Life-Cycle Cost of a Floating Offshore Wind Farm

Laura Castro-Santos

Abstract This chapter describes a general methodology in order to calculate the costs of a floating offshore wind farm. It is based on the analysis of its life-cycle cost system (LCS). In this sense, several phases have been defined: conception and definition, design and development, manufacturing, installation, exploitation and dismantling. The calculation of costs of each of these steps gives the total cost of a floating offshore wind farm. The method proposed has been applied to the particular case of the Galician coast, where a floating offshore wind farm could be installed due to the great offshore wind potential and the depth of its waters. Results indicate that the most important cost in the life cycle of a floating offshore wind farm is the manufacturing cost. It is due to the fact that the floating offshore wind platforms and the offshore wind turbines have a high cost. The methodology proposed can be used by investors in the future to know the real costs of a floating offshore wind farm.

Keywords Life-cycle cost · Floating offshore wind farm · Ocean energy

1 Introduction

Offshore wind energy is an emerging technology which can be subdivided into two main types of devices: fixed (tri-piles, monopiles, etc.) and floating [semisubmersible, spar and tensioned leg platform (TLP)]. Nowadays, fixed structures compose the offshore wind farms in the North Sea. On the other hand, floating offshore wind devices are new technologies, the study of which will be developed in the following years.

In this sense, it is important to know the life cycle of a floating offshore wind farm. It can be studied considering two views [1, 2]: environmental and economic. Nevertheless, this chapter will focus on the economic issue.

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The main objective of this chapter is to define a method to calculate all the costs involved in a floating offshore wind farm. It is composed of two main steps: the Economic Maps Tool (EMT) and the Restrictions Maps Tool (RMT). In addition, the EMT includes the models selection (MS), the technical study (TS), the maps of the costs (MC) and the maps of the economic indexes (MEI) [Net present value (NPV), internal rate of return (IRR), discounted payback period (DPBP), Levelized cost of energy (LCOE) and cost of power]. It is the first step in analysing a floating offshore wind location where a floating farm could be developed.

2 General Methodology to Calculate the Life-Cycle Cost of a Floating Offshore Wind Farm

2.1 Methodology

The method carried out for calculating the costs of a floating offshore wind farm is based on the phases of two different methods of life-cycle cost calculation [1, 2]: the environmental and the economic view. This new methodology will be named as life-cycle cost system of a floating offshore wind farm, LCS_{FOWF}, and it will be composed of several steps:

- **Economic Maps Tool (EMT)**.
- **Restrictions Maps Tool (RMT)**.

The EMT is supported by the following:

- ***Models selection (MS)***: MS defines each of the models which will be taken into consideration in the study according to offshore wind turbines, floating offshore wind platforms, mooring lines, anchors, electric system, installation, accommodation, maintenance, seabed and dismantling.
- ***Technical study (TS)***: TS consists in all the engineering calculation related to floating offshore wind energy platforms technology, electrical cables, mooring and anchoring dimensions and feasibility of mooring lines.
- ***Maps of the costs (MC)***: Considering MS and TS the total cost of a floating offshore wind farm can be calculated (LCS_{FOWF}).
- ***Maps of the economic indexes (MEI)***: All the economic indexes (NPV, IRR, DPBP, LCOE and Cost of power) are calculated considering the costs obtained in MC, the floating offshore wind energy production and the value of the electric tariff.

Results obtained from EMT will be processed with the RMT, which is developed using a geographic information system (GIS) software, the results of which are the allowed areas considering the geographical restrictions of the site.

Consequently, not only EMT results but also RMT results will be used to determine the resulting maps for a particular geographic case.

