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Evaluating capital and operating cost efficiency of offshore wind farms: A DEA approach

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ABSTRACT

An actual growth rate greater than 30% indicates that offshore wind is a reasonable alternative to other energy sources. The industry today is faced with the challenge of becoming competitive and thus significantly reduce the cost of electricity from offshore wind. This situation implies that the evaluation of costs incurred during development, installation and operation is one of the most pressing issues in this industry at the moment. Unfortunately, actual cost analyses suffer from less resilient input data and the application of simple methodologies. Therefore, the objective of this study was to elevate the discussion, providing stakeholders with a sophisticated methodology and representative benchmark figures. The use of Data Envelopment Analysis (DEA) allowed for plants to be modelled as entities and costs to be related to the main specifics, such as distance to shore and water depth, ensuring the necessary comparability. Moreover, a particularly reliable database was established using cost data from annual reports. Offshore wind capacity of 3.6 GW was benchmarked regarding capital and operating cost efficiency, best-practice cost frontiers were determined, and the effects of learning-by-doing and economies of scale were investigated, ensuring that this article is of significant interest for the offshore wind industry.

Contents

Abbreviations: BCC, Banker–Charnes–Cooper; CAPEX, capital expenditures; CCR, Charnes–Cooper–Rhodes; DEA, data envelopment analysis; OPEX, operating expenditures; OWF, offshore wind farm; WEC, wind energy converter

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1. Introduction

More than 20 years after the first offshore wind farm, Vindeby, went operational, the expansion of offshore wind is in full progress, resulting in a cumulative installed capacity of 6.6 GW in the European seas in 2013 [1]. High wind speeds at sea promising a high energy yield and extensive areas available for large-scale projects without negative effects on residents, such as visual impact, noise production and shadow casting, make offshore wind increasingly attractive also compared to its onshore counterpart, resulting in ambitious projections of 40 GW installed capacity in 2020 [2]. Conversely, harsh environmental conditions, increased loadings and great distances to shore lead to high costs, which necessitate governmental support to compensate for the lack of competitiveness [3]. Therefore, cost reduction constitutes the main challenge that will be faced in the offshore wind industry in the coming years, which is reflected by the target to reduce costs by up to 39% through 2020 [4,5], aiming at a levelised cost of energy of 9 ct/kWh (status 2012: 11–18 ct/kWh) [6]. This situation implies that cost evaluation is a significant issue in offshore wind for tracking changes and identifying cost-reduction potentials. Actual cost analyses often suffer from imprecision with regard to handling influencing parameters and poor databases due to stakeholders' restrictive non-disclosure policies and the rapid increase in the number and extent of projects in recent years. This study has overcome these issues by utilising a reliable database and by applying data envelopment analysis (DEA) to offshore wind farms (OWF). This operations research method enables the evaluation of the relative efficiency of multi-input multi-output entities, so-called decision making units (DMU), and the determination of a best-practice frontier.

The idea of developing this model originated from the issue of ensuring comparability within the database when evaluating the costs of OWFs. In offshore wind cost assessments, it is common to use specific capital costs (EUR/kW) to estimate and compare costs or analyse trends (e.g., [7], Exhibit 3.2 [5], Fig. 8.3 [8]). At first glance, using average cost values that are normalised to the installed capacity appear to be an effective approach because it has been used for onshore wind power plants for decades. However, considering the database on which such assessments are grounded—consisting of, for example, the Middelgrunden OWF, commissioned in 2001 with an installed capacity of 40 MW, located in shallow waters measuring 5.5 m deep and a distance to shore of 3.5 km [9], and the Greater Gabbard OWF, commissioned in 2012 with the specifics of 504 MW/29 m/23 km [10]—it is highly questionable whether results based on specific capital costs are significant. Water depth and distance to shore are two of the main cost drivers in offshore wind [11] because they reflect the level of environmental loads to which an OWF is exposed. [12] Hence, these main specifics have a significant impact on cost figures and must be carefully considered. These properties can be properly examined by, for example, regression analysis, as presented in [13]; engineering correlations, as described in [14]; or using a practical approach, as conducted in [15], in which—based on a case study—scale factors that indicate the variation in cost as a function of water depth and distance to shore were calculated. However, all of these approaches appear to be non-optimal because they do not incorporate all of the specifics and available data at once. Herein lies the main advantage of DEA because it enables modelling every OWF as an entity with the specifics as its inputs (outputs). This type of holistic approach might be one reason why this method has gained great popularity in energy and environmental modelling in recent years (see [16] for a review), and there are numerous articles that have used DEA to assess the performance of power plants (see [17] for a survey of relative performance evaluations of conventional power plants applying DEA). However, the literature concerning the investigation of the efficiency of wind farms using this method is scarce (see [18–21] for onshore wind farms). Indeed, this is the first article, to the best of the author's knowledge, in which DEA is applied to OWFs.

The overall objective of this study was, on the one hand, to develop a useful methodology for evaluating how efficiently costs are used for developing, installing and operating OWFs and, on the other hand, to use the methodology as basis for an in-depth cost analysis applying data from already implemented OWFs. Thus, this study closes the aforementioned gap in the literature because it provides stakeholders a reasonable method for reviewing the relative performance of OWFs in terms of costs and reliable figures as a benchmark. It seemed reasonable to divide the analysis into a static model for evaluating capital cost efficiency, which refers to all one-time expenditures associated with development and installation until the takeover of an OWF, and a dynamic model for investigating operating cost efficiency, which refers to all expenditures specified on a yearly basis occurring after the point of takeover until the decommissioning of an OWF [11]. The in-depth cost analysis was aimed at investigating several interesting aspects associated with offshore wind costs using the previously developed model and applying some extensions of DEA within the context of a case study. Thus, in addition to calculating the relative efficiencies by DEA, sources of inefficiency were assessed. Moreover, DEA allows for the identification of best practices, which is the basis for calculating cost efficiency frontiers. Hence, another objective was to provide a chart similar to that presented in [15], which has also been used in other publications (e.g., [22,23]) and shows cost as a function of the main specifics of OWFs. This was implemented through sensitivity analysis with DEA and showed what level of capital (operating) costs would be optimal relative to those of other OWFs already implemented. Finally, the determination of relative cost efficiencies allowed for the analysis of their relationship to other factors, such as year of commissioning or installed capacity, which in turn provided information about the effects of learning and economies of scale. To date, the investigation of these effects—for example, as completed in [12,24,25]—have been based on specific costs, which again calls into question the results due to the previously discussed lack of comparability. As stated in [25], the understanding of and correction for the two cost-increasing effects of water depth and distance to shore could improve learning curve analyses for OWFs. Thus, the methodology presented in the following also offers a reliable method for interpreting cost development and verifying whether and to what extent cost reductions take place.

An important principle for the analyses presented in this article—which posed, at the same time, the most formidable challenge—was the requirement of using input data of the highest possible quality. It is understandable that companies do not want to provide commercially sensitive performance data, but the offshore wind industry appears to be extraordinarily secretive. The reason for this behaviour might be the fact that this industry is quite young and still rapidly developing. Withholding information about experiences that were possibly quite costly promises market

participants the maintenance of competitive advantages and raises barriers to entry. The capital cost estimation completed in [8] shows which typical sources are used for gathering cost data. Sources originate either from offshore wind farm owners' websites or reports, in which it is difficult to detect whether the figures were massaged, or from online databases, such as [26], and reports of consulting companies, where the original source is often not disclosed and it is not clear how data were processed (e.g., deflation). It is clear that these sources are not sufficiently reliable to generate significant results. Therefore, all cost data used for the investigation originate directly from annual financial statements and are verified using only information from owners' websites and reports, which is possible because offshore wind projects are usually arranged through Special Purpose Vehicle (SPV) companies—separate legal entities that are used to isolate the owner from financial risks [27,28]. The annual reports of these SPVs are officially deposited and accessible at the respective register of companies [29–34]. This database is unique and ensures the significance and usefulness of the article's results for stakeholders of the offshore wind industry. The names and cost data of individual OWFs' SPVs are intentionally not quoted because the intention of this publication is to provide a reliable scientific analysis of offshore wind costs and not to compromise anybody on any account.

