Energy Sources, Part B: Economics, Planning, and Policy ›
Volume 13, 2018 - Issue 5

Original Articles

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

Anastasia Ioannou, Andrew Angus & Feargal Brennan

Pages 281-290 | Published online: 04 May 2018

Cite this article https://doi.org/10.1080/15567249.2018.1461150 Check for updates

ABSTRACT

Installed ... cade, with
deploym... ngs within
new farr... e overall
cost of w... nt
investm... ions for
capital ... re
deve... distance from
port (D), ... ped through
a series ... are then
generali... ations for a
typical o... published
cost figu... ories of

expressions will be particularly useful for the preliminary assessment of available deployment sites, offering cost estimates based on global decision variables.

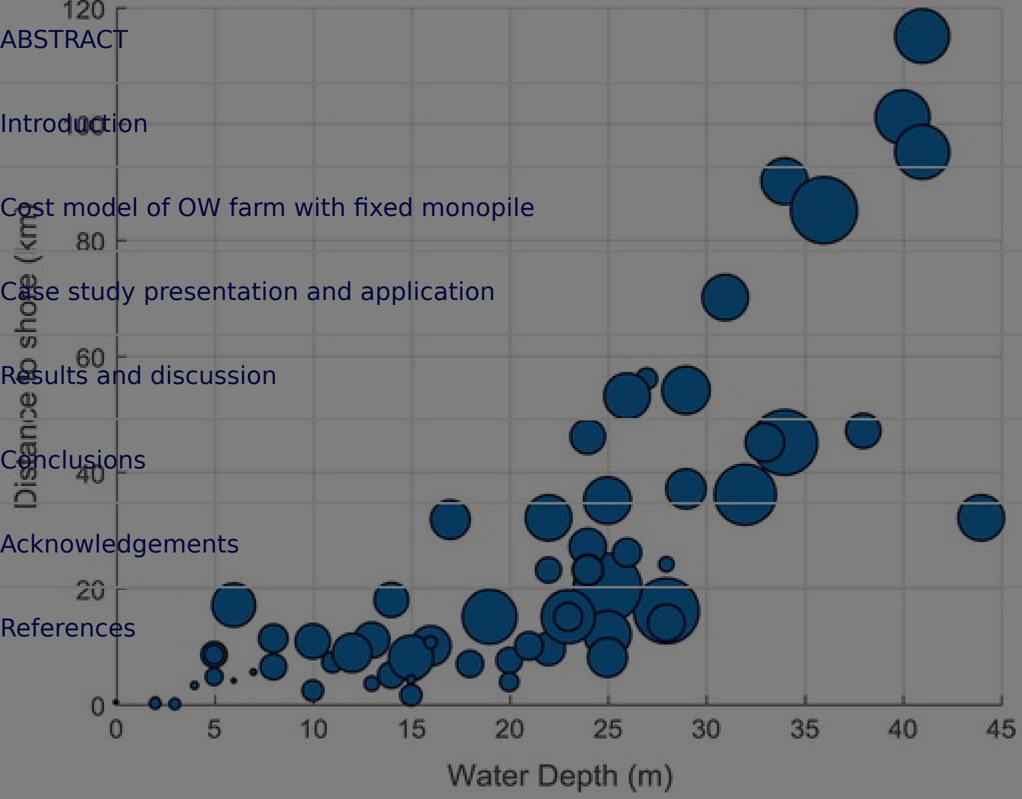
KEYWORDS: CAPEX LCOE nonlinear regression offshore wind farm OPEX parametric expressions

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 processed data from commissioned wind farms with respect to deployment depth, distance from shore, and wind farm capacity, while Figure 2 shows the increase in installed wind turbine ratings from 1995 to 2017 based on data from 4C Offshore 2017.