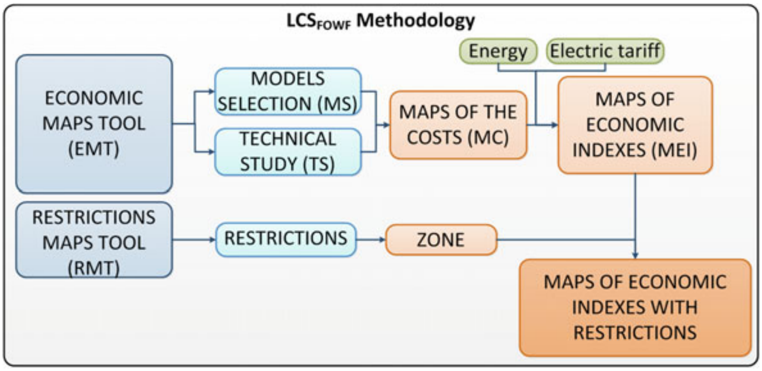

Fig. 1 General methodology

A detailed description of the model has been presented in [3]. A general scheme could be seen in Fig. 1 [4].

2.2 *Models Selection (MS)*

The MS takes into consideration all the models taken into account in the study. In this context, the variables whose costs are dependent on will be classified taking into account three criteria [5]: level 1 variables, level 2 variables and level 3 variables. Level 1 variables are dependent on the general characteristics of the floating offshore wind farm, for instance, wind scale parameter, wind shape parameter, depth, height of waves, electric tariff, distance from farm to shore, number of offshore wind turbines, etc. The second ones are dependent on the particular aspects of the floating offshore wind farm. They will be subdivided taking into account the main components of a floating offshore wind farm: offshore wind turbine, floating offshore wind platform, mooring, anchoring and electric system. Examples of this type of variables are power of wind turbine, diameter of wind turbine, cost per unit of wind turbine, etc. Finally, level 3 variables are independent of the characteristics of the farm. They are focused on the general constants (gravity, air density, sea water density, etc.) or variables dependent on the shipyard where the floating platform will be constructed (cost per hour of labour, salaries, etc.).

2.3 *Technical Study (TS)*

The TS consists in calculating all the dimensions that will be used to calculate the total cost of a floating offshore wind farm.

In this sense, the floating offshore wind energy platforms are defined to their main dimensions (weight, length, draft, etc.), but also the main characteristics of the electrical cables, anchoring and mooring.

Furthermore, the location where the floating offshore wind farm will be installed is defined considered its distance from shore, its depth, its offshore wind resource and its wave resource (period and height of waves).

2.4 Maps of the Costs (MC)

The IEC 60300-3-3:2004 [7] proposes several models to calculate the life-cycle cost. However, the present study will only take into account the model based on the life-cycle phases because it is the most representative of the whole process.

In this context, the categories of the life-cycle cost of a floating offshore wind farm are as follows [6–8]:

- Capital Expenditure (CAPEX): initial investment cost. These costs will be taken into consideration only once.
- Operational Expenditure (OPEX): operation or exploitation cost. These costs will be considered throughout the life cycle of the project.

If we apply this classification to the total costs of a floating offshore wind farm, the CAPEX will include the first four phases (conception and definition, design and development, manufacturing, installation) and the last phase (dismantling), and the OPEX will be composed by the phase 5 of exploitation, as Fig. 2 shows.

2.5 Maps of the Economic Indexes (MEI)

The maps of the economic indexes are based on obtaining the main variables on which the economic indexes are dependent on. These economic indexes will be NPV in €, IRR in %, DPBP in years, the LCOE in €/MWh and Cost of Power in

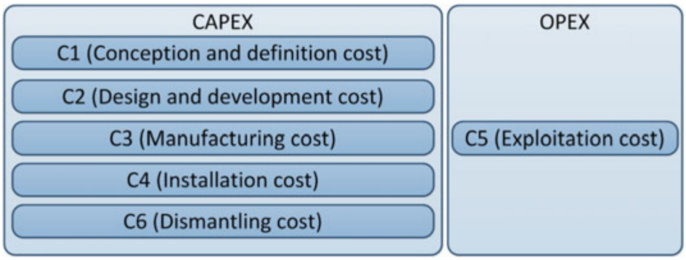

Fig. 2 CAPEX and OPEX components

M€/MW. However, this chapter does not include their calculation, which is taken into account in the next chapter.

2.6 Restrictions

It is important to know that phase MEI can have as a result a good location in economic terms, but not in terms of the real installation process of the floating offshore wind farm.

