Whole Life-Cycle Costing of Large-Scale Offshore Wind Farms

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1. Introduction

Offshore wind energy has experienced exponential growth worldwide over the past decade. The cumulative installed capacity of offshore wind power in the European Union (EU) has increased from 622 megawatts (MW) in the year 2004 to 8,045 MW at the end of 2014 [1], representing an annual growth rate of around %29. Along with the growth of the market for offshore wind energy, the investors and developers need to accurately evaluate the economic feasibility of future offshore wind projects. For this purpose, the capital expenditure (CAPEX), operating expenditure (OPEX) and the levelized cost of energy (LCOE) must be calculated by considering all the costs over the project's life cycle, from the pre-development to the decommissioning phase [2–5].

The concept of life cycle cost (LCC) analysis was first introduced by the U.S. Department of Defense (DoD) in the 1970s. Since then, it has been applied to a wide variety of projects in a range of industry sectors, including construction, energy, transport, manufacturing, and healthcare [6]. However, to the best of authors' knowledge, there is no universal and integrated framework for LCC modeling and analysis of offshore wind farms enabling to compare different projects on a same basis. Therefore, it is crucial to develop an enterprise cost analysis model not only to assist stakeholders in evaluating the performance of ongoing projects, but also to help decision-makers undertake long-term profitable investments and making offshore wind power generation price-competitive with onshore production as well as with other sources of renewable energy (e.g. geothermal, biomass).

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2. Approach

This paper presents a whole life-cycle cost (WLCC) analysis framework for large-scale offshore wind farms throughout the life span (~25 years). The developed model is based on a combined multivariate regression/neural network approach in which the cost experience of completed/ongoing projects provides a baseline for estimating the costs of future offshore wind projects. The key cost drivers of offshore wind projects are identified and a mathematical tool is proposed to evaluate the associated costs. In order to account for the time value of money, all future costs are discounted to their current value using an appropriate discount rate. For this purpose, the cash flows arising at different points in time are converted to a common reference point (i.e., present time) by using the following Net Present Value (NPV) formula [7]:

$$\mathrm{NPV}(d, N) = \sum_{t=0}^{N} \mathrm{C}_t / (1+d)^t \ , \qquad (1)$$

where C_t , d and N represent, respectively, the cash flow at time t, annual interest rate, and the number of years in which the investment takes place. Several critical factors such as geographical location and meteorological conditions, rated power and capacity factor of wind turbines, reliability of subassemblies, and availability and accessibility of transportation means are taken into consideration in cost analyses.

3. Main body of abstract

Based on the extensive literature review conducted for this study, the cost drivers of offshore wind projects mainly fall into five categories: pre-development and consenting (P&C), production and acquisition (P&A), installation and commissioning (I&C), operation and maintenance (O&M), and decommissioning and disposal (D&D) (see Fig. 1). These cost categories are then subdivided into their constituent elements and a database/spreadsheet is built for each cost element. In what follows, the cost categories are described in details:

2.1. Predevelopment and consenting (P&C)

The development of an offshore wind farm normally begins around five years before the time when the installation is executed. From the first idea to the start of the project, many procedures, studies and paperwork must be accomplished to ensure the technical/economical feasibility. These costs are related to project management (C_{projM}), legal authorisation (C_{legal}), the conducted surveys ($C_{surveys}$), engineering activities (C_{eng}) and contingencies ($C_{contingency}$). Thus,