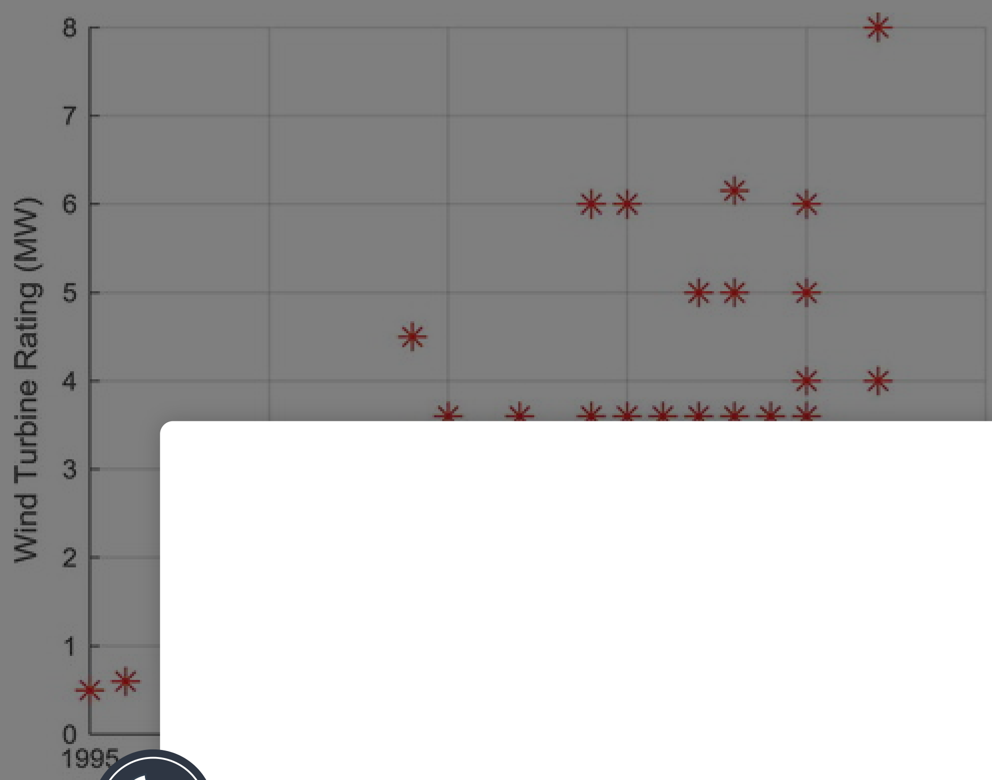
Figure 1. Water depth vs. distance to shore vs. wind farm capacity.

In this article



Display full size

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



Display fu

Referenc … en limited to date wit … he industry and its s … ever, the

In this article

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 literature, while where such equations were not available, most recent data were gathered in order to model specific costs.

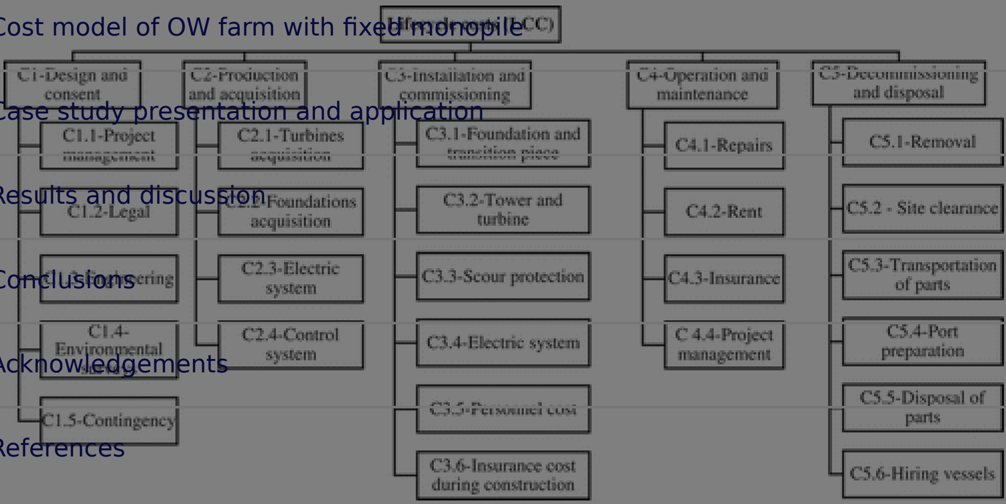
Cost m

The mai ... shed and
further c ... Figure 4, the
cost mo ... he model,
the r ... yed. The life-
cycle pr ... l consent
(C_1), pro ... ation and
mainten ... scheme
adopted ... The Crown
Estate 2