For instance, it can have a good IRR but it can be a navigation area, environmental area, seismic zone, electrical cables, etc., where laws do not allow the installation of the farm.

This is the main reason why the restrictions appear. Thus, the real locations can be selected to carry out the floating offshore wind farm. However, this chapter does not include this step.

3 Life Cycle of a Floating Offshore Wind Farm

3.1 Definition of the Life-Cycle Process

The life-cycle process has been defined modifying the recommendations of IEC 60300-3-3:2004 [7] because this normative is focused more on a product than on a process. Therefore, the main phases of the life cycle of a floating offshore wind farm are as follows:

- Phase 1: Conception and definition.
- Phase 2: Design and development.
- Phase 3: Manufacturing.
- Phase 4: Installation.
- Phase 5: Exploitation.
- Phase 6: Dismantling.

They are all shown in Fig. 3.

3.2 Breakdown Structure of the Process

The process breakdown structure establishes which are the main stages and substages of the process. A floating offshore wind farm is composed of five main

Fig. 3 Life cycle of a floating offshore wind farm

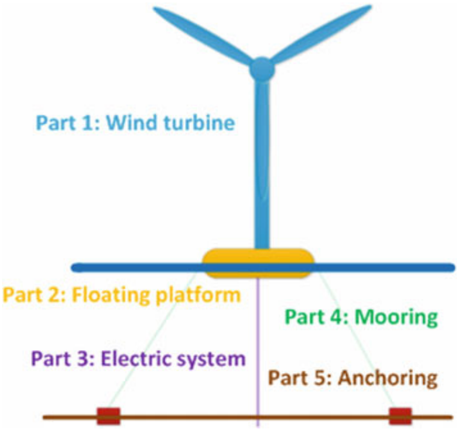

Fig. 4 Main components of a floating offshore wind farm

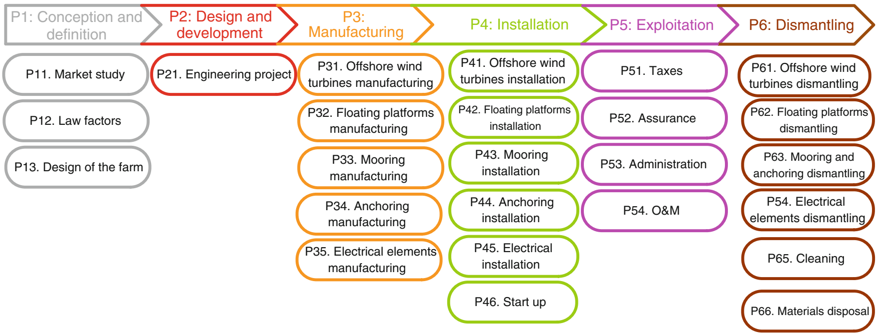

Fig. 5 Breakdown structure of a floating offshore wind farm

components (Fig. 4): offshore wind turbines, floating offshore platforms, moorings, anchorages and electrical elements.

In this context, the majority of the phases of the life-cycle process definition will be developed for each of these elements, as Fig. 5 shows.

3.3 *Initial Cost Breakdown Structure and Calculation of Costs*

3.3.1 Definition of the Cost Breakdown Structure

Initial cost breakdown structure (ICBS) of a floating offshore wind farm is based on the disaggregation of the main costs of its life cycle. In this context, the main costs

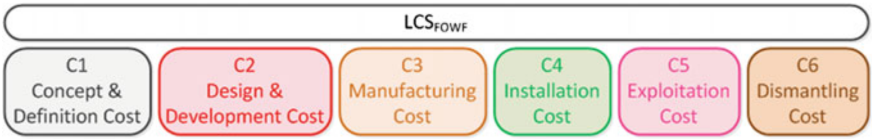

Fig. 6 Initial cost breakdown structure of a floating offshore wind farm

are (Fig. 6) 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 C6 is the cost of dismantling.

Therefore, the $\mathrm{LCS_{FOWF}}(k)$ could be formulated as [9]:

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

As Eq. (1) shows, the total cost will be a geo-referenced map of a floating offshore wind farm, because each k value is a point of the geography where the farm is installed. However, costs $C1$ and $C2$ are independent of the location k factor and constant, because they are mainly related to onshore activities.

