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Sensitivity analysis of floating offshore wind farms

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ABSTRACT

The future of offshore wind energy will be in deep waters. In this context, the main objective of the present paper is to develop a sensitivity analysis of a floating offshore wind farm. It will show how much the output variables can vary when the input variables are changing. For this purpose two different scenarios will be taken into account: the life-cycle costs involved in a floating offshore wind farm (cost of conception and definition, cost of design and development, cost of manufacturing, cost of installation, cost of exploitation and cost of dismantling) and the most important economic indexes in terms of economic feasibility of a floating offshore wind farm (internal rate of return, net present value, discounted pay-back period, levelized cost of energy and cost of power). Results indicate that the most important variables in economic terms are the number of wind turbines and the distance from farm to shore in the costs' scenario, and the wind scale parameter and the electric tariff for the economic indexes. This study will help investors to take into account these variables in the development of floating offshore wind farms in the future.

1. Introduction

The new strategy of the European Union, the objective 2020, envisages that renewables will contribute to 20% of Europe's energy consumption by 2020 [1]. This objective is one of the mean reasons for researching and developing in the offshore energy field in the near future [2,3].

In terms of wind energy, while onshore wind farms have made good progress in the last few decades, the availability of onshore sites is decreasing [4]. Therefore, offshore wind energy is being looked upon as an option for clean energy generation in Europe [5].

Floating offshore wind farms are viewed as the first step in marine energy development, because the offshore wind resource is particularly abundant compared to other types of energy, such as waves [6] or currents [7].

There are two main types of devices offshore wind energy [8]: fixed [9] and floating [10–12]. The first ones are mainly located in shallow waters [13] and the second ones should be installed in deep waters (more than 60 m) [14]. Nowadays, all the offshore wind farms installed are fixed and they are mainly located in the North Sea and the Baltic Sea [15]. In addition, the 74% of the fixed structures are monopiles, followed by gravity based foundation (16%) and jackets (5%) [16]. However, the 70% of the world is composed by deep waters [17], which makes the future offshore wind devices tend to be floating substructures, as the semisubmersible WindFloat in Portugal [18] or the spar Hywind in Norway [9].

In the context of floating offshore wind turbines, there are a wide variety of technical developments. Nevertheless, three main concepts can be taken into account: semisubmersible platforms (Tri-floater [19], WindFloat [20], WINDFLO [21], Quadruple floater [13], Pillbox Floater [13], ITI Energy Barge [22,23], Vertiwind [24], WindSea [25]), Tensioned Leg Platforms (TLP) (MIT TLP [22,23], Diwet [26], TLB [27], SOF [28]) and spar platforms (Hywind [23,29], OC3-Hywind [22], Njord [30], Deep Wind [31], Sway [32], FVAWT [33], SeaTwirl [34]). However, the future of all these technologies will be based on their economic feasibility. In this context, it will be of utter importance to analyse the economic aspects of floating offshore wind farms [35,36].

Floating offshore wind platforms have benefits such as the better offshore wind resource or the reduced visual onshore impact [9].

Issues such as costs [37], the most feasible electric tariff [38], the levelized cost of energy (LCOE) [9] or the life-cycle cost have been developed in other previous articles. In this sense, the life-cycle process can be defined modifying the recommendations of IEC 60300-3-3:2004 [7]. Therefore, the main phases of the life-cycle of a floating offshore wind farm are: conception and definition, design and development, manufacturing, installation, exploitation and dismantling [37,8,39].

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Nowadays, the main difficulties are their high capital and operating expenditures (CAPEX and OPEX) [9]. However, the most important variables and their influences on these economic aspects have not been analysed. In addition, these conditioning issues should be taken into account before the installation of a floating offshore wind farm. This is the main reason why this paper has been developed.

The main objective of the present paper is to develop a sensitivity analysis of a floating offshore wind farm. It will show how much the output variables can vary when the input variables are changing. For this purpose two different scenarios will be taken into account: the life-cycle costs involved in a floating offshore wind farm (cost of conception and definition, cost of design and development, cost of manufacturing, cost of installation, cost of exploitation and cost of dismantling) and the most important economic indexes in terms of economic feasibility of a floating offshore wind farm (internal rate of return, net present value, discounted pay-back period, levelized cost of energy and cost of power). Results indicate that the most important variables in economic terms are the number of wind turbines and the distance from farm to shore in the costs' scenario, and the wind scale parameter and the electric tariff for the economic indexes. This study will help investors to take into account these variables in the development of floating offshore wind farms in the future.

2. Methodology

2.1. Economic aspects

The sensitivity analysis of floating offshore wind farms is the outcome of its economic analysis. In this sense, the economic analysis is composed of the calculation of all the costs considered in the study, its the Net Present Value (NPV), its Internal Rate of Return (IRR), its Discounted Pay-Back Period, the Levelized Cost Of Energy and the Cost of Power [4].

