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Sensitivity analysis on the levelized cost of energy for floating offshore wind farms

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ABSTRACT

In this paper, a sensitivity analysis is performed on the levelized cost of energy (LCOE) for floating offshore wind farms (FOWFs). The analysis is carried out for three floating wind turbine concepts and three different offshore sites. At first, a methodology is presented for calculating the LCOE for a specific FOWF. Afterwards, the base LCOE values for each of the floating wind turbine concepts and sites are obtained. The sensitivity analysis includes over 325 input parameters that are studied in order to identify the ones that most influence the LCOE. Furthermore, a complementary sensitivity analysis is performed by varying the input parameters based on uncertainty ranges provided by each of the concept designers. This serves to obtain maximum and minimum LCOE variation limits and possible cost reduction potentials. It has been observed that the capital cost related parameters such as turbine, substructure and mooring system manufacturing cost as well as power cable cost are some of the most influencing parameters besides common parameters such as the discount rate and energy losses. The LCOE variation limits obtained in this study vary between 67 €/MWh and 135 €/MWh among the different concepts and offshore sites including offshore transmission costs.

1. Introduction

The offshore wind sector has reached a global installed capacity of more than 18.8GW at the end of 2017, of which nearly 84% is located in European waters. The majority of offshore wind farms in Europe are placed in the shallow waters of the North Sea (71%), Irish Sea (16%) and the Baltic Sea (12%) at an average water depth of 27.5 m [1]. Considering the abundant wind resources available offshore, the industry has the potential to continue to grow. However, the current technology based on bottom-fixed offshore wind turbines faces technical and economic limitations with increasing water depths [2]. Since shallow waters are scarce around the world, it becomes necessary to develop technical solutions to unlock the abundant wind resources of deep water areas [3]. Floating substructures for offshore wind turbines are a promising solution that has been under development in recent years. They possess lower constraints to water depths and soil conditions and can be applied from shallow to deep waters, thus allowing to take advantage of the full potential of offshore wind [2].

Several countries such as Portugal, Scotland and France have recognized this potential and have installed prototypes offshore. In addition, the first pre-commercial floating wind farm Hywind Scotland has been commissioned in 2017 and several more are projected to be constructed between 2018 and 2020 [4]. However, in order to reach commercial application, floating offshore wind turbines (FOWTs) need to solve not only the technological challenges faced by its bottom-fixed counterparts but also provide an economic alternative [3]. The levelized cost of energy (LCOE) is generally used to compare power generation technologies [5].

FOWTs possess the potential to provide competitive LCOE values by having the ability to harness the best possible wind resources without depth constraints and applying larger wind turbines to increase power generation [4]. Furthermore, the ability to mount the turbine on the floating substructure dockside and to tow the fully assembled structure by tug boats to the offshore site provides a significant potential for cost reduction along the life cycle, because expensive heavy lift jack-up vessels are avoided [2]. However, since only a few prototypes have been constructed so far, there is a lack of information on the LCOE of large scale floating offshore wind farms (FOWFs). Myhr et al. [6] have estimated in 2013 the LCOE for a number of different FOWT concepts made of steel and supporting a 5 MW wind turbine.

The findings have shown LCOE values ranging between 106.3 €/MWh and 287.8 €/MWh, which appear unfavorable in comparison to the cost of current bottom-fixed offshore wind farms [7]. Further research has been proposed to investigate possible cost reductions and to

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study the impact of different site conditions. Castro et al. [8,9] have developed in 2013 a methodology for the economic evaluation of FOWFs. The emphasis has been more on the modeling of the life cycle cost and less on the computation of the power generation in the system. For instance, the power losses due to the wake effect in the wind farm have not been considered. Ebenhoch et al. [10] have calculated in 2015 the LCOE of a FOWF based on a 4 MW monolithic Spar buoy concept. The LCOE obtained at 175.5 €/MWh has been significantly higher than estimated benchmark values for bottom-fixed structures in shallow waters [10]. The high LCOE value may has been due to the lack of information on the cost structure of FOWFs and several assumptions that have been made in the LCOE estimation. For instance, the operation and maintenance costs have been based on estimations for bottom-fixed offshore wind farms and the decommissioning cost has been considered as a percentage of the capital expenses. Hence, the advantages that FOWTs provide to reduce costs in these life cycle phases have not been taken into account [11]. Besides that, the energy generation and losses in the system have been based on gross load factors and efficiency rates from literature and have not been optimized for the specific location [12].

Following the work done and the proposal for further investigation, the aim of this paper is to provide a comprehensive LCOE calculation for state-of-the-art commercial scale FOWFs based on cost data provided by industrial and academic FOWT developers. The LCOE computation involves both a detailed life cycle cost and energy loss calculation of the system. Furthermore, three different FOWT concepts are analyzed, namely Semi-submersible, TLP and Spar, representing the most promising designs in the sector. Besides that, concrete as well as steel structures are included to represent both manufacturing materials. The calculation is performed for three different offshore locations to study the effect of metocean conditions on the LCOE. Moreover, FOWTs with a rated capacity of 10 MW are considered to represent the trend towards larger offshore wind turbines. A sensitive analysis of 325 input parameters is performed to identify the ones that most influence the LCOE, which provides an useful insight for developers and researchers for further cost reductions.