In addition, in order to obtain their main dependences, each of these costs should be subdivided into sub-costs that should be analysed separately. The following sections are focused on developing each of these sub-costs. Nevertheless, in order to give a notion of the main dependences in costs, the following parameters could be considered [4]:

- Number of wind turbines.
- Power of wind turbines.
- Cost (in €) per MW of wind turbine.
- Mass of the floating platform.
- Mass of the wind turbine.
- Cost of steel necessary to build the floating platforms at the shipyard.
- Cost of direct labour at shipyard.
- Cost of direct materials at shipyard.
- Cost of no direct activities (management, office materials, amortization of the machines, etc.) at shipyard.
- Height and period of waves.
- Wind speed at anemometer height.
- Wind shape and wind scale parameters.
- Depth.
- Weight of anchoring and mooring.
- Anchoring and mooring cost per kilogram.
- Number of mooring lines.
- Cost per section of electrical cables.
- Number of electrical cables.
- Wind turbine diameter.
- Distance to shore.

- Grid and cable voltages.
- Distance to port.
- Distance to shipyard.
- Number, speed and fleet of vessels used in installation phase.
- Failure probability.

3.3.2 Conception and Definition Cost

The conception and definition cost takes into consideration studies, which have been taken in advance to develop the floating offshore wind farm. Aspects as the offshore wind resource or the environmental issues, which are very important to know the main location of the farm, have been considered. In this sense, three sub-costs have been taken into consideration: the market study cost (C11), legislative factors cost (C12) and the farm design cost (C13), as Eq. (2) shows. The market study cost considers the feasibility study, which has been developed to know if the farm is feasible. The legislative factor cost considers the taxes that the investor should pay in a previous phase. It is dependent on the country where the farm is located. The farm design cost considers aspects as the energy resource study or the seabed study.

$$C1 = C11 + C12 + C13 \tag{2}$$

3.3.3 Design and Development Cost

The design and development cost takes into account the engineering cost of the floating offshore wind farm. In this sense, the engineers should consider the number of floating offshore wind turbines which will be involved in the farm, the calculation of the offshore and onshore electric cables, the calculation of the offshore substation and the calculation of the moorings and anchors. This value has been calculated considering the number of wind turbines (NWT) and the power of each of them (PWT), as Eq. (3) shows:

$$C2 = f(\mathrm{NWT}, \mathrm{PWT}) \tag{3}$$

3.3.4 Manufacturing Cost

The manufacturing cost takes into consideration the manufacturing of each of the main components of a floating offshore wind farm: the offshore wind turbines manufacturing ($C31$), the floating wind platforms manufacturing ($C32$), the mooring manufacturing ($C33$), anchoring manufacturing ($C34$) and electric systems manufacturing ($C35$), as equation shows:

$$C3 = C31 + C32 + C33 + C34 + C35 \quad (4)$$

The cost of manufacturing the offshore wind turbines is dependent on the cost of each generator, the number of wind turbines and the power per unit of each wind generator. The manufacturing cost is based on the activity-based cost (ABC) proposed of a traditional shipyard, where the floating offshore wind platforms are constructed. In this context, the cost of materials, direct labour and the activities cost are the main parts in the calculation process of this manufacturing cost. The mooring manufacturing cost is dependent on the mass per metre of the mooring system, its length and the cost per kilogram of this mooring. In addition, the number of lines of mooring per floating platform and the number of floating platforms are also considered. The anchoring manufacturing cost is very similar to the mooring manufacturing cost, but taken into account the mass of the anchor and the price of the anchors per kilogram. Finally, the cost of manufacturing the electric system is dependent on the number of wind turbines, the number of electric cables, their length, the cost per metre of electric cable and the cost of the offshore substation.