The next section presents how capital and operating cost efficiency were modelled using DEA. Section 3 provides a description of the input data for the case study and their preparation. The results of the analysis are presented in Section 4 and subsequently discussed in Section 5.

2. Modelling

Before the DMUs are characterised and the mathematical model is explained, it must be noted that the methodology presented in the following represents the result of a comprehensive analysis in which many different configurations of inputs (outputs) and modifications of DEA were investigated with respect to their reasonableness and applicability to reality.

2.1. Characterisation of DMUs

In the course of researching the literature for this article, it was particularly noticeable that most authors attach importance to a detailed description of the chosen DEA model, whereas there is often a lack of reasoning why specific input (output) parameters were selected, why specific parameters were used as input rather than as output or vice versa and how they are related to the efficiency of the DMU. It is clear that the selection of parameters and how they are included in the model are as significant as the model itself with regard to the quality of the results. Thus, a detailed description of the selected DMUs and how the selected parameters influence the DMU efficiency is provided in the following.

2.1.1. Capital cost efficiency

In this case, the DMU is the entity that develops and installs the OWF. As shown in Fig. 1, this entity transforms the only input specific capital costs into an OWF of a specific size (=installed capacity) for a specific distance to shore and water depth. As mentioned previously, capital costs (also referred to as capital expenditures or CAPEX) are defined as all expenditures that occur until the OWF is commissioned, meaning that they comprise all investments for OWF development, such as soil examinations, environmental assessments and appraisals for certification as well as all investments for OWF deployment, such as the purchase and installation of components and project management [13]. Installed capacity is often used as an indicator for the size of a wind power plant. It is the product of the wind energy converters' (WEC) rated power, defining the level of power for which the turbine and its components are designed, and the number of turbines of the plant. Distance to shore and water depth were included because they are the main drivers for capital costs. Thus, the theoretical production function can be formulated: the greater the specific capital costs invested for deploying the OWF, the larger (installed capacity) it will become, the farther off shore the OWF will be situated and the greater the water depth of the OWF site will be.

2.1.2. Operating cost efficiency

For the operating cost efficiency analysis, the DMU is the entity that is responsible for the OWF during its operational phase, which might be the operation and maintenance department of an energy utility or an external service provider. In the following, this DMU is referred to as the service agent. To be able to select parameters that determine the performance of an offshore wind service agent, it is necessary to understand what affects the efficiency of a WEC, which is discussed in the following. The author of [35] provides a good visualisation of a WEC's efficiency, plotting the energy density as a function of wind speed. Fig. 2 shows an adapted version of this graph using a generic 5 MW WEC as the basis and depicting the annual energy yield per rotor swept area as a function of wind speed. The main input for a WEC is, of course, the wind or, more specifically, the kinetic energy content of the wind. This kinetic energy is given exogenously by nature and can be calculated using the following equation:

$$E_{kin\_wind} = (1/2)A\rho v^3 t \quad (1)$$

where A designates the swept area of the rotor, ρ is the air density, v is the wind speed and t is time. According to Betz's momentum theory, there exists a physical limit for the amount of mechanical energy that can be extracted from a free-stream airflow by an energy converter under ideal conditions, which is 16/27 = 59.3% of E_{kin_wind}. Whereas this loss cannot be avoided, the next sectional area shown in Fig. 2 represents the aerodynamic losses that occur

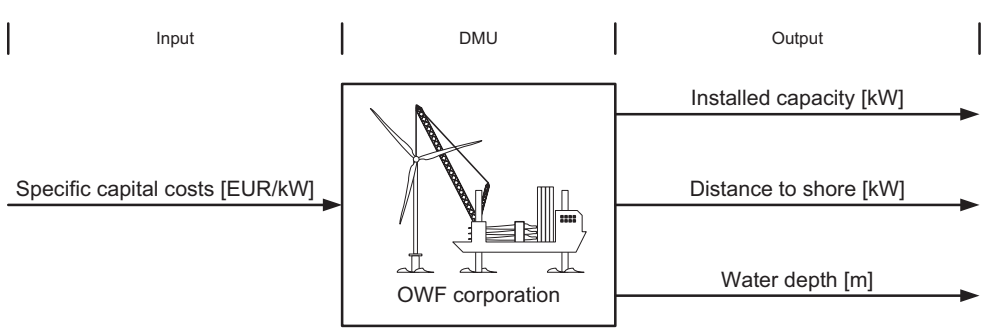

Fig. 1. Model for capital cost efficiency analysis.

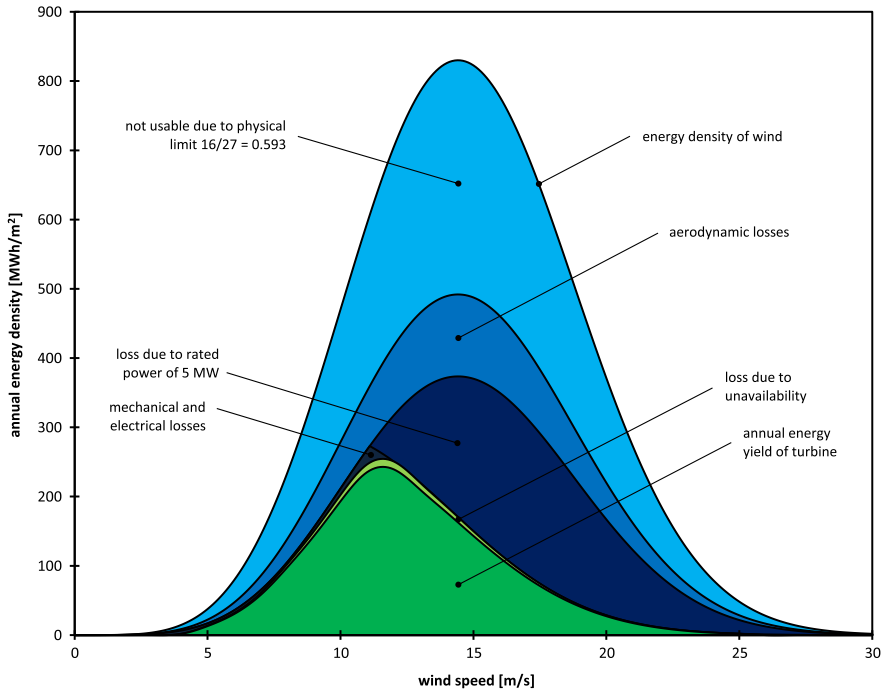

Fig. 2. Efficiency of a wind turbine. (cf. [35]; p. 525).

