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Stochastic Prediction of Offshore Wind Farm LCOE through an Integrated Cost Model

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Abstract

Common deterministic cost of energy models applied in offshore wind energy installations usually disregard the effect of uncertainty of key input variables – associated with OPEX, CAPEX, energy generation and other financial variables – on the calculation of levelized cost of electricity (LCOE). The present study aims at expanding a deterministic cost of energy model to systematically account for stochastic inputs. To this end, Monte Carlo simulations are performed to derive the joint probability distributions of LCOE, allowing for the estimation of probabilities of exceeding set thresholds of LCOE, determining certain confidence intervals. The results of this study stress the importance of appropriate statistical modelling of stochastic variables in order to reduce modelling uncertainties and contribute to a better informed decision making in renewable energy investments.

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Keywords: Offshore wind farm; probabilistic cost model; Monte Carlo simulation, levelised cost of electricity, stochastic inputs

1. Introduction

Sources of uncertainty affecting investment decisions for offshore wind energy projects, can be found in the amount of capital, operating, decommissioning and financing costs, as well as in technical aspects, such as the wind farm availability, aerodynamic, electrical array and other losses. Considering the continuous progress in the sector,

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these input variables are continuously updated, while they also vary significantly across different regions and water depths. These input variables can be, thus, better defined within a range and a probabilistic analysis can be employed, in order to derive probabilities of obtaining a certain amount of cost of energy.

A common measure to evaluate the life-cycle costs of generation of an energy project, as well as to compare different generation technologies is the levelized cost of electricity (LCOE), accounting for the installed capital cost, the annual operating expenses, as well as the annual energy production [1,2]. This metric allows to calculate the per unit of electricity generated cost, expressed in £/MWh. The contribution of the present study lies in the amplification of a deterministic cost of energy model of a representative offshore wind farm (OWF) [3] with the incorporation of uncertainty in key input parameters to derive representative ranges of LCOE values.

2. Costs of offshore wind farms

2.1. Capital and operating costs of an offshore wind farm

Capital expenditure comprises costs for building and commissioning of the plant, such as costs associated with the project development and consenting up to financial investment decision (FID), material and labor costs for the turbine, support structure, tower, foundations, array cables, installation, transmission build and insurance during the construction phase. Capital costs in the offshore wind energy industry have been increasing over the last decade owing to a number of reasons: installations in deeper waters and farther from shore bearing increased construction and installation costs, rise in turbine prices due to design improvements ensuring higher reliability levels (as a result of the higher awareness of technical risks), constraints in port and vessel availability, changes in global and national macroeconomic drivers, such as labor, increasing prices of commodities and energy and fluctuations in exchange rates impacting the capital cost structure. CAPEX values range across a number of sources as illustrated in Fig. 1a.

Operation and maintenance (O&M) costs account for ongoing costs needed to operate and maintain the plant. OPEX usually consists of fixed costs that do not depend on the plant uptime and variable costs that depend on the time the plant operates. Operations mostly represent activities associated to high level management of the plant, such as remote and environmental monitoring, administration, marketing, insurance, payment of the rent and other back office activities. Maintenance is the task that bears most of the effort, cost and risk, consisting of preventative (costs of proactive repairs based on condition monitoring systems) and corrective maintenance tasks (involving costs for reactive repair or replacement of equipment). A number of recent publications (Fig. 1b) have attempted to estimate ranges of operating costs for offshore wind installations either based on historical data of installed projects, or through publically available data and direct surveys of project developers [4, 5].

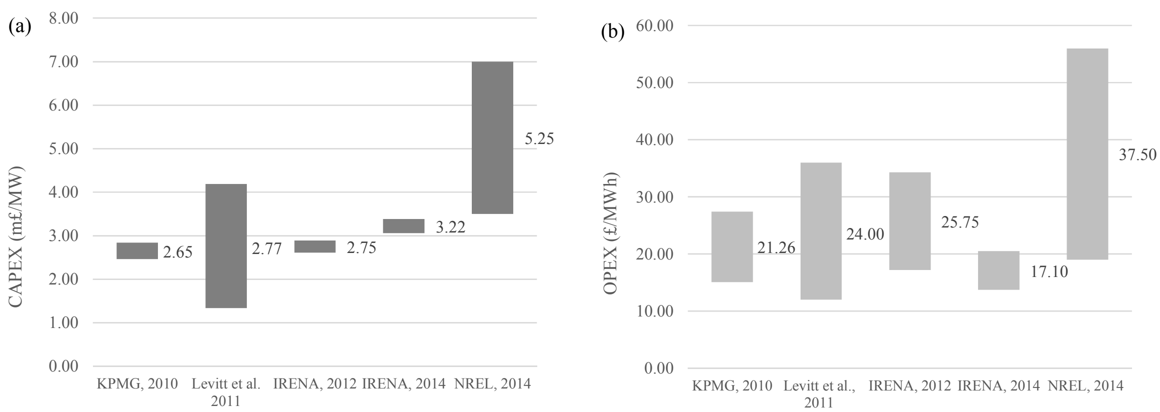

Fig. 1. (a) Range and average values of capital costs (£m/MW) in existing literature compiled and converted to 2015 £ currency; (b) Range and average values of operating costs (£/MWh) in existing literature compiled and converted to 2015 £ currency (Sources:[4–8])

