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Parametric CAPEX, OPEX, and LCOE expressions for offshore wind farms based on global deployment parameters

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cases, estimating the predicted values with a maximum error of 3.3%. These expressions will be particularly useful for the preliminary assessment of available deployment sites, offering cost estimates based on global decision variables.

KEYWORDS:

CAPEX LCOE nonlinear regression offshore wind farm OPEX parametric expressions

Introduction

Latest targets for Europe as reported from Wind Europe aim for 320 GW of wind energy capacity to be installed by 2030, 66 GW of which is planned to come from offshore wind (OW) energy (EWEA 2015). Deployment in deeper waters and further offshore is driven by the higher wind speeds, unrestricted space, and lower social impact in the marine environment (Kolios et al. 2016; Regueiro-Ferreira and Villasante 2016), where it is estimated that the same wind turbine can produce around 50% higher power output compared to onshore. High construction costs, especially foundation and electrical connection, and limitations in operation and maintenance are key barriers that need to be overcome in order to deploy in such environments in a cost-effective way. Figure 1 presents ... ployment depth, d ... e increase in install ... Offshore 2017.

Figure 1.

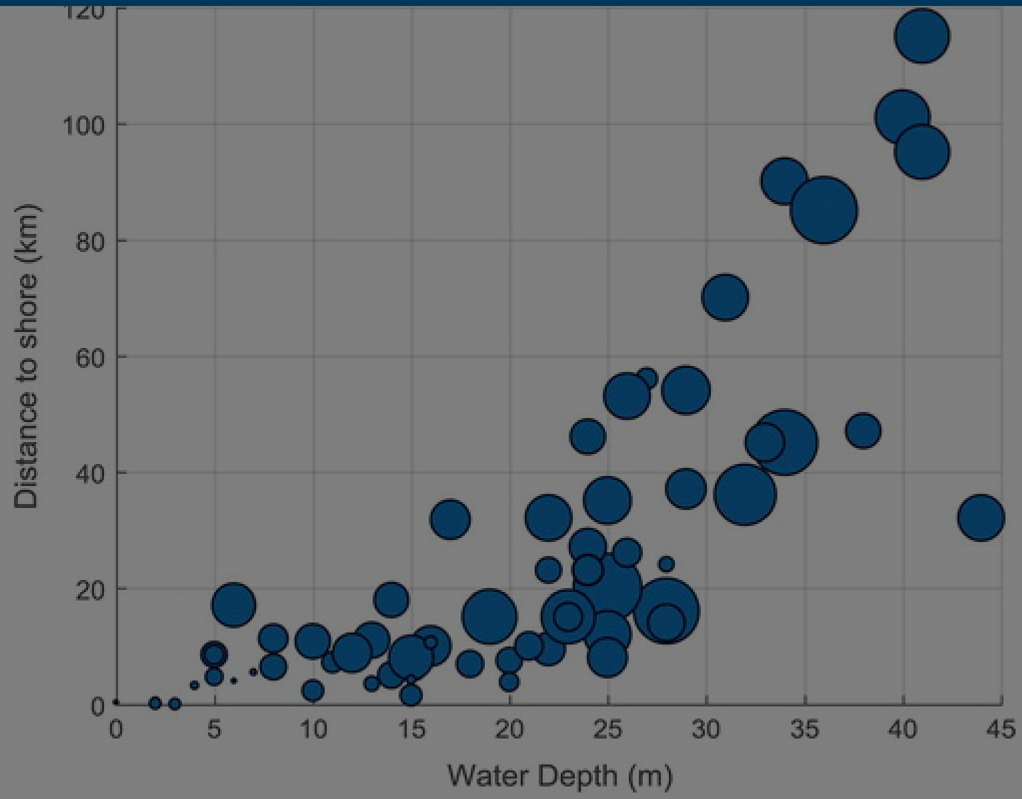

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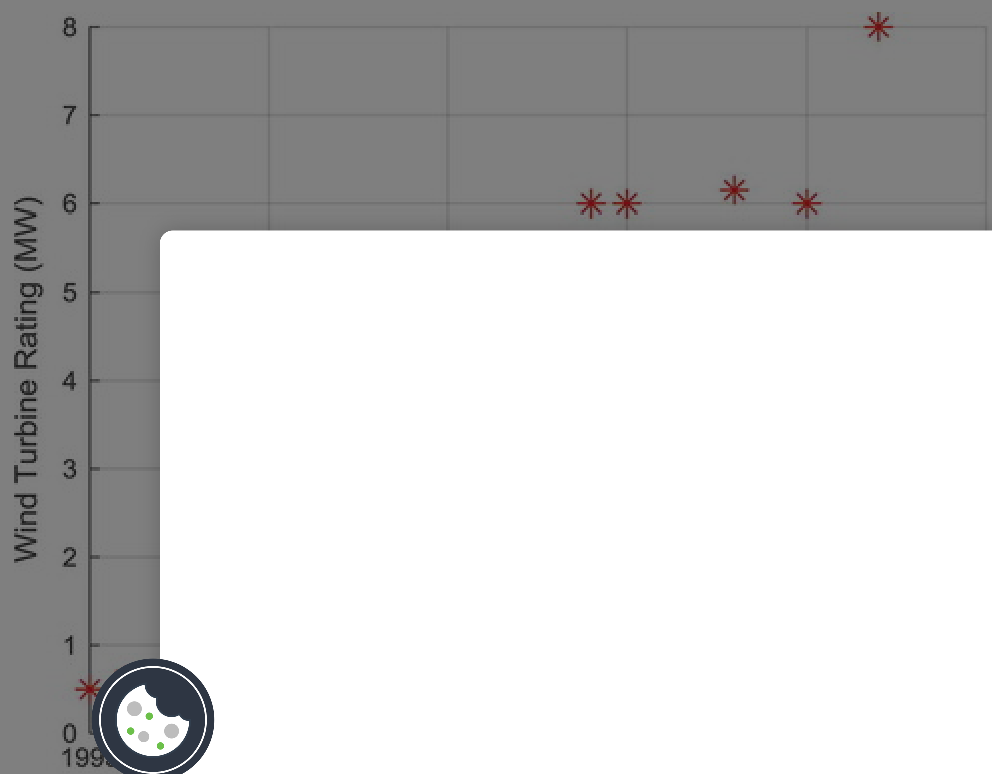
Figure 2. Turbine rating vs. wind farm year of commissioning.



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pertinent toward benchmarking the potential of different investment decision alternatives.

This article reports the development of a set of parametric models for capital expenditure (CAPEX), operational expenditure (OPEX), and levelized cost of energy (LCOE) as a function of a set of global variables for potential deployment sites. These account for the wind turbine capacity (), water depth (WD), distance from port (D), and wind farm capacity (). These variables were selected due to their significant effect on the cost-effectiveness of the investment (Shafiee et al. 2016). After mapping the multidimensional cost domain based on these variables, through a series of simulations performed by a fully integrated and tested cost model developed by the author, results are translated into analytical expressions to interpolate cost figures for potential wind farms within the applicability range of the expressions. A parametric analysis and a number of test cases illustrate the effectiveness of the models, drawing useful conclusions.

These expressions are expected to assist investors, researchers, and other stakeholders to undertake an initial estimate of CAPEX, OPEX, and LCOE values for OW farm projects with varying design parameters, as well as use them as reference for estimating the effect in the change of one of the selected design parameters. The cost model developed incorporates the most up-to-date available parametric expressions in the literatur … were gathere …

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Figure 3. Breakdown of life-cycle costs.