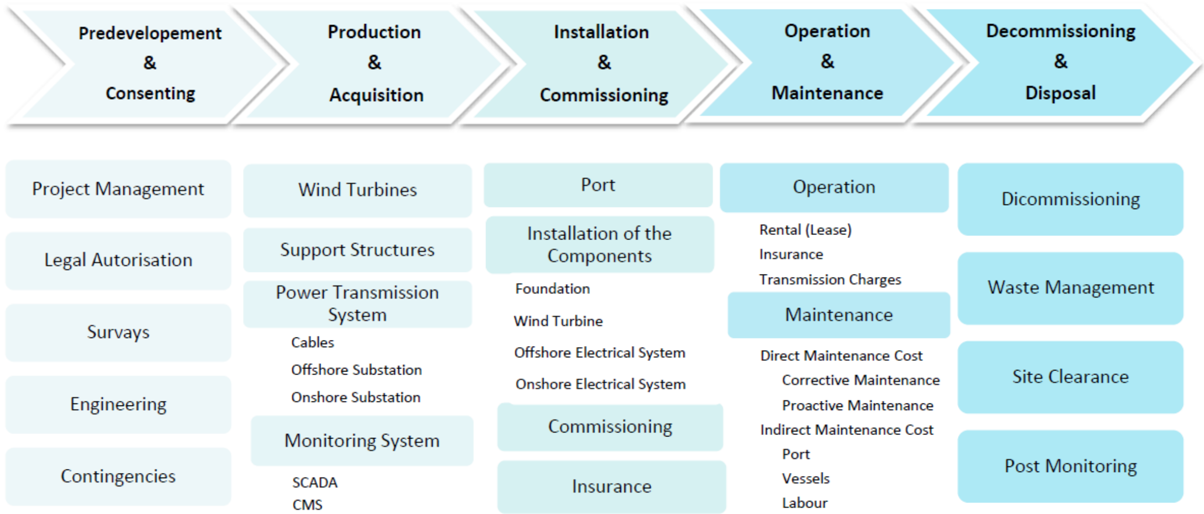

Figure 1. Cost Breakdown Structure (CBS) for offshore wind farms.

$$C_{P\&C} = C_{projM} + C_{legal} + C_{surveys} + C_{eng} + C_{contingency}. \quad (2)$$

2.2. Production and acquisition (P&A)

The production and acquisition (P&A) cost includes all costs associated with the procurement of wind turbines (C_{WT}), support structure or foundation (C_{SS}), power transmission system (C_{PTS}), and the monitoring system ($C_{monitoring}$). Then,

$$C_{P\&A} = C_{WT} + C_{SS} + C_{PTS} + C_{monitoring}. \quad (3)$$

2.3. Installation and commissioning (I&C)

The installation and commissioning (I&C) phase involves all activities related to the construction of offshore wind farms. The costs incurred at this stage include those related to port ($C_{I\&C\text{-}port}$), installation of the components ($C_{I\&C\text{-}comp}$), commissioning of the wind turbines and electrical system (C_{comm}), and the construction insurance ($C_{I\&C\text{-}ins}$). Hence,

$$C_{I\&C} = C_{I\&C\text{-}port} + C_{I\&C\text{-}comp} + C_{comm} + C_{I\&C\text{-}ins}. \quad (4)$$

2.4. Operation and maintenance (O&M)

The O&M cost of an offshore wind farm is divided into two parts, one for the operational expenses (C_O) and the other one for the maintenance expenses (C_M). Thus,

$$C_{O\&M} = C_O + C_M. \quad (5)$$

2.5. Decommissioning and disposal (D&C)

The decommissioning and disposal is the final stage of a wind project lifecycle, whose procedure is the reverse of the installation and commissioning (I&C) process. The wind turbines at the end of their anticipated operational life are decommissioned, the wind farm equipment depending on the chosen waste management strategy are either removed or recycled, the offshore site is cleared, and lastly, some post-decommissioning monitoring activities are performed. Then,

$$C_{D\&C} = C_{decom} + C_{WM} + C_{SC} + C_{postM}, \tag{6}$$

where C_{decom}, C_{WM}, C_{SC} and C_{postM} represent the costs associated with, respectively, decommissioning, waste management, site clearing, and post-monitoring.

4. Conclusion

The proposed whole life cost methodology is applied to an offshore wind farm consisting of 100 5MW wind turbines. The offshore wind farm is planned to be built in the United Kingdom's waters at 40 km far from shore and 45 m depth. The cash flows over the life cycle of the project are distributed as given in Table 1.