In this article

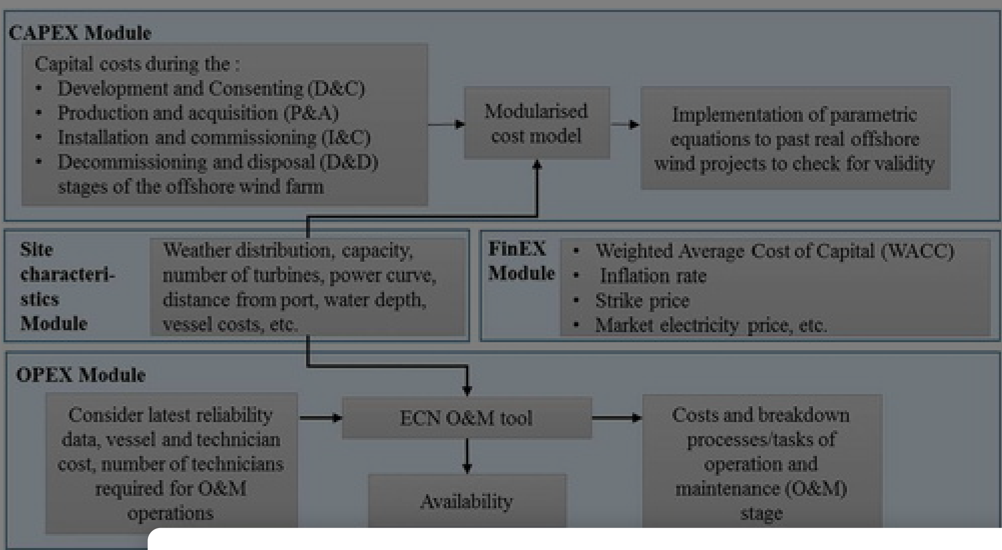
(1)

Figure 3. Breakdown of life-cycle costs.



Display full size

Figure 4. Integrated cost model structure.



Display ful

The desi … mental survey (… The costs of this sta …) according to Sh … and marine life in th … f data.

The proc … owing: the acquisiti … e control system (… urbine

In this article

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). Although installation usually takes place during spring and summer time in order to avoid adverse weather conditions, they still play an important role to activities taking place offshore (Kaiser 2009); hence, for estimating the final installation cost of the wind farm, a v … d also by other au … 2). Therefor … ents of the wind far … oad capacity and diffe … t.

The … ed into the repai … The estimati … Centre of the Netherla … et al. 2011), w … and unplann … 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 (), the number of vessels (workboats, heavy lift vessels, SOVs, and jack-up vessels) (), and the cost of technicians (). As such, . The site clearance cost depends mainly on the area of the wind farm, which can be calculated by taking into account the rotor dia [...] ce cost per km^2 (), a [...] d to the total ma [...] e capacity of truck [...]

Case [...]

Key assu [...] ded in Table 1. [...] alculation of the ener [...] ived from

In this article

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.

Display Table

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)

(2)

where was assumed equal to 8.81% (BVGA 2015) and 2.5%. Further, the levelized cost of energy (), which estimates the net present value of the unit cost of electricity produced over the lifetime of the OW asset, can be calculated as

(3)

where (
decomm ... ove into
consider ... ed total
OPEX () ... s conform
well with ... mmissioned
in 20 ... 3.8%).

The para ... ly, the wind
turbine ... with the
OPEX, C ... from a
number

In this article

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.

Display Table

Results and discussion

Based on the data presented in Table 1, which illustrate the results of the different scenario … ables (, , D, and) wa … gression expressi … wed for a series of … ent these trends n … he different scenari … as found from … ables were better fi … nt from water de … tions. Accordir … ynomial equation … lly, for P_{WF}, linear … he LCOE

In this article

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.

Table 3. Testing scenarios and results produced by model and parametric expressions.