3.3.5 Installation Cost

The installation cost is composed of the cost of installing the offshore wind turbine ($C41$), the cost of installing the floating offshore wind platforms ($C42$), the cost of installing the mooring and anchoring ($C43$), the cost of installing the electric system ($C45$) and the cost of the start-up, as equation shows:

$$C4 = C41 + C42 + C43 + C44 + C45 \quad (5)$$

The costs of installing the wind turbine and the floating platform are dependent on the shipyard or port operations, the transport of the wind turbine or the floating platform from the port to the farm and the offshore installation of the wind turbine or the floating platform. It is important to know that the cost of transporting the offshore wind turbines is included in the cost of transporting the floating platform when the transport process is carried out considering a tug which tows the platform from the shipyard or the port to the farm. The process of installing the mooring and the anchoring is carried out considering an anchor handling vehicle (AHV). Therefore, the cost is dependent on the direct labour cost per day, the cost of pumps and divers, the number of anchors or moorings considered and the number of wind turbines. Finally, the cost of installing the electric system takes into account the installation of the electric cables and the installation of the offshore substation. Therefore, variables as the cost of installing the electric cable, the metres of electric cables installed per day or the number of lines of wind turbines have been considered.

3.3.6 Exploitation Cost

The exploitation cost is composed of the assurance cost ($C51$), the business and administration cost ($C52$) and the operation and maintenance cost ($C53$), as Eq. (6) shows:

$$C5 = C51 + C52 + C53 \tag{6}$$

The assurance cost is dependent on the previous costs (conception and definition, design and development, manufacturing and installation). The business and administration cost is composed of the number of years of the life cycle of the farm, the cost of administration of the farm and the legal costs. On the other hand, the cost of operating and maintenance considers the corrective and the preventive aspects during the number of years of the life cycle of the floating offshore wind farm. In this sense, aspects as inspections of equipments, calibration and adjust of sensors, substitution of equipments, cleaning and visual reviews, among others, have been considered. In the case of the corrective maintenance the probability of failure is considered for each of the pieces of the offshore wind turbine, the floating platform, the mooring and anchoring and the electric system.

3.3.7 Dismantling Cost

The floating offshore wind farm should be dismantled in order to clean and recover the area where it has been installed. First, the farm is disassembled and, then, the main material obtained (steel, copper, etc.) can be sold. This income is considered as a negative cost. In addition, the cost of dismantling is dependent on the cost of dismantling the offshore wind turbines ($C61$), the cost of dismantling the floating platforms ($C62$), the cost of dismantling the mooring and anchoring systems ($C63$), the cost of dismantling the electric system ($C64$), the cleaning cost of the location ($C65$) and the removal cost of the materials ($C66$), as equation shows:

$$C6 = C61 + C62 + C63 + C64 + C65 + C66 \tag{7}$$

4 Case of Study

The case of study considers a floating offshore wind farm of 21 wind Repower 5 M turbines (NWT) of 5 MW of power (PWT) and located in Galicia (North-West of Spain). This region has been selected because it has deep waters, which is a condition to the installation of floating offshore wind platforms, it has a good offshore wind resource, which will give better economic results in terms of profitability of the investment, and, finally, this area has a great experience in onshore wind and naval sector. In this sense, the port and the shipyard considered are located in Ferrol (A Coruña, North-West of Galicia).