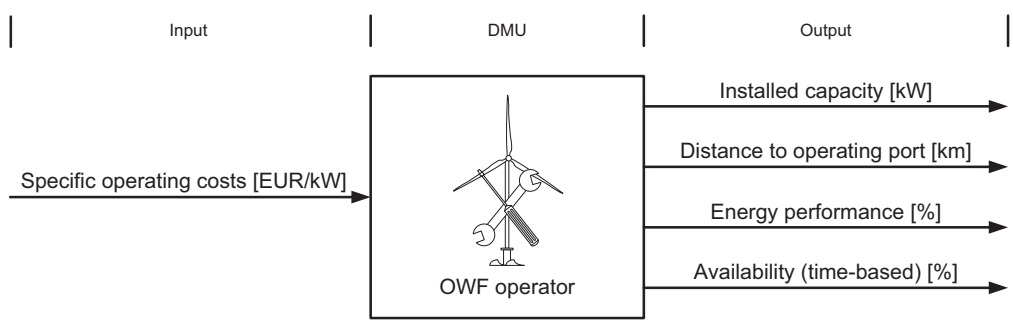

Fig. 3. Model for operating cost efficiency.

because a real wind rotor has an efficiency below the theoretical limit. Due to economic and technological constraints, a WEC is designed for a specific rated power, which causes another major loss. Finally, the remaining area, after subtracting mechanical and electrical losses, represents the gross annual energy yield. This yield can be calculated using the power curve of the WEC and the wind resource at the wind farm site. Thus far, all losses are a result of physical constraints or the wind turbine's design.

The last portion indicates the loss due to the WEC being unavailable, which is in principle the only loss that can be influenced by the service agent.[2] This is why availability is a common performance metric for the operation and maintenance of wind power plants [36]. Unfortunately, the distinction between time-based and production-based (also referred to as energy- or yield-based) availability is often overlooked, although the difference between the two is significant for evaluating operational performance. One reason for this oversight might be that an international standard for defining the latter is still under development [37]. According to IEC/TS 61400-26-1 [38], time-based availability is defined as the "fraction of a given operating period in which a wind turbine generating system is performing its intended services within the design specification". Therefore, 95% time-based availability means that the WEC does not perform its intended service (i.e., it is not able to convert energy due to malfunction, maintenance, etc., for 5% of the operating period). However, this figure is not actually tantamount to an energy loss of 5% because it depends on the prevailing wind speed during the downtime of the turbine. Because the operator is remunerated for the energy fed into the grid, the time-based availability is only an indicator but not an optimal performance metric. Refs. [39–41] provide empirical studies and reviews of this topic.

The amount of energy lost during the period of turbine unavailability depends on the technical quality of the wind turbine and the performance of the service agent. The quality of a wind turbine can be specified in terms of reliability (i.e., the probability that the WEC satisfactorily performs its intended function under given circumstances for a specified period of time) [38]. In terms of energy loss, it is important that the turbine is reliable, particularly during periods of high wind, during which the WEC would generate high yield. The reliability issue is even more important offshore because rough weather conditions do not allow access to the WEC; therefore, the turbine remains unavailable until troubleshooting by a maintenance team is possible [42]. Finally, the energy loss due to unavailability reflects

[2] This is not entirely true because wear and tear, blade degradation, etc., lead to an efficiency loss during the WEC's lifetime, which can be limited up to a certain point through qualified maintenance by the service agent. Because this effect is usually rather small, efficiency losses that cannot be eliminated by the service agent were neglected.

the performance of the service agent because he or she is responsible for keeping the WEC in good condition, organising spare parts and scheduling maintenance. Therefore, in a benchmarking analysis of service agents, both time-based availability and a metric that reflects the loss of energy during unavailability should be considered.

Fig. 3 shows the selected parameters for the operating cost efficiency analysis. The only inputs are the specific operating costs (also referred to as the operating expenditures or OPEX), which comprise all expenditures that occur during operation, such as maintenance, insurance and administrative expenses [13]. In contrast to the capital costs, which are one-time investment costs, operating costs are usually assessed on an annual basis. Therefore, this operating cost efficiency analysis assesses the performance of different OWFs in different operational years. Installed capacity is again an output, which also appears to be a good measure in this case for the service agent's scale effort because it combines the number and size of WECs. In addition, the distance to shore has again been identified to be significant for these investigations [43]. Because there is usually only one port used as the base for the operational phase, which is not always the case for the construction phase, the distance to the operating port is used. Following the argument regarding a service agent's influence on the turbine's energy efficiency, a metric reflecting energy performance is needed. The optimal way to quantify energy performance might be to determine the energy lost during downtimes using the measured wind speed and the power curve of the wind turbine [39,41]. However, this calculation would require detailed operational data, which was not available for this study; therefore, the output energy performance was defined as follows:

$$\eta_p = \frac{AEP}{E_{kin\_wind}N} = \frac{AEP}{(1/2)A\rho v^3 tN} \tag{2}$$

where AEP designates the annual energy production of the OWF and N is the number of turbines. As shown in Fig. 2, the kinetic energy of wind would be calculated precisely using the wind speed frequency distribution, which was also not available for this study. Thus, the annual average wind speed at hub height was used for v. In addition, ρ was assumed to be 1.225 kg/m^3, t was assumed to be 8760 h and for A, the rotor swept area of the respective plant's WEC was used. Therefore, the output energy performance reflects how efficiently the available kinetic energy content of the wind was converted into electrical energy during an operating year. At first glance, this approximation appears to be deficient because it incorporates all losses described before and not only the losses due to unavailability. However, because all other losses always account for nearly the same proportion of the energy yield and because DEA is a purely relative evaluation, this approximation appeared to be a valid approach. In addition, the time-based availability was also included as an output in the analysis.

Hence, the theoretical production function can be formulated in the following way: the higher the specific operating costs a service agent requires, the larger and the farther away from the operating port the OWF that is being maintained can be and the higher the energy performance and time-based availability will be.

2.2. Mathematical models

2.2.1. DEA application

DEA was developed with the aim of assessing the relative efficiencies of multi-input, multi-output production units. Therefore, DEA provides a methodology that allows for the identification of, within a set of comparable DMUs, those units exhibiting best practices and forming an efficient frontier. In addition, DEA allows for the measurement of the level of inefficiency of non-frontier units and identification of benchmarks against which they can be compared [44]. The main advantage of DEA is that prior assumptions regarding the underlying functional relationship between inputs and outputs are not required [45]. Because DEA is a well-established method for relative efficiency evaluation and extensively applied in the literature, only a brief description is provided in the following. The application presented in this article, and therefore the description provided, is mainly based on [44], which provides a focused overview, and [46], which is a comprehensive reference book for DEA.

The two basic DEA models are the Charnes–Cooper–Rhodes (CCR) model [47], which assumes constant returns to scale, and the Banker–Charnes–Cooper (BCC) model [48], which assumes variable returns to scale. Both models use a radial efficiency measure, which means that all inputs and outputs are adjusted proportionally. Depending on the selected orientation, either inputs are proportionally reduced while outputs remain fixed (input-oriented) or outputs are proportionally increased while inputs are held constant (output-oriented). These adjustments are made until the efficiency frontier, which is determined by the production possibility set (i.e., the set of feasible activities or, in other words, the combinations of inputs and outputs) is reached. Using the input-oriented model appeared to be appropriate for this application because it could ensure that the outputs would not be maximised to an implausible level. According to [44], the CCR model in the envelopment form can be formulated assuming a set of n DMUs, with each DMU j ($j=1,\ldots,m$) using m inputs x_{ij} ($i=1,\ldots,m$) and generating s outputs y_{rj} ($r=1,\ldots,s$), in the following manner:

$$\begin{aligned}
&\min \theta_o - \varepsilon \cdot \left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+ \right) \\
&\text{subject to } \sum_{j=1}^{n} x_{ij} \cdot \lambda_j + s_i^- = \theta_o \cdot x_{io}, \quad i \in 1,\ldots,m \\
&\sum_{j=1}^{n} y_{rj} \cdot \lambda_j - s_r^+ = y_{ro}, \rightarrow \quad r \in 1,\ldots,s \\
&\lambda_j, s_i^-, s_r^+ \geq 0, \quad \forall i,r,j \\
&\theta_0 \text{ unrestricted}
\end{aligned} \tag{3}$$