Table 1. Cash flow distribution over the life cycle [8].

Investment year	0	1	2	3	4	5	6-9	10-24	25
Operational year	-4	-3	-2	-1	0	1	2-5	6-20	21
Phase	Weighted investment distribution over the years (%)								
D&C	34	2	2	21.5	40	0.5	0	0	0
P&A	0	0.1	16.3	37.3	43.4	2.9	0	0	0
I&C	0	1.65	1.65	32.5	61.4	2.80	0	0	0
O&M	0	0	0	0	0	0	0	100	0
D&D	0	0	0	0	0	0	0	0	100

The LCC analysis is carried out in terms of three elements, namely, CAPEX, OPEX and LCOE, enabling the decision-makers to compare systematically the cost of different offshore wind projects. The CAPEX consists of the P&C, P&A and I&C costs, whereas the OPEX only includes the O&M costs. Table 2 and Table 3 report the cost estimates obtained for, respectively, CAPEX and OPEX of the baseline offshore wind farm. The CAPEX and annual OPEX are estimated at about £1,449m and £79.25m, respectively.

Table 2. Results for the CAPEX.

	Cost		% Contribution	
Cost element	Total ($\times 10^3$ £)	Per MW installed (£/MW)	Phase	CAPEX
P&C				

C_{projM}	41,724	83,448	20.6%	2.9%
C_{legal}	16,460.5	32,921	8.1%	1.1%
$C_{surveys}$	18,889	37,778	9.3%	1.3%
C_{eng}	1,127.5	2,255	0.6%	0.1%
$C_{contingency}$	124,618	249,236	61.4%	8.6%
$C_{P\&C}$	202,819	405,638	100.0%	14.0%
P&A				
C_{WT}	420,265.5	840,531	44.5%	29.0%
C_{SS}	365,465	730,930	38.7%	25.2%
C_{PTS}	156,478.5	312,957	16.6%	10.8%
$C_{monitoring}$	2,472	4,944	0.2%	0.2%
$C_{P\&A}$	944,681	1,889,362	100%	65.2%
I&C				
$C_{I\&C-port}$	14,689	29,378	4.9%	1.0%
$C_{I\&C-comp}$	265,769	531,538	88.1%	18.3%
C_{comm}	240	480	0.1%	0.1%
$C_{I\&C-ins}$	20,800	41,600	6.9%	1.4%
$C_{I\&C}$	301,498	602,996	100%	20.8%
CAPEX	1,448,998	2,897,996		

Table 3. Results for the annual OPEX.

	Cost		% Contribution
Cost element	Total ($\times 10^3$ £)	Per MW installed (£/MW)	OPEX
O&M			
C_{rent}	1,947.5	3,895	2.5%
$C_{O\&M-ins}$	7,280	14,560	9.2%
$C_{transmission}$	35,895	71,790	45.3%
$C_{M-indirect}$	5,033.7	10,067	6.3%
C_{ProM}	15,690.6	31,381	19.8%
C_{CM}	13,394.7	26,789	16.9%
$C_{O\&M}$	79,241.5	158,483	100%

5. Learning objectives

- Development of a realistic and accurate method for life cycle cost (LCC) analysis of large-scale offshore wind farms

- A parametric whole life cost (WLC) analysis model to identify the key cost drivers of offshore wind projects
- A cost analysis model based on a combined multivariate regression/neural network
- A cost breakdown structure (CBS) to identify various cost elements involved in five phases of offshore wind projects, namely, pre-development and consenting (P&C), production and acquisition (P&A), installation and commissioning (I&C), operation and maintenance (O&M), and decommissioning and disposal (D&D).
- The results of our analysis can be used as a guideline to reduce the costs of offshore wind projects, thanks to a better understanding of how key parameters influence the overall cost.

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