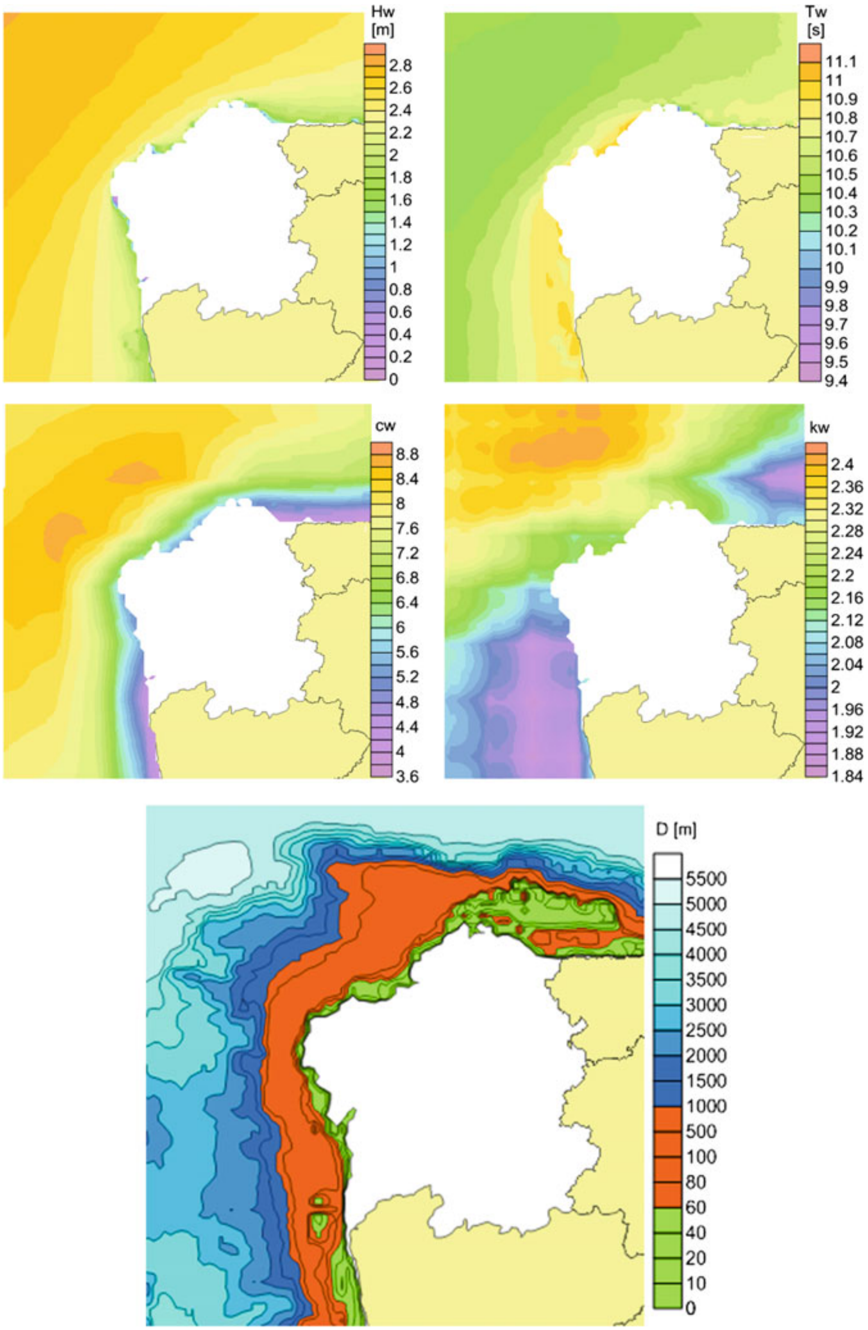

Fig. 7 Geo-referenced variables regarding waves (H_w, T_w), wind (c_w, k_w), depth (D), distances from farm to shore (d), the storage area ($d_{storage}$) and the construction area ($d_{construction}$)