For the BCC model, the following constraint must be added:

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{4}$$

The result is an efficiency score θ^*_{CCR} (θ^*_{BCC}) between zero and unity for each DMU under consideration, which is a proportionality factor by which each input is reduced to reach the efficiency frontier. Thus, the radial projection to the frontier respective to the efficiency target for each input (output) can be calculated as follows:

$$\begin{aligned}
&\hat{x}_{io} \leftarrow \theta^* \cdot x_{io} - s_i^{-*}, \quad i \in 1,\ldots,m \\
&\hat{y}_{ro} \leftarrow y_{ro} + s_r^{+*}, \quad r \in 1,\ldots,s
\end{aligned} \tag{5}$$

Additionally, it is also interesting to investigate the sources of inefficiency (i.e., whether the inefficiency is caused by the inefficient operation of the DMU itself or by the disadvantageous conditions under which the DMU is operating). Due to their characteristics (i.e., the radial expansion and reduction of all DMUs and their nonnegative combinations are possible resp. convex combinations of the DMUs, which form the production possibility set), the CCR (BCC) score is also called the global technical efficiency (local pure technical efficiency). A DMU is operating on the most productive scale size if both the CCR and BCC scores indicate full efficiency (100%). Hence, a DMU that has full BCC efficiency but a low CCR score is operating efficiently only locally and not globally as a result of its scale size. Consequently,

according to [46], scale efficiency is defined as follows:

$$\theta^*_{scale} = \frac{\theta^*_{CCR}}{\theta^*_{BCC}} \tag{6}$$

and because the CCR score is always lower than the BCC score, the value of θ^*_{scale} is also between zero and unity.

Finally, the definitions of the output availability and energy performance for the operating cost analysis imply that the measures can never exceed 100%; this restriction had to be incorporated into the model by modifying the standard DEA models. According to the so-called bounded variable model described in [46], this limit can be considered by adding the following constraint:

$$\sum_{j=1}^{n} y_{bj}\lambda_j \le l_u, \quad b \in 1, \ldots, s \tag{7}$$

where l_u designates the upper bound for the bounded output y_b.

2.2.2. Best-practice frontier

The idea of calculating and providing the best-practice frontier arose from the policy of not publishing cost data for individual OWFs in this article. Otherwise, it would have been possible to simply provide the projection of the input for each OWF. However, to determine the best-practice frontier, a generic DMU was added. The first step was to choose a set of values for the generic DMU's outputs (e.g., 100 MW installed capacity, 10 m water depth, 10 km distance to shore) in the range between the minimum and maximum values of the respective output of the existing DMUs. The value for the generic DMU's input was chosen to equal the maximum value of the input of the existing DMUs. This ensured that the efficiency frontier was not altered. Calculating the projection of the generic DMU's input reveals the point on the efficiency frontier for the chosen set of output values. Thus, it was possible to vary the set of output values and trace the projection of the generic DMU's input to scan the best-practice frontier. Fig. 4 shows a simplified visualisation of this procedure for the single-input, single-output case.

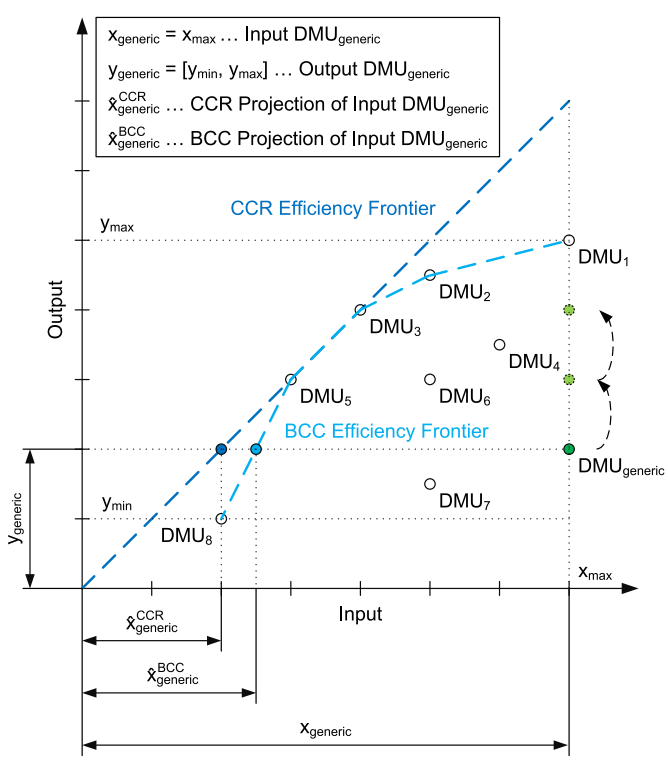

Fig. 4. Determination of best-practice frontier.

2.2.3. Tobit regression and learning-by-doing

To investigate the relationship between certain factors—for example, the year of commissioning—and the efficiency scores obtained with DEA, the Tobit model proposed in [49] was applied. This model is a regression model that can address censored data and is needed because DEA efficiency scores are between zero and unity. Therefore, the Tobit model is a common second-stage analysis that has been frequently applied in the literature in conjunction with DEA [50]. Nevertheless, it is important to mention that this approach is not uncontroversial. For example, in [51], it is criticised that contextual variables used in Tobit models are probably correlated with the efficiency scores calculated previously, which leads to the inconsistency problem of estimators; therefore, the authors propose the use of bootstrapping. However, [52–54] conclude after their investigations that the application of the Tobit model as a second-stage analysis is valid.

In contrast to similar applications in this field, every factor under investigation is analysed on its own instead of performing a multiple regression. In this manner, the relationship between the efficiency scores and every individual factor was determined. According to [50], the Tobit model applied in a DEA second-stage analysis can be described as follows:

$$\theta^*_j = \beta \cdot C_j + \varepsilon_j \text{ with } \varepsilon_j \sim N(0, \sigma^2)$$

$$\theta_j = \begin{cases} 0 & \text{if } \theta^*_j \le 0 \\ \theta^*_j & \text{if } 0 < \theta^*_j < 1 \\ 1 & \text{if } \theta^*_j \ge 1 \end{cases} \tag{8}$$

where θ_j designates the CCR/BCC/scale efficiency score, β the set of parameters to be estimated, C_j the respective factor under investigation and ε_j the error term. Tobit regression was used to determine the relationship with respect to the factors YEAR (year of commissioning), CAP (installed capacity), CUMCAP (cumulative installed capacity), RATPOW (rated power of WECs) and NUMWEC (number of WECs). In addition, the factor OPYEAR (year of operation) was included for the operating cost analysis.

As described in the introduction, another objective of applying the Tobit regression model was to analyse cost development as a function of technological change, which is commonly described by learning curves. Therefore, the obtained relationship between cost efficiency and cumulative installed capacity was used to determine the so-called learning-by-doing rate. The concept of measuring learning through cumulative production or capacity was first introduced by [55] and describes the process of gaining productivity increases and cost reductions by the accumulation of experience [56]. A common approach is to investigate the learning-by-doing effect based on specific capital costs using the cumulative installed capacity as a proxy for the accumulation of experience. Following this approach, using the efficiency scores instead of specific capital costs and the equations provided by [57], the learning-by-doing effect can be calculated using the following equations:

$$\theta_t = \theta_{t_0}\left(\frac{CUMCAP_t}{CUMCAP_{t_0}}\right)^{\beta}$$

$$LBD = 1 - 2^{\beta} \tag{9}$$

where θ_{t_0}/θ_t is the efficiency score at time zero/t, $CUMCAP_{t_0}/CUMCAP_t$ is the cumulative installed capacity at time zero/t, β is the learning coefficient and LBD is the learning-by-doing rate. LBD is typically expected to be positive because a positive value indicates a reduction in unit cost. Because the cost efficiency should increase, it is important to note that for this

Table 1
Data for capital cost efficiency analysis.

