Life-cycle cost analysis of floating offshore wind farms

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Abstract

The purpose of this article is to put forward a methodology in order to evaluate the Cost Breakdown Structure (CBS) of a Floating Offshore Wind Farm (FOWF). In this paper CBS is evaluated linked to Life-Cycle Cost System (LCS) and taking into account each of the phases of the FOWF life cycle. In this sense, six phases will be defined: definition, design, manufacturing, installation, exploitation and dismantling. Each and every one of these costs can be subdivided into different sub-costs in order to obtain the key variables that run the life-cycle cost. In addition, three different floating platforms will be considered: semisubmersible, Tensioned Leg Platform (TLP) and spar. Several types of results will be analysed according to each type of floating platform considered: the percentage of the costs, the value of the cost of each phase of the life-cycle and the value of the total cost in each point of the coast. The results obtained allow us to become conscious of what the most important costs are and minimize them, which is one of the most important contributions nowadays. It will be useful to improve the competitiveness of floating wind farms in the future.

Keywords

Cost Breakdown Structure (CBS); floating offshore wind farm; marine renewable energy; life-cycle cost

1. Introduction

The development of new energy sources is necessary to sustain our current lifestyle. This occurs due to the fact that fossil fuels have a limited life span [1]. Hence, the use of renewable energies, the use of which is unlimited, will be of utter importance. Moreover, in 2009 the European Union (EU) has established that 20% of final energy consumption should come from renewable sources in 2020 [2].

In relation to renewable energies, the future will be directed toward its use in the marine environment. In this sense, offshore wind will make a substantial contribution to meeting the EU's energy policy requirements through a sharp increase – in the order of 30 – 40 times by 2020 and 100 times by 2030 – in installed capacity compared to present day. Otherwise, the distance to the shore and the depth are the main constraints in this technology. Thus, the next step is to develop floating structures, which can operate in deep waters. In this context, two different floating platforms prototypes have already been installed: spar substructure called Hywind in Norway and the WindFloat semisubmersible platform in Portugal [3].

However, one of the most important difficulties in the development of a new technology is the absence of procedures which allow us to evaluate the costs of the floating structures [4]. In this sense, there is an approximation to the cost of a spar system which describes the general costs, but which has not taken into account the relationships between variables [5]. Furthermore, other studies are focused on technical or theoretical aspects [6]. Considering that the availability of knowledge in relation to floating wind farms is scarce, cost experiences of fixed offshore wind energy or onshore wind energy [7] can be used as a starting point, being useful to determine tariffs in the future [8].

Therefore, the main objective of this article is to become aware of what the main costs are involved in a floating offshore wind farm and which are the fundamental variables involved in each phase of their life cycle. In addition, three different floating platforms will be considered: semisubmersible, Tensioned Leg Platform (TLP) and spar. Results allow us to be conscious of what the most important costs are and minimize them in the future improving the competitiveness of floating wind farms.

2. Methodology

The study of the life-cycle can be considered in several ways: the economic [9], the environmental [10], among others. Nevertheless, the methodology used for the present analysis is based on the Cost Breakdown Structure (CBS), which is part of the life-cycle cost system of the floating offshore wind farm [11]. CBS defines the main costs and sub-costs taking into account the disaggregation of the process.

Firstly, the main phases in the process of the floating offshore wind farm are defined. Thus, the total Life-Cycle Cost System (LCS) of a Floating Offshore Wind Farm (FOWF) is decomposed in the costs of each of the main phases of the process: definition cost (C1), design cost (C2), manufacturing cost (C3), installation cost (C4), exploitation cost (C5) and dismantling cost (C6). Therefore the LCS can be formulated as [12]:

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

However, in order to obtain their main dependences, each of these costs can be subdivided in the correspondent sub-costs which will be analysed separately in the following steps.

Finally, the LCS_{FOWF} will be applied to the particular case of the Galician coast (North-West of Spain). For this purpose, a tool has been developed in order to obtain the maps of the costs in this region. The application of this resource to the three most typical floating platforms will give an approximation of which of the three are more cost-effective [13]. There is multi-criteria decision-making in order to select the most important floating offshore wind platforms. They are based on cost and technical challenges as to minimise the induced motion, design the wind turbine, improve the coupling between the floating platform and the wind turbine or the installation and O&M process [14]. In this sense, the three floating platforms most cost-effective: the semisubmersible, the Tensioned Leg Platform (TLP) and the spar.