3. Development of a cost model for offshore wind farms through life costing

3.1. Breakdown of cost model of the offshore wind farm

The breakdown and structure of the cost model have been adopted from the "Simple Levelised Cost of Energy Model" developed in the context of DECC Offshore Wind Programme [9]. The use of a broadly available simple cost model can increase the consistency and transparency of the calculations, considering that the purpose of the paper was not to provide a detailed cost model of an offshore wind energy investment; but, rather, to indicate how assessment and results would change if the deterministic analysis is expanded to take into account systematically the stochasticity of some uncertain financial and technical variables. The CAPEX and OPEX components of the OWF are depicted in Fig. 2.

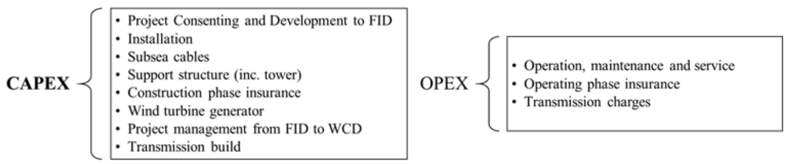

Fig. 2. OPEX and CAPEX break down (Source:[9])

3.2. Stochastic expansion – A Monte Carlo simulation approach

The deterministic cost model developed was expanded with the view to include stochastic parameters and to derive probabilities of exceeding set thresholds of the output variables at the same time assigning confidence intervals to the reported results. Towards this direction, the parameters of the cost model were divided into stochastic variables, design parameters and output variables.

Stochastic are the variables whose values are subject to variations and cannot be approximated with a deterministic value. Stochastic variables are assigned probability density functions (PDF) defining the frequency of occurrence of a value within a range. Evidently, not all parameters of the model are useful for a probabilistic analysis. Design parameters are the ones that need to be determined by the designer of the offshore wind installation and hence whose values cannot be approximated by a PDF. For the investigated case study, the wind farm design parameters are listed in Section 4.

In the present cost analysis, the variables that were considered as stochastic were: the CAPEX components, the operational expenses, the gross load factor, the wind farm availability, the aerodynamic array losses, the electrical array losses, other losses, the decommissioning cost as well as the discount rate. While the design parameters of the problem were the asset life, the type of the monopile, the capacity of the wind farm and the construction duration (years). Finally, LCOE was set as the output variable.

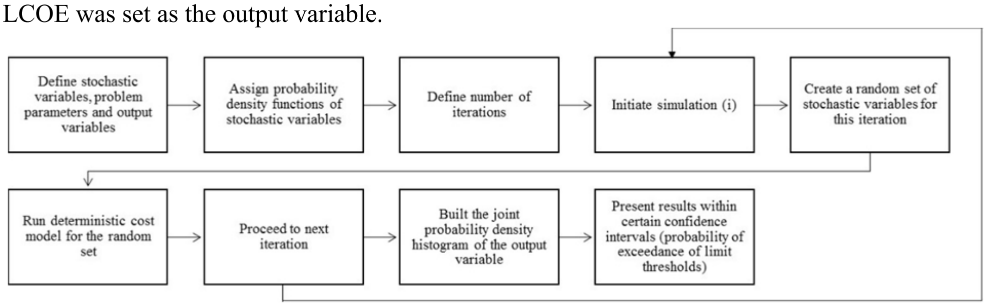

Fig. 3. Description of the simulation process

The proposed methodology (Fig. 3) has been modelled in Microsoft Excel, using Monte Carlo simulations to generate stochastic inputs, which are then undertaken in the @RISK extension.

4. Stochastic evaluation of LCOE through accumulated industry databases

4.1. Case study description, definition of stochastic variables, design parameters and output variables

The case study employed was based on the design (problem) parameters of a simple LCOE model developed by BVGA (as mentioned earlier) allowing for comparison against a base case scenario OWF with deterministic values. As such, the case study concerns an OWF of 500MW installed capacity, representing a typical UK Round 2 site installation (ranging from 65MW- 900MW). The wind farm design parameters of the cost model consider a distance to O&M port of 40km, average mean wind speed at 100m above mean sea level 9m/s, fixed monopile foundation type, 20 years of asset life, nameplate capacity of 6MW and construction duration to be 5 years.