This paper is organized as follows. In Section 2, the methodologies are presented that are applied in the LCOE calculation and sensitivity analysis. In Section 3, a description is provided of the different FOWT concepts that are considered as well as the offshore locations and the associated FOWF configurations. Section 4 presents the results of the LCOE calculation and the sensitivity analysis. A conclusion of the main findings is given in Section 5.

2. Methodology

This paper is partially based on the work performed in the LIFES50plus project [13]. Two of the four concepts studied in the project are considered in this analysis. However, a third concept has been added to represent the whole range of the main FOWT designs available in the market. The analysis is performed by using the tool FOWAT (Floating Offshore Wind Assessment Tool), which was developed within the project. A detailed description of the methodology and the tool is provided by Benveniste et al. [14]. However, an outline of the methodology is given next in order to provide the background for the rest of the paper.

2.1. Levelized cost of energy

The LCOE calculation is a method used to obtain the cost of one unit energy produced and is typically applied to compare the cost competitiveness of power generation technologies. The LCOE model sets in relation the life cycle costs (LCCs) to the electrical energy provided (E_{el}) as follows [5]:

$$LCOE = \frac{LCC}{E_{el}} = \frac{\sum_{t=1}^{n} \frac{CAPEX_0 + OPEX_t + DECEX_{n+1}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t + L_t}{(1+r)^t}}. \quad (1)$$

The LCCs include all costs occurring in the lifetime of the FOWF such as the capital expense (CAPEX), the cost during the operation and the maintenance phase (OPEX) as well as the decommissioning expense (DECEX) at the end of lifetime [12]. CAPEX includes the costs related to development, manufacturing, transportation and installation of the wind farm. These costs are also defined as investment costs since they occur at the beginning of the project before the wind farm starts to generate energy.

OPEX contains the costs related to operation and maintenance (O&M) activities during the lifetime of the project and DECEX represents the costs occurring at the end of the lifetime for the decommissioning of the wind farm [12]. The total LCCs are obtained as the sum of all phases and as shown in Eq. (2) [14].

$$LCC = C_{Dev} + C_{Manuf} + C_{Transport} + C_{Instal} + C_{O\&M} + C_{Decom} \quad (2)$$

The development phase (C_{Dev}) includes all activities related to the initial development and design of the FOWF up to the point at which the official orders for production and purchasing are made [15]. This first phase is highly important for the projects outcomes since a well-planned design and schedule will enable a construction on time and with low added costs [16]. The development costs are considered in the LCC calculation as a percentage of the CAPEX. The manufacturing cost (C_{Manuf}), as defined in Eq. (3), includes the expenses for either the acquisition or production of each of the components of the FOWF such as the turbines, floating substructures, anchor and moorings, substations and power cables [8].

$$C_{Manuf} = C_{Turb} + C_{Substruct} + C_{Anchor} + C_{Mooring} + C_{Substation} + C_{Cable} \quad (3)$$

Transportation is considered between the fabrication site, the assembly port and the offshore site. The total transportation cost ($C_{Transport}$) is dependent on vessel specific parameters such as the day rate and fuel consumption, the rental time and usage of the vessel as well as mobilization and demobilization cost [17]. No transportation is considered for delivering the components from the supplier to the port, because this cost is included in the purchasing price. However, costs accounting for port activities such as the utilization of cranes and auxiliary means as well as the lease of area for storage and loading purposes are considered [18]. The total installation cost (C_{Instal}), as defined by Eq. (4), consists of the individual cost for the installation of the offshore turbine and the floating substructure ($C_{Turb\&FS_{instal}}$), the pre-installation of the anchor and mooring system ($C_{A\&M_{instal}}$) as well as the inter-array and export cable laying ($C_{IAC\&EX_{instal}}$). Besides that, the offshore and onshore substation cost ($C_{Subst_{instal}}$) are also considered in the installation phase as well as the commissioning ($C_{Commission}$) of the complete wind farm [14].

$$C_{Instal} = C_{Turb\&FS_{instal}} + C_{A\&M_{instal}} + C_{IAC\&EX_{instal}} + C_{Subst_{instal}} + C_{Commission} \quad (4)$$

The installation costs of each component are based on the vessel used for the installation as well auxiliary means and divers [17]. The O&M begins after the commissioning of the FOWF and the associated costs occur annually. The operation expenses include, for example, insurances, transmission charges and leases [16]. The maintenance is used to ensure a high availability of the FOWF and to reduce the downtime. It includes preventive and corrective maintenance. Preventive maintenance cost covers all activities that aim to avoid a failure of a machine such as inspections and replacements of wear parts or lubricants. An accurate planning of the maintenance activities is crucial to limit maintenance costs and prevent breakdowns of the machines. Corrective maintenance, on the other hand, responds to the failure of a component of the wind farm. In contrast to preventive maintenance,