3. Calculation of the Total Cost

3.1. Definition Phase

The Definition Phase is composed by all the preliminary studies needed to carry out the floating offshore wind farm as, for instance, the economic viability of the project, the environmental and wind resource studies which indicate the best exploitation area, etc. In this sense, the definition cost (C1) will be composed of three main sub-costs [15]: market study cost (C11), legislative factors cost (C12) and farm design cost (C13), as is shown in Fig. 1. In this sense, the legislative factors considered will be the social and environmental impact surveys and the authorization for the farm installation. Furthermore, the farm design cost is composed by the study of the offshore wind resource, the sea conditions and the geotechnical characteristics of the seabed.

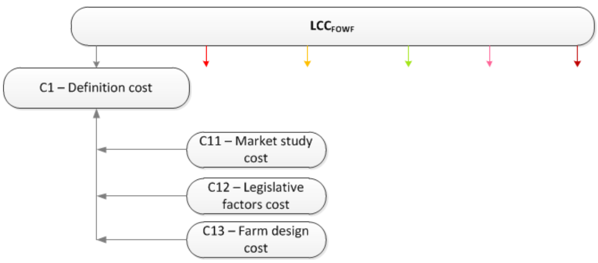

Fig. 1. Definition cost.

Considering all the sub-costs explained, the main dependences in definition cost are the number of wind turbines (NWT) and the power of each wind turbine (PWT) [13] . Although other parameters, such as depth, wind resource or geotechnical conditions, can be taken into consideration, they will be excluded from the C1 formulae because of the lack of data.

$$C1 = f(NWT, PWT) \tag{2}$$

3.2. Design Phase

The economic viability calculated in the definition phase will determine if the rest of the stages will be carried out. Therefore, if this study has positive results, the design will be the next phase. In this sense, the design phase will focus on the costs of the management and the engineering of the real floating wind farm designed, as Fig. 2 shows. It includes, for instance, the calculation of the distance between wind turbines and lines of wind turbines, the number of wind turbines of the farm depending on the population or the industry consumption, the dimensioning of the electric cables and substation, the calculation of the mass of the mooring and anchoring, etc. Furthermore, although in the present study the floating platform and the wind turbine dimensions has been considered as fixed, the design phase can also include these calculations in other studies.

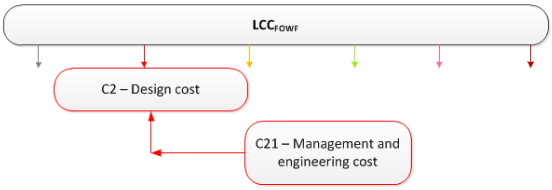

Fig. 2. Design cost.

The main dependences in relation to design cost also are the number of wind turbines and the power of each wind turbine involved:

$$C2 = f(NWT, PWT) \quad (3)$$

3.3. Manufacturing Phase

The manufacturing phase involves the fabrication of each of the components in a floating wind farm: wind turbines manufacturing (C31), floating platforms manufacturing (C32), mooring manufacturing (C33), anchoring manufacturing (C34) and electrical component manufacturing (C35), Fig. 3.

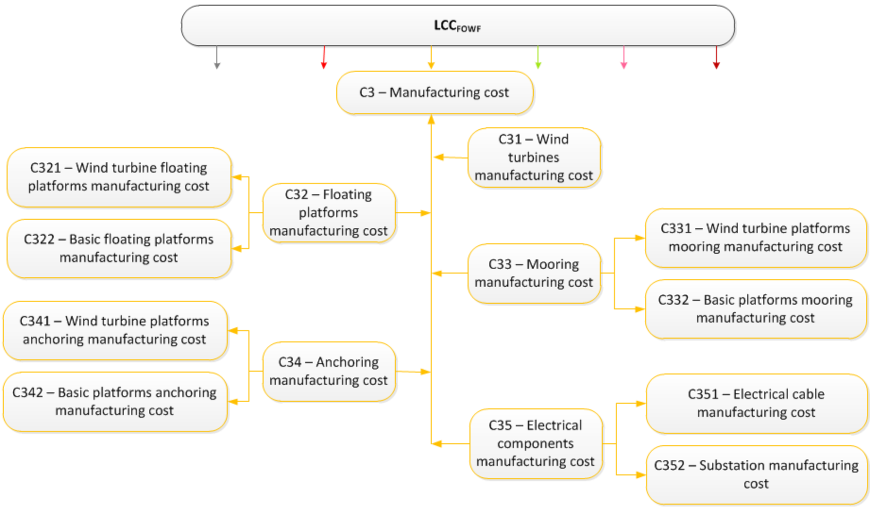

Fig. 3. Manufacturing cost.