As far as the unknown input variables are concerned, in the absence of detailed statistical data, accumulated data from different sources of literature were sought and their impact on LCOE was investigated with a view to highlight the importance of appropriate statistical modelling of stochastic variables in order to reduce modelling uncertainties. To stochastically model the uncertain variables, the CAPEX and OPEX ranges identified in literature (Fig. 1a and 1b) were used to estimate the coefficients of variation, in order to observe the impact of variation on the accuracy of results. In the case that real data are available through operators' experience, the same process could be adopted, following distribution fitting of the real data or estimates with determined confidence levels.

4.2. Determination of probability density functions of stochastic variables

Initially, the ranges of values from literature were considered to follow a normal probability distribution. Based on this assumption, and for given minimum, maximum and mean data values for operating and capital costs (retrieved from literature), the standard deviations and hence the coefficient of variation values were estimated as shown in Table 1. It should be noted that non-normal distributions can accommodate relevant set of data.

Table 1. Standard deviation (σ) and coefficient of variation values (COV) derived from literature sources illustrated in Fig. 1a and 1b

	Capital costs (million £/MW)		Operating costs (£/MWh)	
	σ_CAPEX	COV	σ_OPEX	COV
KPMG, 2010	0.12	0.04	3.76	0.18
Levitt et al. 2011	0.87	0.32	7.30	0.30
IRENA, 2012	0.09	0.03	5.20	0.20
IRENA, 2014	0.10	0.03	2.07	0.12
NREL, 2014	1.07	0.20	11.20	0.30

The coefficient of variation values of capital and operating costs (summarized in Table 2) were used to estimate the standard deviations for each of the OPEX and CAPEX elements of the DECC cost model, respectively. The mean values, μ of the stochastic variables (adopted from the DECC cost model) are shown in the left side of Table 2. The rest of the unknown input variables (associated with energy generation and financial variables) were also approximated through normal distributions and standard deviations of 10% over their mean values.

4.3. Results

The base case deterministic LCOE value using the mean values of the unknown variables as listed in Table 2 was found to be 116.3£/MWh. Accordingly, the stochastic cost modelling was performed for the five (5) sets of standard deviations calculated in Section 4.2 through Monte Carlo simulation (MCS). Fig. 4 illustrates the generated joint probability distributions of LCOE values derived for all five (5) sets of data, while in Table 3 the resulting summary statistics are presented. LCOE1 calculation corresponds to data retrieved from KPMG (2010); LCOE2 to data from IRENA (2011) and so on (as shown in Table 3).

Table 2. Mean values and standard deviations of the stochastic variables (mean values are adopted from DECC cost model)

CAPEX: (£000s/MW)	μ
Project Consenting and Development to FID	160
Project management from FID to WCD	37
Construction phase insurance	41
Turbine (exc. Tower)	1117
Support structure (incl. tower)	467
Array cables	81
Installation	271
Transmission build	429
Construction contingency	244
OPEX: (£000s/MW/yr)	
Operation, maintenance and service	67
Operating phase insurance	15
Transmission charges	10

Energy generation	
Gross load factor (%)	Normal (μ=52.1%, σ=5.21%)
Wind farm availability (%)	Normal (μ =95.4%, 4.8%)
Aerodynamic array losses (%)	Normal (μ =9.0%, 0.09%)
Electrical array losses (%)	Normal (μ =1.0%, 0.1%)
Other losses (%)	Normal (μ =4.6%, 0.46%)
Decommissioning cost (£)	Normal (μ= 247000, σ=24700)
Financial variables	
Discount rate (%)	Normal (μ=8.9%, σ=0.89%)

Table 3. Summary statistics derived from the five (5) different data sets

(£/MWh)	LCOE 1	LCOE 2	LCOE 3	LCOE 4	LCOE 5
Input source	KPMG, 2010	Levitt et al. 2011	IRENA, 2012	IRENA, 2014	NREL, 2014
Min value	72.74	49.28	71.26	67.12	70.89
Max value	216.25	228.33	203.72	210.24	214.79
μ	117.91	117.92	117.93	117.92	117.92
σ	15.65	21.22	15.83	16.14	16.07

Unsurprisingly, the LCOE probability distribution associated with the highest COV is characterized by the highest standard deviation; hence, the highest variation in the results. Among the cases that were considered above, the one with the highest standard deviation is LCOE2 with σ=21.22 £/MWh (Table 3), represented in Fig. 4 by the dark grey coloured histogram. Conversely, the probability distribution with the steepest probability of occurrence peak and the lowest standard deviation (σ=15.65 £/MWh) corresponds to LCOE1 (light grey colour), which demonstrates a considerable concentration of results around the mean LCOE value. Fig. 4 illustrates the frequency histograms of the output variable (LCOE) with figures for the highest and lowest scatter datasets. In fact, for the lower scatter dataset (LCOE1), the 5% and 95% percentiles are presented with LCOE values of 94.7 and 145.7 £/MWh, respectively. For the latter values of LCOE, the corresponding percentiles for the highest scatter dataset (LCOE2) are 12.5% and 90.2%. Probability distributions of LCOE with intermediate scatter datasets are also included in Fig. 4 (i.e. LCOE 3, 4 and 5).