#	OWF	Ref.	Country	Commissioning	Number of turbines	Rated power (kW)	Installed capacity (MW)	Distance to shore (km)	Water depth (m)
1	alpha ventus	[59]	DEU	2010	12	5000	60.0	60.0	30.0
2	Baltic 1	[60]	DEU	2011	21	2300	48.3	16.0	17.5
3	Belwind Phase 1	[61]	BEL	2010	55	3000	165.0	46.0	28.5
4	Barrow	[62,63]	GBR	2006	30	3000	90.0	8.0	15.0
5	Burbo Bank	[64]	GBR	2008	25	3600	90.0	7.0	5.0
6	Egmond aan Zee	[65]	NLD	2007	36	3000	108.0	14.0	18.0
7	Greater Gabbard	[10]	GBR	2012	140	3600	504.0	23.0	29.0
8	Gunfleet Sands 1 & 2	[66]	GBR	2010	48	3600	172.8	7.0	7.5
9	Horns Rev 2	[67]	DNK	2010	91	2300	209.3	30.0	13.0
10	Kentish Flats	[68–70]	GBR	2005	30	3000	90.0	10.5	5.0
11	Lillgrund	[71]	SWE	2007	48	2300	110.4	7.0	6.0
12	Lynn and Inner Dowsing	[72]	GBR	2009	54	3600	194.4	7.0	9.5
13	Middelgrunden	[9]	DNK	2001	20	2000	40.0	3.5	5.5
14	North Hoyle	[73–76]	GBR	2004	30	2000	60.0	7.5	9.0
15	Ormonde	[77]	GBR	2012	30	5000	150.0	10.0	23.5
16	Rhyl Flats	[78]	GBR	2009	25	3600	90.0	8.0	9.5
17	Robin Rigg	[79]	GBR	2010	60	3000	180.0	10.0	9.0
18	Rodsand 2	[79]	DNK	2010	90	2300	207.0	4.0	10.0
19	Scroby Sands	[79–82]	GBR	2004	30	2000	60.0	3.0	15.0
20	Sheringham Shoal	[83]	GBR	2012	88	3600	316.8	20.0	20.0
21	Thanet	[84]	GBR	2010	100	3000	300.0	12.0	22.5
22	Walney 1 & 2	[85]	GBR	2012	102	3600	367.2	20.1	22.0
Minimum							40.0	3.0	5.0
Maximum							504.0	60.0	30.0
Average							170.1	15.3	15.2
Median							150.0	10.0	15.0

application, *LBD* is negative in the case of a positive learning effect. Thus, a *LBD* of -10% indicates that a doubling of cumulative experience has led to an increase of 10% in cost efficiency.

3. Case study

Although the data collection was challenging, the DEA convention indicating that the minimum number of DMUs has to be greater than three times the number of inputs plus outputs [58] was adhered to. For the analysis of the capital cost efficiency, $22 \geq 3 \times (1+3)$ observations were included, and for the operating cost efficiency, $26 \geq 3 \times (1+4)$ observations were included.

3.1. Capital cost efficiency

For the capital cost efficiency analysis, the data for 3.6 GW of offshore wind capacity was used. The inclusion of plants in the analysis was based on the principles that they have a distance to shore greater than 3 km, an installed capacity greater than 30 MW and that the financial statements of the commissioning year be available. The data provided in Table 1 were selected very carefully, which means that only data from the owner's official websites were used.

To ensure comparability, it was necessary to apply the same method for assessing the specific capital costs to every OWF. The method was applied using the highest value for tangible assets stated in the respective SPVs' annual financial statements, which usually occurs during the year of commissioning because depreciation is applied afterwards. Tangible assets are all assets that have a physical form, such as property, plant and equipment. According to the international standard [86], the cost of a corresponding item is composed of the purchase price, any costs directly attributable to bringing the asset to the location, the conditions necessary for operation and the initial cost estimate for dismantling and removing the item and restoring the site on which it is located. Using this approach ensured a high quality of input data for the relative analysis and the generation of significant results. On average, the specific capital cost of these 22 OWFs was 2992.90 EUR/kW (Median = 2520.51 EUR/kW).

3.2. Operating cost efficiency

Unfortunately, access to operational data of OWFs is very limited. Nevertheless, Table 2 provides an overview of the OWFs included in the analysis. One data source was the operational reports of the four UK round 1 OWFs—Scroby Sands [80–82], Kentish Flats [68–70], North Hoyle [73–75] and Barrow [62,63]—that were obliged to publish these data due to the UK Offshore Wind Capital Grants Scheme [87]. These reports contain data about wind speed, availability, annual energy production, operation and maintenance costs, etc. [88] provides a good summary and first analysis of these projects' data. The operation and maintenance costs mentioned in those reports were compared with the annual financial statements of the projects' SPVs, and the annual energy production was compared with data provided by [89] to ensure comparability. In addition, the offshore wind farms alpha ventus [59,90–92], Egmond aan Zee [93,94] and Middelgrunden [9,95,96] were included in the analysis. Operating costs for Middelgrunden were obtained from [95], whereas the data for alpha ventus and Egmond aan Zee required an assessment of the SPVs' annual reports.

For this case study, operating costs were defined to be all expenditures needed to keep the OWF operating over its lifetime. In other words, all costs stated in the profit and loss account of a SPV, such as administrative expenses, operation and maintenance costs for WECs and grid connection facilities, insurance costs,

Table 2
Data for operating cost efficiency analysis.

#	OWF	Ref.	Installed capacity (MW)	Distance to operating port (km)	Annual wind speed[a] (m/s)	Annual energy production[a] (GWh)	Energy performance[a] (%)	Availability (time-based)[a] (%)	Years of available data
1	alpha ventus	[59,90–92]	60.0	57.0	9.5	267.4	41.0	95.8	1
2	Barrow	[62,63]	90.0	17.0	9.1	231.8	29.6	72.7	2
3	Egmond aan Zee	[93,94]	108.0	20.5	8.7	337.8	42.5	88.0	6
4	Kentish Flats	[68–70]	90.0	11.8	8.0	230.1	44.2	83.2	3
5	Middelgrunden[b]	[9,95,96]	20.0	3.5	6.6	44.5	64.3	95.0	8
6	North Hoyle	[73–75]	60.0	16.2	8.4	183.9	39.5	87.7	3
7	Scroby Sands	[80–82]	60.0	8.5	8.0	142.3	35.6	81.0	3
Minimum			20.0	3.5			25.0	67.3	
Maximum			108.0	57.0			72.4	98.9	
Average			62.2	13.5			47.2	87.9	
Median			60.0	11.8			44.4	88.6	

[a] Average value over all operational years included in the analysis of the respective OWF.
[b] Only operational data of the 10 southern WECs owned by Middelgrunden Wind Turbine Cooperative were available and therefore considered in the analysis.

rent for port facilities, etc., were summed. Depreciations were not included, and governmental grant credits were subtracted. The specific operating costs of these OWFs account for 63.49 EUR/kW (Median=46.88 EUR/kW) per year on average. Finally, the output energy performance was calculated using formula (2).