Display

Followin ced and are

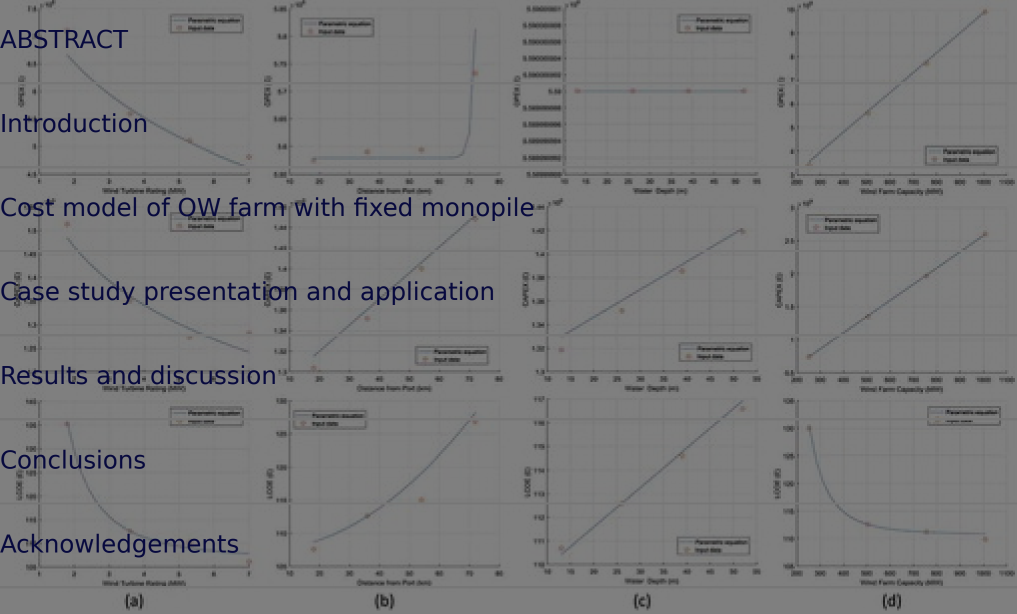
presente ables to the

depe

Figure 5. distance

from por

In this article



Display full size

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 inverse exponential reduction trend to LCOE for the given wind turbine rating due to the higher energy production and the reduced costs per wind turbine. It should be noted that the applicability range of these equations yields mainly for interpolation of values fo ... nd lower limits in ... nge would introduc ... set of initial simulati

Con

As the O ... s of wind farm dev ... bility of different ... king wind turbine ... ith the ... f

In this article

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.

Acknowledgments

This work was supported by grant EP/L016303/1 for Cranfield University and the Universi ne Structur d Physical Sciences

Refer

1. 4C Off
http://
Goog

In this article

2. Barro, Robert J. (1997), Macroeconomics (5th ed.), Cambridge: The MIT Press, United States of America, ISBN 0-262-02436-5.
Google Scholar

3. BEIS. 2016. Electricity generation costs. Accessed November, 2016. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/566567/BEIS_Electricity_Generation_Cost_Report.pdf.
Google Scholar

4. BVGA. 2010. A guide to an offshore wind farm, BVG associates on behalf of the crown estate. www.thecrownestate.co.uk/guide_to_offshore_windfarm.pdf.
Google Scholar

5. BVGA. 2015. DECC offshore wind programme – simple levelised cost of energy model. Revision 3–26/10/2015. http://www.demowind.eu/LCOE.xlsx.
Google Scholar

6. Carroll, J., A. McDonald, and M. David. 2016. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy 19 (6):1107–19. doi:10.1002/we.1887.
Web of Science ® | Google Scholar

7. The Crown Estate. 2010. A guide to an offshore wind farm. London, UK.
Goog

8. Dicora … essment of
invest … 043–51.
doi:10

9. EWEA … opean Wind
Energy
Goog

In this article

10. Kaiser, M. J., and B. F. Snyder. 2012. Offshore wind energy cost modeling – installation and decommissioning. London, UK: Springer-Verlag.
Google Scholar

11. Kaiser, M. J. 2009. The impact of weather on offshore energy losses. Energy Sources, Part B: Economics, Planning, and Policy 4 (1):59–67. doi:10.1080/15567240701421864.
Web of Science ® | Google Scholar

12. Kolios, A., V. Mytilinou, E. Lozano-Minguez, and K. Salonitis. 2016. A comparative study of multiple-criteria decision-making methods under stochastic inputs. Energies 9 (7):566. doi:10.3390/en9070566.
Web of Science ® | Google Scholar

13. Myhr, A., C. Bjerkseter, A. Ågotnes, and T. A. Nygaard. 2014. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. Renewable Energy 66:714–28. doi:10.1016/j.renene.2014.01.017.
Web of Science ® | Google Scholar

14. Regueiro-Ferreira, R. M., and S. Villasante. 2016. Recent development of offshore marine power in Galicia. Energy Sources, Part B: Economics, Planning, and Policy 11 (8):760–65. doi:10.1080/15567249.2013.787471.
Web of Science ® | Google Scholar

15. Sarker ... on costs for
turbin ...
doi:10 ...

16. Sha ... cost model
for off ... t 21
(7):96 ...

7. van de Pieterman, R. P., H. Braam, T. S. Obdam, L. W. M. M. Rademakers, and T. J. J. van der Zee. 2011. Optimisation of maintenance strategies for offshore wind farms. The Netherlands: Energy Research Center of the Netherlands.

Google Scholar

18. Wilkinson, M. et al., 2010. Methodology and Results of the Reliawind Reliability Field Study; European Wind Energy Conference, Warszaw, April 2010.

Google Scholar