The method proposed to calculate the costs involved in a floating offshore wind farm is based on its life-cycle. In this context, the life-cycle of a floating offshore wind farm is composed of six main steps: conception and definition, design and development, manufacturing, installation, exploitation and dismantling. Therefore, the Life-cycle Cost System of a Floating Offshore Wind Farm ($\mathrm{LCS_{FOWF}}$) is based on Eq. (1) [40]:

$$\mathrm{LCS_{FOWF}} = C1 + C2 + C3 + C4 + C5 + C6 \tag{1}$$

Each of the costs defined in Eq. (1) consider the life-cycle phases of the farm taken into account. In this sense, $C1$ is the cost of conception and definition, $C2$ is the cost of design and development, $C3$ is the cost of manufacturing, $C4$ is the cost of installation, $C5$ is the cost of exploitation and, finally, $C6$ is the cost of dismantling. In addition, although these costs can be subdivided in their respective sub-costs to deeply analyse their value, it is not the objective of the present paper.

The total cost is dependent on the input variables which have been considered for the sensitivity analysis:

$$\begin{aligned}\mathrm{LCS_{FOWF}} = f\big(&H_{\mathrm{w}}, u_{\mathrm{current}}, T_{\mathrm{w}}, c_{\mathrm{w}}, k_{\mathrm{w}}, D, d, d_{\mathrm{construction}}, d_{\mathrm{storage}},\\ &\mathrm{NWT}, P_{\mathrm{kW\,h}}, \mathrm{ND_{WT}}, \mathrm{ND_{lines}}, D_{\mathrm{WT}}, D_{\mathrm{tower}}, h_{\mathrm{tower}}, C_{\mathrm{MW}}, C_{\mathrm{DL}}, K_{\mathrm{ba}},\\ &A_{\mathrm{mean\ shipyard}}, \mathrm{AM_{mean\ shipyard}}, \mathrm{NPY}, K_{\mathrm{financing}}, r, C_{\mathrm{steel}}\big)\end{aligned} \tag{2}$$

Considering the total cost of the life-cycle of the floating offshore wind farm, the Net Present Value, the Internal Rate of Return, the Discounted Pay-Back Period, Levelized Cost Of Energy and Cost of Power [41] can be determined.

The Net Present Value (NPV) of a project is a way of considering costs (cash outflows) and revenues (cash inflows) together [42]. In this case, the revenues are given by the electricity price and the offshore wind resource, and the costs considered are the total investment cost previously defined ($C1; C2; C3; C4; C6$) and the operational costs ($C5$) [43]. It is calculated considering Eq. (3):

$$\mathrm{NPV} = -F_0 + \frac{F_1}{(1+r)^1} + \frac{F_2}{(1+r)^2} \ldots + \frac{F_n}{(1+r)^n} \tag{3}$$

Being:
- F_n: net cash flow in year n.
- n: analysis period.
- r: anual discount rate.

The Internal Rate of Return (IRR) for an investment that has a series of future cash flows ($F_0, \ldots, F_n$) is the discount rate calculated when the NPV is equal to zero [42].

$$0 = -F_0 + \frac{F_1}{(1+r)^1} + \frac{F_2}{(1+r)^2} \ldots + \frac{F_n}{(1+r)^n} \rightarrow r = \mathrm{IRR} \tag{4}$$

The discounted pay-back period (DPBP) is the number of years necessary to recover the project cost of an investment while accounting for the time value of money [42].

The Levelized Cost Of Energy (LCOE) compares different technological alternatives which have different investment and time operations and which were located in the same place. The equation taken into account depends on the total cost of the floating offshore wind farm in the "n" period ($\mathrm{LCS_{FOWF}}$), which goes from the year 1 to the number of year of the life-cycle of the project (N_{farm}), and the capital cost of the project (r) (see Eq. (5)). The value of LCOE is in €/kW h.

$$\mathrm{LCOE} = \frac{\sum_{n=0}^{N_{\mathrm{farm}}} \frac{\mathrm{LCS_{FOWF}}_n}{(1+r)^n}}{\sum_{n=0}^{N_{\mathrm{farm}}} \frac{E}{(1+r)^n}} \tag{5}$$

Being:
- E: offshore wind energy produced (kW h) [44].

Finally, the cost of power (C_{power}) is calculated considering the total cost previously taken into account and the total power installed in MW, as Eq. (6) indicates. Its value can be a useful way to compare the general costs of different types of onshore and/or offshore renewable energy sources.

$$C_{\mathrm{power_{location}}} = \frac{\mathrm{LCS_{FOWF_{location}}}}{\mathrm{NWT} \times \mathrm{PWT}} \tag{6}$$

Being:
- NWT: Number of floating offshore wind turbines considered in the farm.
- PWT: Power of each floating offshore wind turbine.

2.2. Sensitivity aspects

The sensitivity analysis will show how much the output variables can vary when the input variables are changing.

Oracle Crystal Ball™ has been used to carry out the study, converting the spreadsheet in a laboratory, modelling uncertainty under different scenarios.

It has lots of uses in different contexts [45], including the creation of different types of graphs: tornado, radar, matrix and overlay plots, cobweb plots, amongst others. Several authors have before considered this software in many fields to develop a sensitivity analysis: life-cycle of green buildings [46], photovoltaic energy [47], electric feed-in tariffs [48] or repowering onshore wind farms [49]. In fact, a general approach of a sensitivity analysis of an offshore wind farm has been taken into account by Koukal et al. [50]. However, in order to our energy future development, it is important to develop this tool in the field of floating offshore wind energy, which is the main purpose of this paper.