Wind turbine manufacturing cost is made up of the cost of the rotor, tower and nacelle of each wind turbine installed in the offshore wind farm.

Moreover, costs related to platforms, mooring or anchoring have two sub-costs which depend on the type of platform involved. In this sense, two different sub-structures will be considered:

wind turbine platforms and basic platforms (substation platforms, whose number will be dependent on the power of the offshore wind farm, and accommodation platform). Their cost will be calculated taking into account their construction in a shipyard and their certification cost. In terms of the electrical components manufacturing, there also are two different sub-costs: electrical cable manufacturing cost (C351) and substation manufacturing cost (C352).

Wind turbines manufacturing cost depends on the number of wind turbines (NWT) [16], the power of each wind turbine (PWT) and the cost per MW of turbine (C_{MW}) [17]:

$$C31 = f(NWT, PWT, C_{MW}) \qquad (4)$$

However, platforms construction is the most outstanding cost in terms of manufacturing [5]. To evaluate its value an activity-based cost (ABC) method has been used. It distributes direct labour [18], material [19] and activity costs [20] of the platforms taking into account their construction in a conventional shipyard. Therefore, considering this non-traditional cost system, the main variables in terms of manufacturing costs are: the number of wind turbines (NWT), the power of each wind turbine (PWT), the mass of the platform (m_P), the mass of the wind turbine (m_{WT}), steel cost (C_{steel}), cost of direct labour (C_{DL}), cost of direct materials (C_{DM}) and cost of activities (C_A):

$$C32 = f(NWT, PWT, m_P, m_{WT}, C_{steel}, C_{DL}, C_{DM}, C_A) \qquad (5)$$

Mooring manufacturing cost (C33) and anchoring manufacturing cost (C34) depend on the environmental forces acting on the platforms [21]. Three different forces have been considered in the design: wind force, wave force and current force. They are function of period (T_{wave}) and height of waves (H_{wave}), speed of current ($u_{current}$), wind speed at anemometer height (u_{za}), shape parameter (k_w) and scale parameter (c_w) of wind [22]. It determines length of mooring, which will consider depth (P) as part of its calculation. Moreover, the forces applied determine the weight of anchoring (w_a) and mooring (w_m). Finally, anchoring cost per kilogram (C_a) [21], mooring cost per kilogram (C_m) [23] and the number of mooring lines of each platform (LP) must be borne in mind:

$$C33 + C34 = f(NWT, H_{wave}, T_{wave}, u_{current}, u_{za}, k_w, c_w, P, w_a, w_m, C_a, C_m, LP) \qquad (6)$$

According to the electrical system manufacturing, the suitable cable section to transport the power required must be calculated [24]. Furthermore, the different length of cables considered depends on the line studied: wind turbines lines (offshore), line to connect wind turbines with substation (offshore considering offshore substation and offshore-onshore bearing in mind onshore substation) and electrical line to connect substation with general grid (offshore-onshore considering offshore substation and onshore taking into consideration onshore substation). The cable section will determine the cost per section (C_{cable}) and the number of cables needed to make the connection (N_{cable}) [25]. Moreover, other aspects that can be considered are: the number of wind turbines (NWT), number of wind turbines per line ($NWTL$), the diameter of the wind turbine (D), depth (P), distance to shore (d), distance in shore ($d_{onshore}$), general grid voltage (V_{II}), voltage of the cable (V_I) and other electrical features of substation, which are of a minor importance:

$$C35 = f(C_{cable}, N_{cable}, NWT, NWTL, D, P, d, d_{onshore}, V_I, V_{II}) \qquad (7)$$

3.4. Installation Phase

The installation phase is composed by all the costs involved in the process of installing each part of the floating wind farm [26]. In this sense, there are wind turbines installation costs (C41), platform installation costs (C42), mooring and anchoring installation costs (C43) [27], electrical installation costs (C44) [28] and starting or commissioning costs (C45), as shown in Fig. 4.