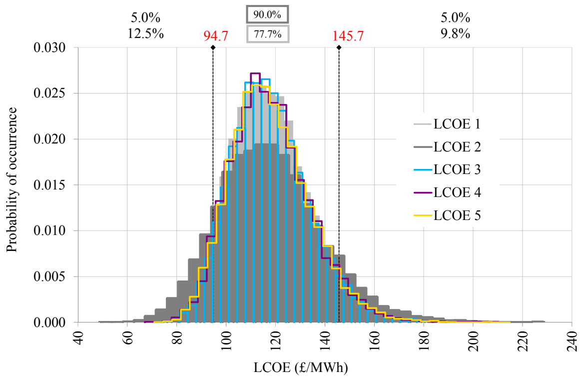

Fig. 4. Probability distributions of LCOE values for different sets of stochastic input variables (percentiles for two extreme scatter datasets)

4.4. Sensitivity analysis

The stochastic cost modelling was followed by a sensitivity analysis in order to investigate the impact of the unknown input parameters on the LCOE mean value. The baseline mean value was calculated around 117.9 £/MWh following the stochastic expansion of the cost model.

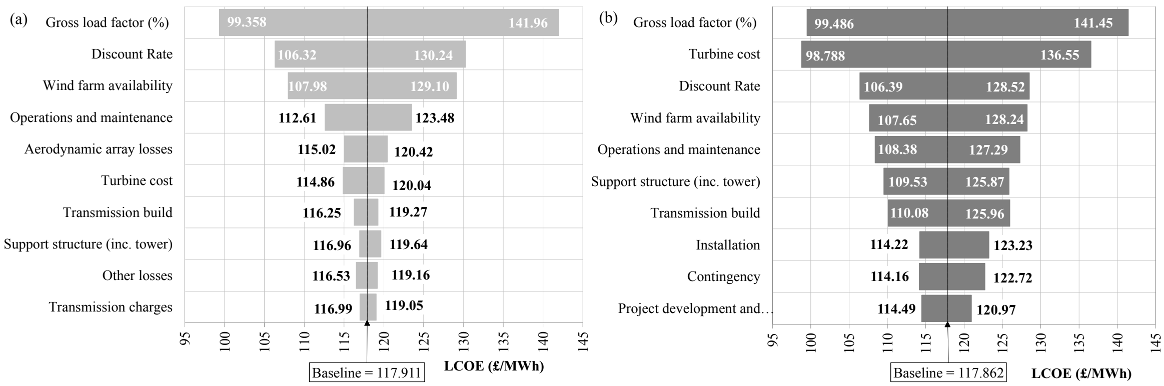

Fig. 5. Tornado diagram for (a) LCOE1 (lowest scatter dataset); (b) LCOE2 (highest scatter dataset)

Tornado diagrams for the lowest and highest scatter datasets are presented in Fig. 5a and 5b, respectively. As shown, the sensitivity of LCOE to the problem variables changes when different variabilities of stochastic parameters are considered. For instance, when wider ranges (higher scatter dataset) in turbine cost, O&M and support structure costs are considered, they appear to have a higher impact on LCOE than in the case of the lowest scatter dataset. Additionally, a few parameters such as installation, contingency and project consenting and development costs that are found to have considerable impact in the highest scatter dataset case, they are not as impactful on the LCOE for the lowest scatter dataset.

5. Conclusions

The LCOE models of renewable energy technologies are usually deterministic, generating results under specific conditions and assumptions. Nevertheless, some of the input parameters are uncertain or may change over time; hence, they should be better defined in a range. Examples are the different components of capital and operating costs, the discount rates as well as technical parameters such as the capacity factor. A probabilistic analysis intends to account for these uncertainties and to quantify their influence on the cost of energy. This study has extended a deterministic cost model to account for uncertainties associated with investing in an OWF.

Results illustrate that appropriate statistical modelling can significantly influence accuracy in prediction of LCOE. The proposed methodology suggests the application of probabilistic methods such as Monte Carlo simulation for the systematic modelling of uncertainties towards a better informed decision making framework in renewable energy investments. The framework developed for the extension of the deterministic method to account for stochastic inputs, can be further applied to other cost models and similar engineering problems.

Acknowledgements

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