ	Exclusive Economic Zone
EWEA	European Wind Energy Association
IRR	internal rate of return
kW	kilowatt
LCOE	levelized cost of electricity
MW	megawatt
OWF	offshore wind farm
OWTG	offshore wind turbine generator

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2014.02.060.

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