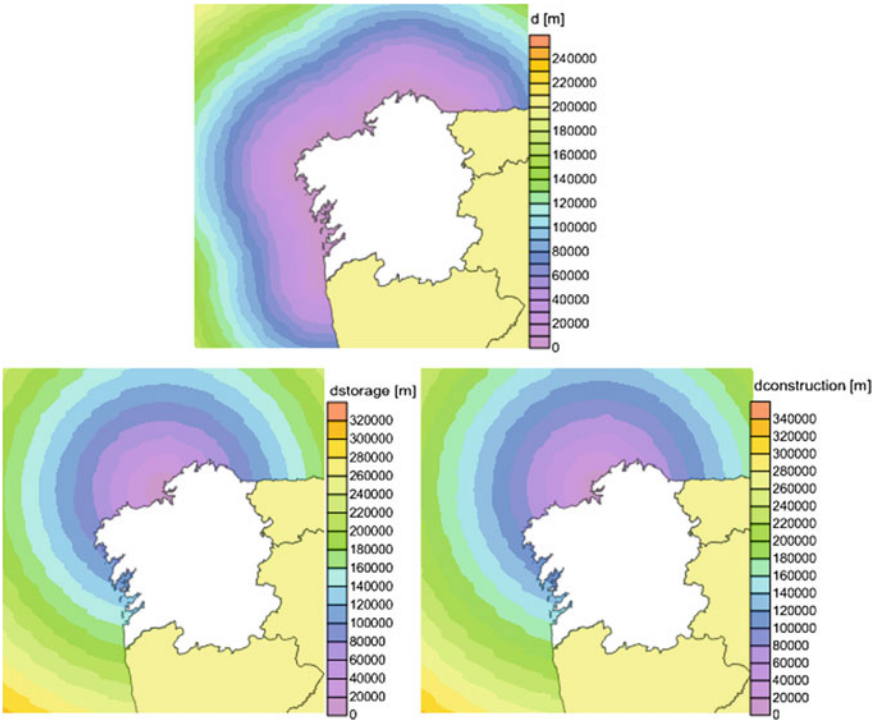

Fig. 7 (continued)

In addition, the methodology has been applied to each of the points of the geography where the floating offshore wind farm can be installed (k). Therefore, several variables are geo-referenced: shape parameter (k_w) and scale parameter (c_w) of the wind [10], period (T_w) and height of the waves (H_w) [11, 12], depth (D), distance to shore (d), distance from the farm to the storage area ($d_{storage}$) and distance from the farm to the platform construction area ($d_{construction}$), as Fig. 7 shows [13].

Moreover, a semisubmersible platform based on the Dutch tri-floater [14] has been considered for the study. It is composed of three steel columns joined using several steel pontoons. The offshore wind turbine is located in the centre of them.

5 Results

The conception and definition cost and the design and development cost, as mentioned before, are independent of the area selected to install a floating offshore wind farm. Therefore, their maps do not exist. Their constant values are 6.79 and 0.24 M€, respectively.

On the other hand, costs of the other phases of the life cycle of a floating offshore wind farm are dependent on the location. In this sense, aspects as distance to shore and depth have influence on costs. It means that they can be drawn as independent maps of the geography selected, in this case the Galician coast.

The cost of manufacturing goes from 215 M€ for the closest areas to the Galician shore to 406 M€ for the most remote areas. The installation cost goes from 19 to 392 M€. As Fig. 8 shows, these costs are dependent on the distance from shore, mainly due to the fact that the installation cost is calculated considering the transport from the port or the shipyard to the farm, which is developed using a particular vessel whose trip depends on the distance.

The exploitation cost goes from 108 to 114 M€ and dismantling cost values from 0.0058 to 31 M€. As we can see in Fig. 9, the cost of exploitation, which is mainly composed of the cost of operation and maintenance, is less dependent on the distance from shore than the cost of dismantling, whose value depends on the trips of the vessels which are decommissioning the floating offshore wind farm.

Finally, the total life-cycle cost of a floating offshore wind farm of 21 wind turbines of 5 MW values is from 366 to 946 M€, as Fig. 10 shows.

Figure 11 shows the main cost of a floating offshore wind farm: the manufacturing cost, with the 62 % of the total cost. It is mainly due to the offshore wind