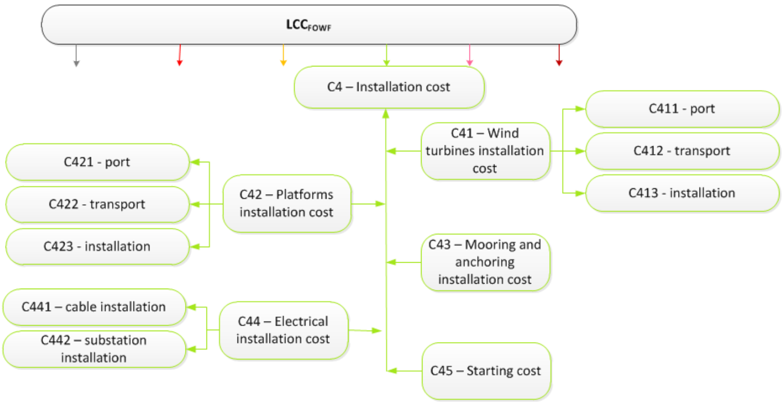

Fig. 4. Installation cost.

In addition, the installation of wind turbines and platforms is divided in three different stages: those related to port, to transport and to the installation process. The port and shipyard location is one of the most important issues when a floating wind farm is developed. They should be close to the location where the farm will be constructed. In this sense, the distance to the port (d_{port}) and the distance to the shipyard ($d_{shipyard}$) are very important to ensure the viability of the project. On the other hand, the transport of the components and their installation processes require several specific vessels, which can load and install each of the pieces of the system. In this sense, tug boats [27], cargo barges [29], sheeleg cranes or heavy lift cranes can be involved. Thus, several dependences on the installation process would be the number of vessels used (N_{vessel}), the speed of the vessel (v_{vessel}) and the fleet of the selected vessel (C_{vessel}):

$$C4 = f(NWT, d_{port}, d_{shipyard}, N_{vessel}, v_{vessel}, C_{vessel}, N_{cable}, LP) \quad (8)$$

3.5. Exploitation Phase

The exploitation phase is composed by tax cost (C51), assurance costs (C52) [21], exploitation management costs (C53) and operation and maintenance (O&M) costs (C54) [30]. Although the O&M cost in the oil and gas industry is taken into account as a separate stage, in the present study this cost will be considered within the exploitation cost because it will be used in different terms regarding the other costs (C1, C2, C3, C4 and C6), when the viability study is calculated in future papers. In fact, these costs will be taken into consideration in the CAPEX (Capital Expenditure) and the exploitation cost in the OPEX (Operational Expenditure). Furthermore, preventive and corrective costs are part of O&M [31]. The preventive maintenance cost is divided into transport, direct labour and materials of each of the components of a floating offshore wind farm: wind turbine, platform, mooring, anchoring and electrical system, Fig. 5 [32].