3.3. Cost data preparation

For the relative cost analysis comparing OWFs that were commissioned (operated) in different years, it was particularly important to deflate costs well considered. Unfortunately, studies regarding costs of offshore wind often do not contain a description of how the costs were deflated, which seriously calls into question their quality, especially when OWFs that were commissioned more than 10 years ago are included. Moreover, it is very likely that the costs of offshore wind did not increase with normal inflation. For example, [8] showed that there is a relationship between capital costs and steel price, and [25] references the recent cost increase in offshore wind to a surge in prices of commodities, such as copper and steel. Considering the value breakdown of costs presented in [11], this is reasonable. According to [11], the CAPEX of a conventional OWF consists of 35% labour, 34% material and 31% other costs, and the OPEX consists of 35% labour, 14% material and 52% other costs. Labour costs are defined to include direct and indirect labour; material costs include all raw materials and components, consumables, equipment, plant and buildings, and other costs comprise services (e.g., vessels, cranes), insurances and other overheads. Ref. [97] also provides an illustrative breakdown of material in a 500 MW offshore wind farm with 100 turbines, which shows that a large proportion of the used material is indeed steel, copper, aluminium, etc., whose price increase was beyond the normal inflation rate. To incorporate this fact, all costs used in this analysis were deflated using a rate based on the cost split presented in [11] and using the deflator for labour costs, a commodity price index for the material costs and the GDP deflator for other costs provided by [98]. Therefore, all costs mentioned in this article refer to a price level in the European Union in 2012.

4. Results

4.1. Cost efficiency

Tables 3 and 4 present the results of the capital (operating) cost efficiency analysis in the form of efficiency scores. An efficiency score of 100% indicates full cost efficiency, and values below indicate the level of cost inefficiency. When interpreting these results it should be kept in mind that DEA is a relative analysis method. Thus, one reason for the full capital and high operating cost efficiency of alpha ventus might be a lack of peers, i.e., OWFs that have specifics in the same range, which would ensure better comparability. Furthermore, the fact that the operating cost efficiency scores of each OWF are on fairly the same level—apart from a few outliers, which might be due to a year with good wind conditions or exceptional damage—indicate that the model generated reasonable results. Because the output installed capacity and distance to operating port do not change with operating year, this characteristic result is expected. Another part of the results would be the projections of all parameters (i.e., the target value assuming that the DMU operates efficiently). Because the provision of the projection would show the costs of individual OWFs instead, the best-practice frontiers are presented in the next section.

Table 3
Results of capital cost efficiency analysis.

OWF	θ^*_{CCR} (%)	θ^*_{BCC} (%)	θ^*_{scale} (%)
alpha ventus	100.00	100.00	100.00
Baltic 1	54.97	54.99	99.95
Belwind Phase 1	94.59	96.43	98.09
Barrow	72.56	81.85	88.66
Burbo Bank	31.82	66.72	47.69
Egmond aan Zee	100.00	100.00	100.00
Greater Gabbard	100.00	100.00	100.00
Gunfleet Sands 1 & 2	55.08	83.35	66.09
Horns Rev 2	100.00	100.00	100.00
Kentish Flats	44.20	85.29	51.82
Lillgrund	55.22	100.00	55.22
Lynn and Inner Dowsing	59.35	84.66	70.11
Middelgrunden	41.23	100.00	41.23
North Hoyle	41.55	66.88	62.13
Ormonde	73.21	77.67	94.26
Rhyl Flats	50.10	75.33	66.50
Robin Rigg	48.44	68.77	70.44
Rodsand 2	68.69	95.08	72.25
Scroby Sands	69.88	78.82	88.66
Sheringham Shoal	53.54	56.45	94.85
Thanet	72.19	73.65	98.02
Walney 1 & 2	84.18	88.39	95.24
Minimum	31.82	54.99	41.23
Maximum	100.00	100.00	100.00
Average	66.85	83.38	80.05
Median	64.02	84.00	88.66

4.2. Best-practice frontier

In examinations of the best-practice frontier, it is important to keep in mind that DEA is a relative efficiency analysis method (i.e., the significance of the results strongly depends on the disposability of benchmarks for the DMU under investigation). DEA would, for example, also allow for the projection of the specific costs of OWFs that are farther offshore and at sites with greater water depths than those of the OWFs that were included in the analysis. However, the validity of such projections is questionable, and because the objective of this article was to provide reliable results, the best-practice frontier was calculated over a range where it was ensured that a sufficient number benchmarks were available. Therefore, the capital cost best-practice frontier shown in Fig. 5 was assessed for installed capacities of 100, 200 and 300 MW, for distances to shore of up to 25 km and water depths of up to 25 m. Due to the limited database, the operating cost best-practice frontier was assessed for installed capacities of 60, 80 and 100 MW and distances to operating port between 5 and 20 km. The output energy performance was set to 45%, and the time-based availability was set to 95%. The results are shown in Fig. 6.

As described previously, the CCR score describes the global technical efficiency of a DMU, and the BCC score describes the local pure technical efficiency. Therefore, an OWF that achieves a level of costs lying on the BCC frontier is considered to be locally efficient but not globally efficient, which would require reaching the CCR frontier as well. The point (segment) where the two frontiers overlap is also interesting because it indicates the most productive scale size.

Table 4
Results of operating cost efficiency analysis.

OWF	Operating year	θ^*_{CCR} (%)	θ^*_{BCC} (%)	θ^*_{scale} (%)
alpha ventus	1.	98.73	100.00	98.73
Barrow	1.	37.81	37.81	99.98
	2.	40.97	40.98	99.98
Egmond aan Zee	1.	68.70	68.71	99.99
	2.	76.56	76.57	99.99
	3.	86.30	86.30	100.00
	4.	99.99	100.00	99.99
	5.	97.32	100.00	97.32
	6.	61.37	100.00	61.37
Kentish Flats	1.	69.29	69.29	100.00
	2.	69.30	69.30	100.00
	3.	100.00	100.00	100.00
Middelgrunden	1.	63.99	69.64	91.88
	2.	100.00	100.00	100.00
	3.	81.22	100.00	81.22
	4.	62.94	63.31	99.41
	9.	43.28	79.72	54.28
	10.	50.44	100.00	50.44
	11.	39.05	39.31	99.34
	12.	42.74	43.65	97.91
North Hoyle	1.	48.06	48.07	99.97
	2.	58.71	58.73	99.97
	3.	53.72	53.74	99.97
Scroby Sands	1.	56.90	59.41	95.78
	2.	50.86	55.93	90.94
	3.	55.32	57.87	95.59
Minimum		37.81	37.81	50.44
Maximum		100.00	100.00	100.00
Average		65.91	72.24	92.85
Median		62.15	69.30	99.69

4.3. Tobit regression and learning-by-doing

Table 5 provides the results of the Tobit regression analysis performed during a second stage and the learning-by-doing rate for the different efficiency scores. For the factor CUMCAP, the cumulative installed offshore wind capacity in Europe provided in [1] was used.

5. Discussion

In general, the presented methodology based on the concept of DEA appears to provide a practicable approach for benchmarking OWFs. It enables stakeholders to evaluate the reasonableness of the capital and operating cost levels relative to those of other OWFs and to estimate the target costs that would be optimal corresponding to the specifics (operating parameters) of the OWF under investigation.