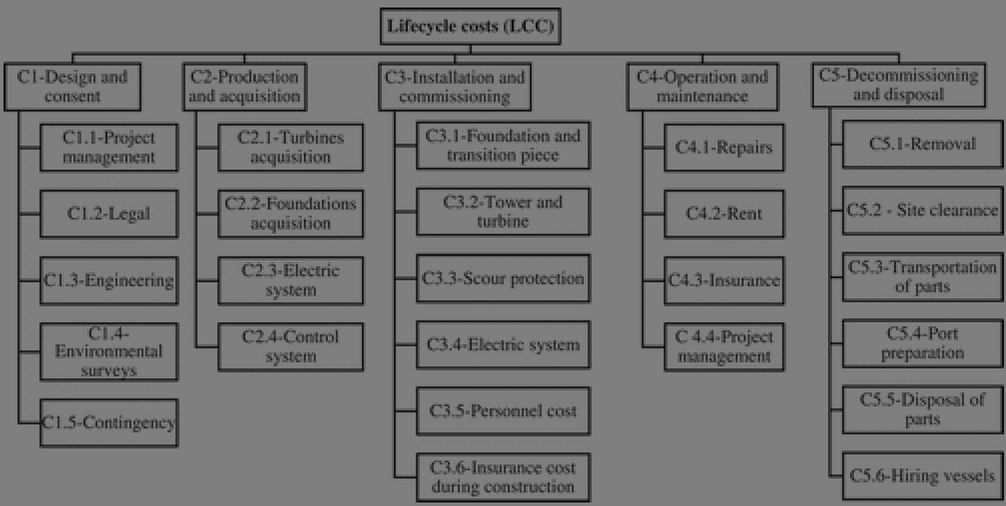

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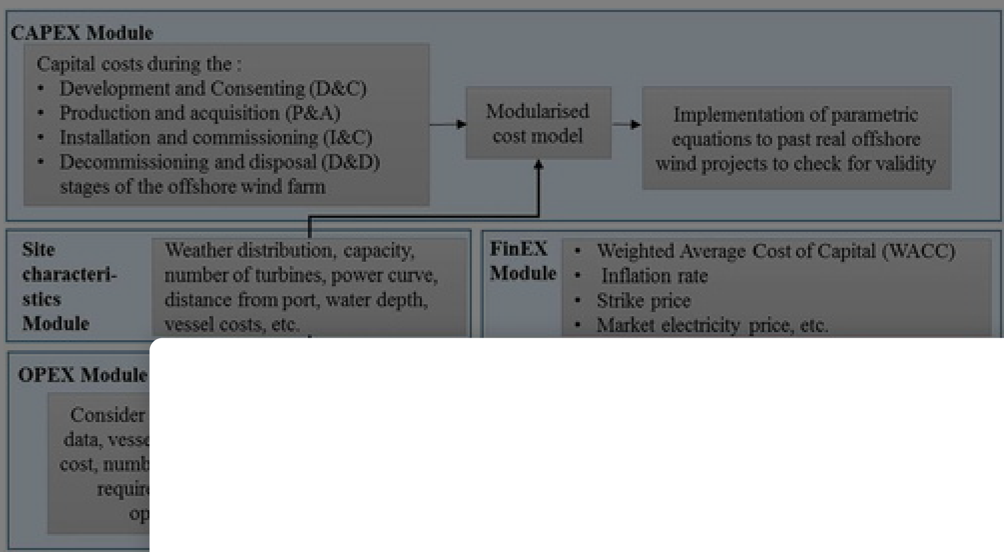
Figure 4. Integrated cost model structure.



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capacity (, while the cost of foundation as a function of the , , h, and d (; Dicorato et al. 2011).

The cost of the electric system comprises the cost of array, export and onshore cables ( ), and the cost of the substation (); the first, depending on the number of the wind turbines (), the rotor diameter (d), and the distance from shore (D)—; the second, depending on the number of the wind turbines, rated power of transformer (), the nominal voltage transformer (), and the wind farm capacity () according to Dicorato et al. 2011—. Onshore substation cost was assumed to be half the cost of the offshore substation. The control system cost was also taken from the same source to be equal to = 75 k£/turbine.

Next, the installation and commissioning costs of the OW farm comprise the installation of the wind turbine and tower (), foundation and transition piece (), scour protection (), electric system (), and the insurance costs (), a categorization also used by BVGA 2010, Dicorato et al. 2011, and Shafiee et al. 2016. The installation cost of the wind turbines is a function of the vessel day rates (), the number of vessels (workboats, heavy lift vessels, Special Operations Vessels (SOVs), and jack up vessels;), the duration of the installation (), and the cost for the personnel () required for carrying out the installation. Specifically for the installation of the wind turbines, the onshore pre-assembly method ( ) is also expected to greatly affect the cost of installation (Sarker and Faiz 2017). Althoug [illegible] order to avoid ad [illegible] ies taking place of [illegible] of the wind farm, a [illegible] d also by other au [illegible] 2). Therefor [illegible] ents of the wind far [illegible] oad capacity and [illegible] t.