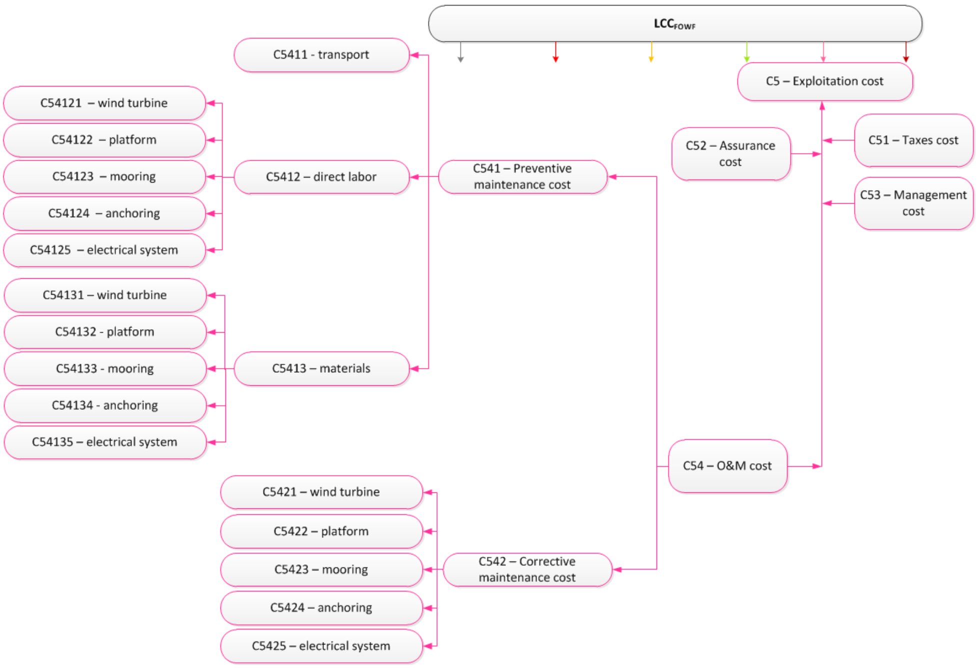

Fig. 5. Exploitation cost.

On the other hand, corrective maintenance implies being aware of the failure probability ($P_{failure}$) of each of the components of the floating wind farm [33], which is dependent on the main characteristics of the loads (wind, wave and currents). Moreover, the number of elements needed (N_{cable}, LP, NWT), the type of vessel or helicopter used for maintenance (C_{v_maint}) and the distance from farm to port (d_{port}) are evaluated:

$$C5 = f\left(P_{failure}, N_{cable}, LP, NWT, C_{v\_maint}, d_{port}\right) \tag{9}$$

3.6. Decommissioning Phase

Finally, decommissioning occurs when the floating offshore wind farm life cycle has finished, approximately 20 years [34]. Its purpose can be repowering or cleaning the wind farm area [35]. Each of the main components of the farm will be dismantled: wind turbines, platforms, mooring, anchoring and electrical system, but the farm area will be cleaned and the materials involved in the whole process will be eliminated (Fig. 6). Both dismantling and installing involve works as far harbour, transport and uninstalling the components are concerned. On the other hand, the elimination process requires processing [36], transportation and elimination of all the materials used in the construction of the farm. In this sense, some materials, as the aluminium of the electrical cables or steel of the floating platforms can be sold. It implies an income which will be reduced from the costs.

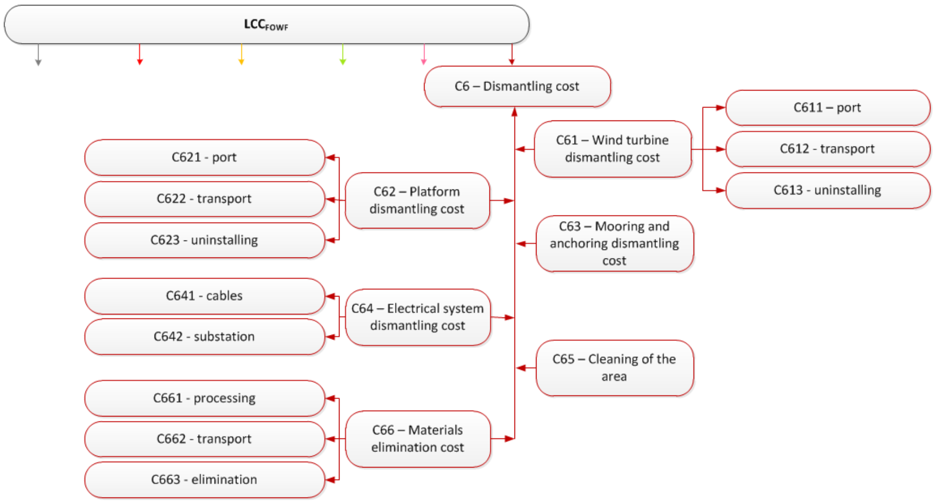

Fig. 6. Dismantling cost.

According to dependences, the dismantling is based on the same variables as the installation phase, but also including these ones related to cleaning and the final elimination process, as the cost of steel (C_{sj}) and the cost of aluminium (C_{aj}) taken as junk:

$$C6 = f\left(NWT, d_{port}, d_{shipyard}, N_{vessel}, v_{vessel}, C_{vessel}, N_{cable}, LP, w_a, w_m, C_{sj}, C_{aj}\right) \quad (10)$$

4. Case of study

The case of study will be defined by several different types of variables: constant parameters, grid parameters and platform parameters.