At first glance, the capital cost best-practice frontier indicates a strong dependence of the specific capital cost on distance to shore

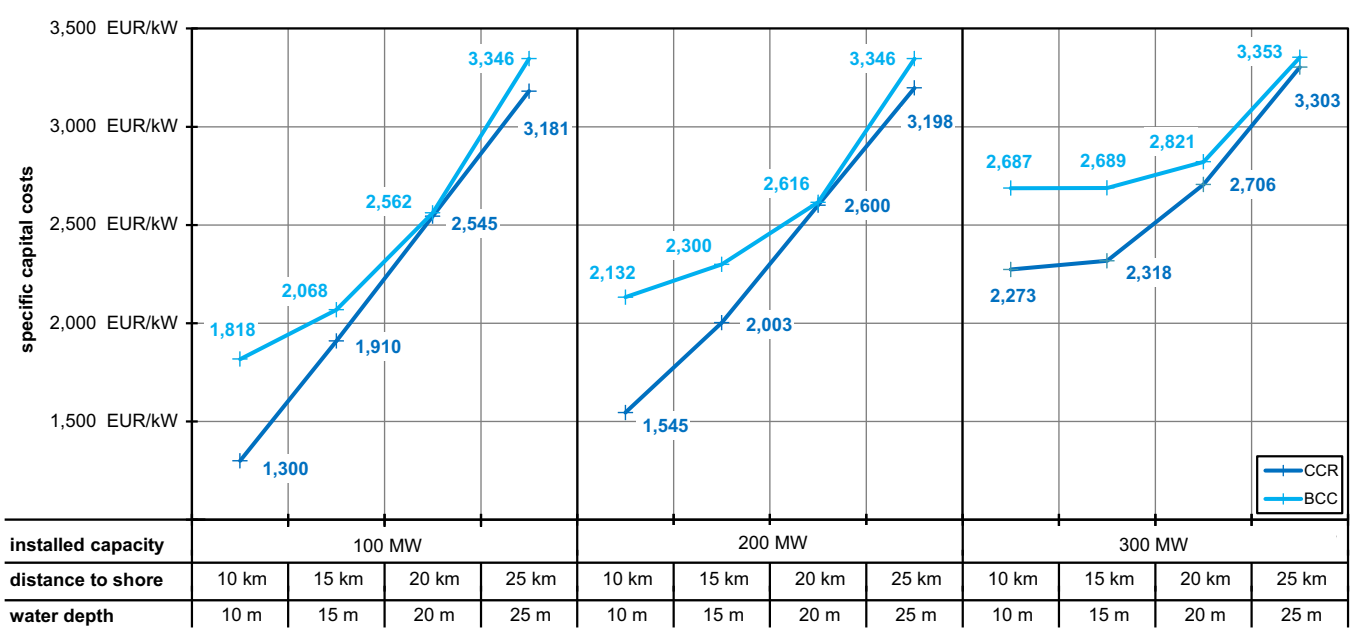

Fig. 5. Capital cost efficiency frontier.

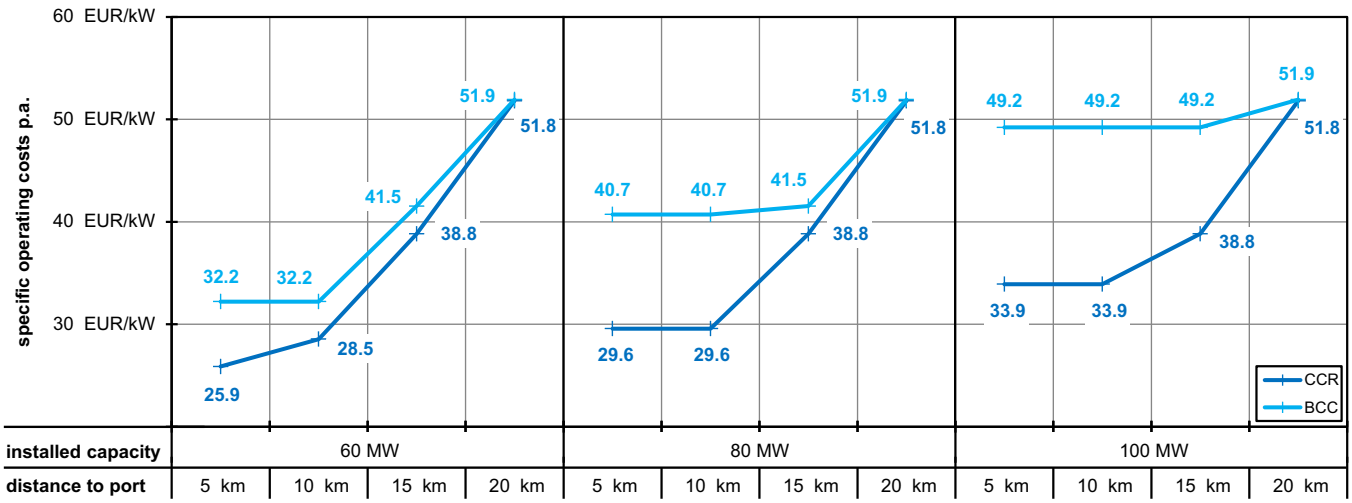

Fig. 6. Operating cost efficiency frontier.

Table 5
Results of Tobit regression analysis and learning-by-doing effect.

	Capital cost efficiency			Operating cost efficiency		
	θ^*_{CCR}	θ^*_{BCC}	θ^*_{scale}	θ^*_{CCR}	θ^*_{BCC}	θ^*_{scale}
OPYEAR				-2.140×10^{-2}	3.796×10^{-3}	-2.573×10^{-2}
				$(1.259 \times 10^{-2})^{+}$	(1.887×10^{-2})	(8.611×10^{-3}) **
YEAR	3.878×10^{-2}	-8.029×10^{-3}	4.821×10^{-2}	-2.478×10^{-3}	2.037×10^{-2}	-1.470×10^{-2}
	(1.715×10^{-2}) *	(1.498×10^{-2})	(1.352×10^{-2}) ***	(1.467×10^{-2})	(2.114×10^{-2})	(1.090×10^{-2})
CAP (MW)	9.178×10^{-4}	1.779×10^{-4}	9.410×10^{-4}	2.564×10^{-3}	1.999×10^{-3}	1.614×10^{-3}
	(4.629×10^{-4}) *	(3.694×10^{-4})	(4.301×10^{-4}) *	(1.162×10^{-3}) *	(1.797×10^{-3})	$(9.528 \times 10^{-4})^{+}$
CUMCAP (MW)	7.533×10^{-5}	-9.586×10^{-6}	9.557×10^{-5}	1.958×10^{-6}	6.506×10^{-5}	-3.725×10^{-5}
	(3.398×10^{-5}) *	(2.862×10^{-5})	(2.705×10^{-5}) ***	(3.012×10^{-5})	(4.405×10^{-5})	$(2.180 \times 10^{-5})^{+}$
RATPOW (MW)	8.060×10^{-2}	-5.485×10^{-3}	8.387×10^{-2}	1.456×10^{-1}	1.841×10^{-1}	5.737×10^{-2}
	(6.490×10^{-2})	(5.043×10^{-2})	(5.896×10^{-2})	(5.383×10^{-2}) **	$(9.665 \times 10^{-2})^{+}$	(4.601×10^{-2})
NUMWEC	3.190×10^{-3}	1.023×10^{-3}	2.970×10^{-3}	$-1.535 \times 10^{+0}$	-2.046×10^{-3}	4.976×10^{-3}
	(1.569×10^{-3}) *	(1.261×10^{-3})	(1.465×10^{-3}) *	(1.477×10^{-1}) ***	(5.807×10^{-3})	$(2.908 \times 10^{-3})^{+}$
LBD	−9.61%	0.93%	−10.28%	−0.25%	−6.89%	3.34%

Standard errors are in parentheses.