The ope [illegible] d into the repair () [illegible] The estimati [illegible] Centre of the Netherla [illegible] et al. 2011), w [illegible] and unplann [illegible] ach different severity and frequency levels, which is introduced in the software by means of a mean time to failure. The different fault type classes are classified as minor repairs, major repairs, and major replacements following the Reliawind categorization scheme (Wilkinson et al. 2010). Further data needed for the prediction of the unplanned corrective maintenance costs include the average repair times, number of required technicians, and material costs, which were adopted from Carroll et al. 2016. For the condition-based maintenance, a certain number of repairs can be set for inclusion, while the calendar-based maintenance applies to all turbines of the wind farm. For calendar-based maintenance, a yearly small maintenance operation and a longer one occurring every 5 years were considered.

Decommissioning and disposal cost of the wind farm includes the following: the removal of the wind turbine (nacelle, tower, and transition piece) as well as the balance of the plant (foundations, scour protection, cables, and substations;), the site clearance (), the onshore transportation to the disposal sites (), the port preparation (), the disposal process (), and finally the hiring vessels costs (). To accomplish this stage of the life cycle, jack-up vessels are used to transport the removed items to shore, as well as workboats to transfer personnel who will support the operation. Substations are also removed by means of a reverse installation process (with the support of a heavy lift vessel), and the jacket foundations are also cut and removed. Removal costs depend on the removal duration per turbine (), the capacity of the jack-up vessel (), the vessels' day rate ... jack-up vessels) ... depends mainly ... account the rotor dia... ...ce cost per km^2 (), a... ...d to the total ma... ...e capacity of truck...

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Key assu... ...ded in Table 1. ... ...alculation of the ener... ...ived from efficiency factor of 90% was assumed accounting for losses due to wake effects, cable losses, and so on. The electrical system consists of 33 kV array cables and two offshore substations of 336 MW HVAC transmission system. Additionally, the transmission assets are connected to the onshore substation by three AC export cables of 132 kV.

Table 1. Baseline specifications.

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The total undiscounted CAPEX aggregating,,, and were estimated equal to 1,698.3 M£, while the mean undiscounted annual OPEX was found around 56.3 M£/year under the baseline scenario. Nevertheless, the above figures need to be adjusted for the inflation rate and the interest rate, in order to account for the time value of money considering that the service life of an OW farm is approximately 25 years. All costs were therefore discounted and inflated with the real discount rate () integrating the nominal cost of capital () with the inflation rate (), according to Fisher equation (Barro 1997)

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set of complex relationships was assumed for this study based on the observation of the relationship between the input global parameters and the output variables (dCAPEX, dOPEX, and LCOE), ensuring a realistic approximation and avoiding cases of overfitting which may reduce accuracy in the results. The outcome of the finite number of scenarios that were run in order to map the cost domain is listed in Table 2, where the effect of the variable variation on CAPEX, OPEX, and LCOE can also be observed. It was shown that wind turbine and wind farm capacity have the greatest effect on CAPEX, OPEX, and LCOE. In fact, doubling the while keeping the rest of the variables stable results in 14%, 5.2%, and 5.8% decrease in the respective investment performance indicators; the corresponding effect of resulted in 77%, 92.3%, and −2.4% variation from the baseline case. The next most impactful variable on LCOE proved to be the distance from port.

Table 2. Results from the application of the model to a number of scenarios.

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Once the most appropriate regression expressions were determined, a set of overall relationships were developed for each of the dependent variables, and the nonlinear coefficients were estimated through application of the maximum likelihood method for a predetermined shape of the target equation. The analysis also returned the overall value for the regression coefficients, providing an indication on the overall quality of fit of the quantities considered. Based on the above, the following three expressions are proposed, considering the most up-to-date information and high-fidelity cost modelling structure in order to link the macro variables, namely (MW), WD (m), D (km), and (MW) to the OPEX, CAPEX, and LCOE figures.