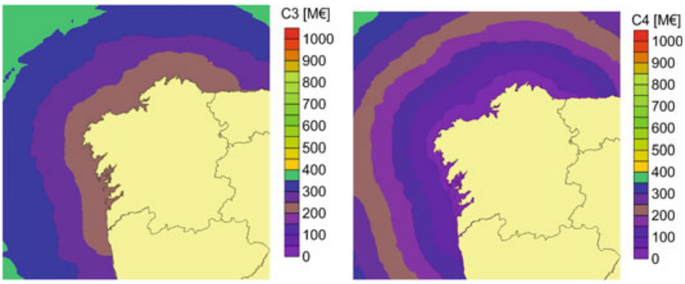

Fig. 8 Manufacturing and installation cost of a floating offshore wind farm

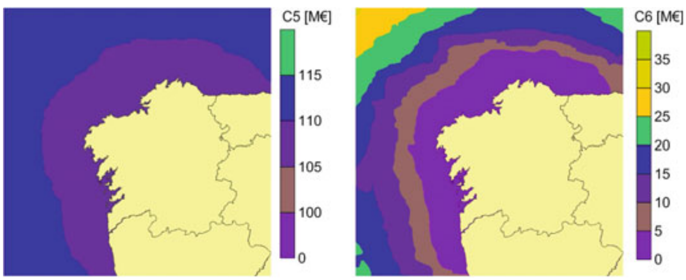

Fig. 9 Exploitation and dismantling cost of a floating offshore wind farm

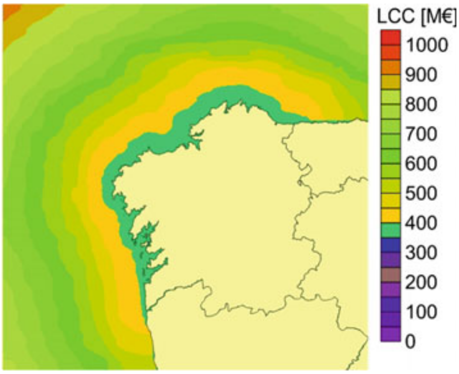

Fig. 10 Total life-cycle cost (*LCS*) of a floating offshore wind farm

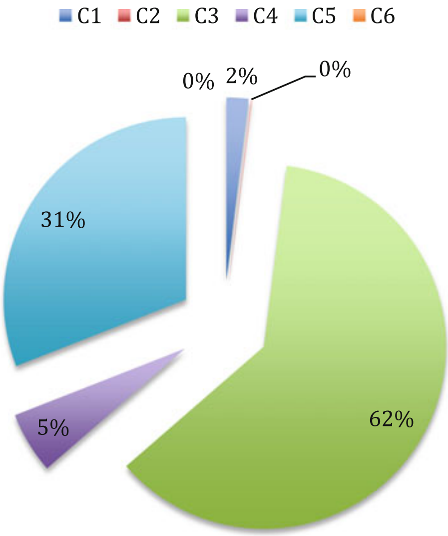

Fig. 11 Percentages of the life-cycle cost of a floating offshore wind farm

turbine cost and the floating platform cost, which is built in a shipyard. It is followed by the exploitation cost (31 %), which includes the operation and maintenance cost (corrective and preventive). The other significant cost is the installation cost, with a 5 %. However, costs of conception and definition, costs of design and development and costs of dismantling are irrelevant in comparison with the other costs.

On the other hand, considering the CAPEX and the OPEX, values of 241 and 108 M€ are, respectively, obtained, as Fig. 12 shows.

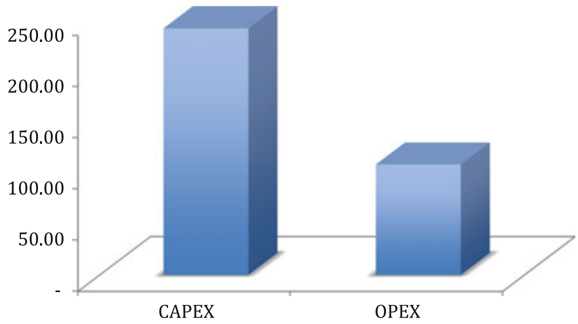

Fig. 12 CAPEX and OPEX of the life-cycle cost of a floating offshore wind farm

6 Conclusions

This chapter describes a general methodology to calculate the costs of a floating offshore wind farm. It is based on the analysis of its life-cycle cost system (LCS). In this sense, several phases have been defined: conception and definition, design and development, manufacturing, installation, exploitation and dismantling. The calculation of costs of each of these steps gives the total cost of a floating offshore wind farm.

The method proposed has been applied to the particular case of the Galician coast, where a floating offshore wind farm could be installed due to the great offshore wind potential and the depth of its waters.

Results indicate that the most important cost in the life cycle of a floating offshore wind farm is the manufacturing cost. It is due to the fact that the floating offshore wind platforms and the offshore wind turbines have a high cost.

The methodology proposed can be used by investors in the future to know the real costs of a floating offshore wind farm. However, not only the economic aspects are important. In this sense, you can be also limited by the area where you want to install the farm. Therefore, a complementary study using GIS and considering environment, fisheries, navigation and fault lines, among others, should be developed.

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