$^{+}$ Statistically significant at 10% level.
* Statistically significant at 5% level.
** Statistically significant at 1% level.
*** Statistically significant at 0.1% level.

and water depth. This finding underlines the importance of quoting OWF specific capital costs as a function of the main specifics and the significance of this analysis. Furthermore, comparing the values with the scale factors provided by [15], the impact of these cost drivers appears to have been underestimated in the past. A closer look at the capital cost efficiency frontier reveals three implications. First, the most productive scale size suggested by the model (i.e., where the CCR and BCC frontiers touch) shows that smaller wind farms should be installed closer to shore and in shallower water. Second, at least for the range under investigation, it is possible to build a smaller OWF that is comparatively less expensive than a larger one at the same distance to shore and water depth. Third, the size of the OWF has a weaker impact on costs the farther away from shore and the deeper the water at the OWF site. These implications suggest that the best-practice OWFs have been developed and installed with negative economies of scale and that this effect levels off the farther offshore and the deeper the water at the OWF site.

Although the presence of negative economies of scale is also reported by other sources (e.g., [25]), it must be kept in mind that the presented frontiers reflect the best practices and not the overall trend. Furthermore, the evaluation of economies of scale in offshore wind should be well considered because installed capacity, which is commonly used to specify the scale of an OWF, does not refer to the number of produced and installed units (e.g., WECs, foundations). Thus, it is important to distinguish between dimension (installed capacity) and quantity (number of WECs). Considering the results of the Tobit regression analysis in this context reveals that for every 100 MW increase in OWF size, the CCR and scale efficiency improved by 9.2% and 9.4%, respectively, and by approximately 0.3% per additional WEC. In conclusion, although the best-practice frontier reveals that it might be possible to develop and install a smaller OWF at a comparatively lower cost than a larger one, the overall trend shows that the larger the OWF is, the higher the capital cost efficiency will be. The best-practice frontier for the operating cost efficiency reveals similar implications, and the Tobit regression analysis also reveals the positive effect of installed capacity on cost efficiency. However, the database used for the operating cost efficiency analysis and the OWFs considered were rather small (the largest is Egmond aan Zee OWF, with an installed capacity of 108 MW). Therefore, it is questionable to what extent the results of the operating cost

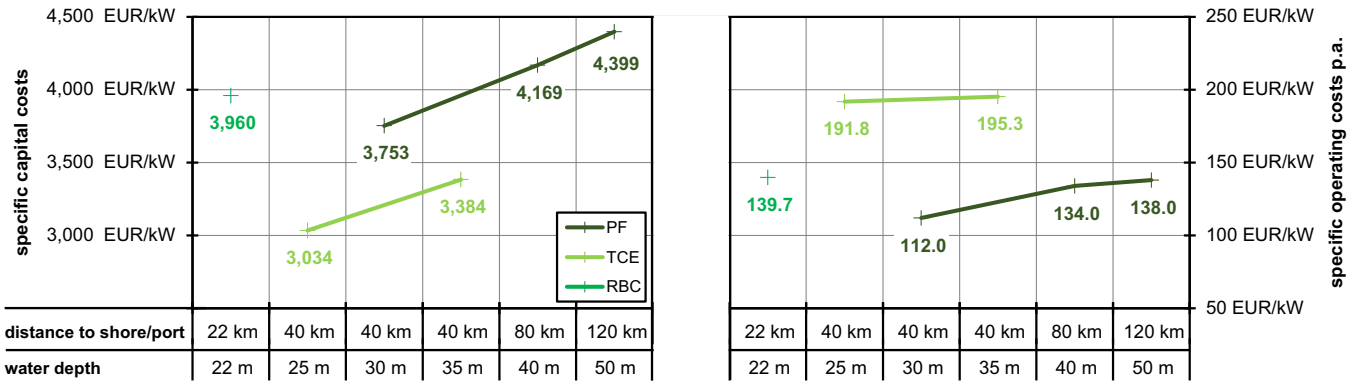

Fig. 7. Specific CAPEX and OPEX estimations by PF [4]; TCE [5] (adjusted from 2011) and RBC [6] (adjusted from 2013).

efficiency are applicable to large-scale projects that have recently become operational.

In general, the Tobit regression analysis generated the expected results. Nevertheless, it is remarkable that the expected relationships were verified partly even with high statistical significance. The results show that the global capital cost efficiency (CCR) improved by 3.9% per year, and the scale efficiency improved by 4.8% since the commissioning of the Middelgrunden OWF in 2001. Furthermore, the results reveal a negative relationship (−2.1% p.a.) between the global operating cost efficiency (CCR) and the year of operation, which is reasonable because wear and tear induces increased maintenance effort and thus higher operating costs the older an OWF becomes. Finally, an interesting issue to explore may be the role of WEC size because all OWFs considered have been developed, installed and operated during a period of rapid increase in WEC size that is still on-going. Although it is not verified with high statistical significance, the results indicate the expected increase in capital and operating cost efficiency with increasing WEC size.

The learning-by-doing rate for capital cost efficiency shows that global technical and scale efficiency have increased significantly (−9.6% and −10.3%, respectively) with accumulated experience. These values contradict the low values of 3% and 5%, respectively, presented in [25] and thus demonstrate how important it is to incorporate the distance to shore and water depth in these investigations, which was also noted by the authors of [25]. However, it must be kept in mind that the concept of learning-by-doing usually relates specific costs to cumulative capacity, and the basis of this analysis were efficiency scores limited to 100%.

Fig. 7 shows a visualisation of specific CAPEX and OPEX estimations provided by key references in this field for the base year 2012 (partly adjusted). These estimations deviate significantly from each other and also from the figures processed and calculated in this analysis. Given that these reports are inter alia the basis of decision making on energy policy issues such as remuneration schemes and expansion targets again demonstrates the importance of reliable input data and the application of comprehensive and advanced cost analysis methods. However, the relative cost reduction targets presented in these publications appear to be realistic. The calculated learning-by-doing rate suggests that the benchmarks presented previously should be reached with an accumulated experience of approximately 12 GW, which corresponds to the year 2016 according to recent projections.

Finally, it should be noted, which might also be the main point of criticism and uncertainty, that the results depend highly on the input data. It is clear that the more data included in the analysis, the more significant the results will be. Admittedly, the database for the operating cost efficiency was not excessively large, and the selection of input/output configurations was also influenced by the availability of data. In addition, there may also be other cost drivers that were not included in the model, such as the tightness in the market of wind turbine manufacturers and installation service providers [25]. However, the developed methodology generated plausible results, verifying the method's practicality for offshore wind cost analysis.

6. Conclusions

In this article, the functionality of the operations research tool DEA was exploited with the aim of providing a useful methodology that enables the evaluation of the relative capital and operating cost efficiency of OWFs based on their main specifics. Furthermore, best-practice frontiers were determined that overcome the difficulties regarding the appraisal of capital and operating costs by providing offshore wind stakeholders benchmark figures. The results revealed that more sophisticated cost assessments are needed and how meaningless the declaration of averaged specific cost figures for OWFs is. Finally, a Tobit regression analysis verified and quantified the expected relationships between the efficiency scores calculated by DEA and certain factors of interest, such as an increasing capital cost efficiency as a function of time, a decreasing operating cost efficiency as a function of the operating year and the presence of economies of scale and learning-by-doing. Gathering cost inputs mainly from annual reports ensured a particularly reliable database and high scientific quality, which stands out and will hopefully contribute to the development of an industry that is challenged to improve cost efficiency to gain competitiveness.

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