(4)

(5)

(6)

The R^2 for each of the expressions are 0.986, 0.999, and 0.983, respectively, denoting a satisfactory fit to the original data. Further, the data for the independent variables for the different scenarios were used as predictors using the regression coefficients, and the average value of the absolute errors that were measured in each case were 1.62%, 0.83%, and 0.82%. Finally, a series of separate test scenarios were run in order to test the performance of the model while interpolating, and the results are summarized in Table 3.

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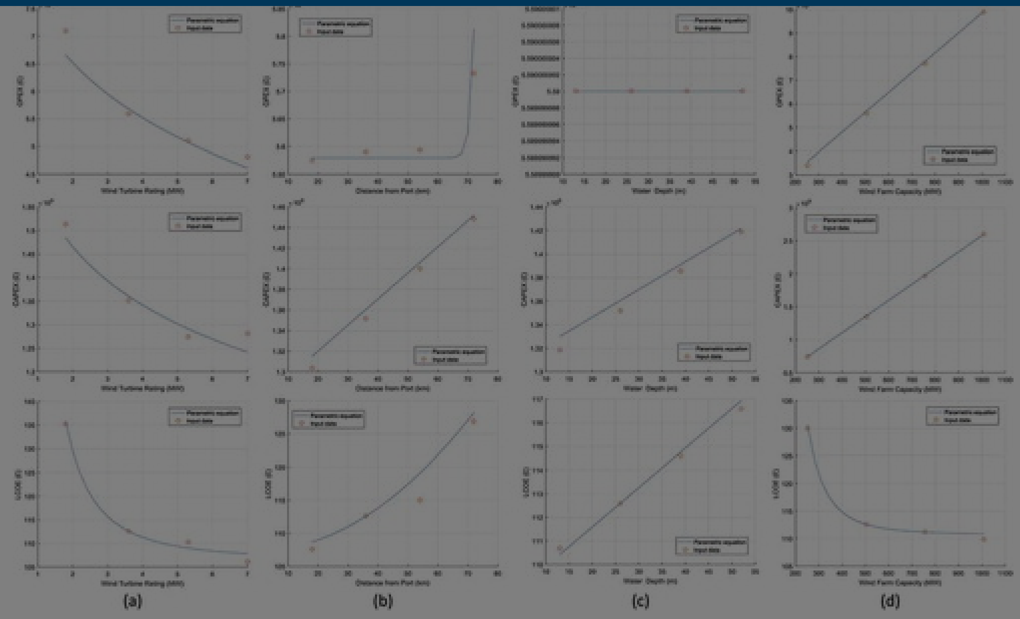

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Increase in the wind turbine rating results in an inverse exponential reduction in all three costs: CAPEX and OPEX due to the fact that less units need to be installed and maintained, and LCOE due to the reduced costs and increased expected power production. Distance from shore increases CAPEX linearly, while OPEX and LCOE increase exponentially. Increase in water depth does not affect OPEX, while it results in almost a linear increase in CAPEX and LCOE mainly due to the additional cost of the foundation and support structure as well as installation. Finally, increase in total wind farm capacity increases proportionally the amount of OPEX and CAPEX, while presents an inver ating due to the high uld be noted th polation of values fo nd lower limits in nge would introduc set of initial simulati

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high-fidelity cost simulations and regressions of the results. Further, this article characterizes the effect of these variables on CAPEX, OPEX, and LCOE. It was shown that wind turbine and wind farm capacity have the greatest effect on CAPEX, OPEX, and LCOE. A future expansion of the model could potentially include more variables, so as to increase the accuracy of results, such as the interest rate which has a considerable effect on LCOE and on the discounted values of capital and operational costs. Further, the inclusion of the wind resource of the installation site could potentially improve the energy output prediction and hence, provide a better informed expression for LCOE; while the inclusion of the soil conditions, aerodynamic, and wind and wave loads at the installation site would increase the accuracy of the production and acquisition cost of the foundations and wind turbines, leading, however, to more complex relationships requiring more input data.

The high-level expressions developed in this work are expected to assist investors, researchers, and other stakeholders to derive initial estimates for wind farm projects based on global variables within the applicability range as defined above. Additionally, it should be highlighted that results from the above expressions should be treated with caution as input data have been adopted from wind farms mainly installed in North Europe, since no data currently exist for the USA or Asian OW farms.

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