Firstly, the floating offshore wind farm considered will be composed of 21 wind turbines (NWT) of the model Repower 5M and it will be located in Galicia (North-West of Spain), an area where offshore wind resource is high. Furthermore, the other constant parameters will be defined in **¡Error! No se encuentra el origen de la referencia.**:

Table 1: Constant parameters.

Concept	Nomenclature	Value	Units	Reference
Number of wind turbines	NWT	21	-	-
Power of each wind turbine	PWT	5.075	MW	[13], [14], [17], [37], [38]
Diameter of the wind turbine	D	126	m	
Cost per MW of turbine	C_{MW}	1.2014	€/MW	
Mass of the wind turbine	m_{WT}	697,500	kg	[39], [40]
Steel cost	C_{steel}	524	€/ton	[27]
Number of wind turbines per line	$NWTL$	3	-	-
Distance to shore	$d_{onshore}$	5,000	m	-
General grid voltage	V_I	220,000	V	[41]
Voltage of the electrical cable	V_{II}	20,000	V	
Cost of steel as junk	C_{sj}	0.3562	€/kg	[42]
Cost of aluminium as junk	C_{aj}	1.5318	€/kg	
Plate anchor cost per kilogram	C_a	2	€/kg	[18], [21]
Mooring cost per kilogram	C_m	6.82	€/kg	[23]

Electrical 20 V cable cost per section	C_{cable}	172 – 223	€/m	[24], [25]
Number of electrical cables	N_{cable}	7	-	Depending on total power
Cost of the vessel/helicopter for maintenance	C_{v_maint}	12,157	€/day	-
Number of vessels used	N_{vessel}	1	-	-

Secondly, the main grid input parameters have been classified depending on the floating offshore wind farm location (location variables) or depending on the special characteristics of the farm (special variables) [43]. In this sense, the location variables considered have been [44]: wave height in m (H_{wave}), speed of wind at anemometer height in m/s (u_{za}), speed of the current in m/s ($u_{current}$), wave period in s (T_{wave}), scale parameter (c_w), shape parameter (k_w) and depth in m (P). On the other hand, the special variables considered have been [45]: distance to shore (d), distance from farm to shipyard ($d_{shipyard}$) and distance from farm to port (d_{port}), all of them in metres. All these variables will depend on the point of the shore taken into account, being the main inputs used to calculate the economic maps of each type of floating platform.

Alternatively, three different platform dimension models have been considered: semisubmersible platform (Model A), TLP platform (Model B) and spar platform (Model C), as we can see in Fig. 7 [13].

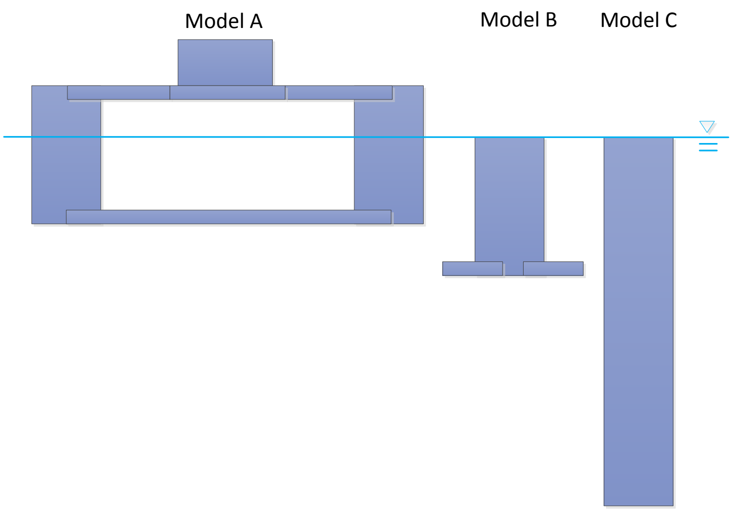

Fig. 7. Models of floating offshore platforms.

In this sense, there are some parameters which will depend on the model considered, as

Table 2 shows. Some of them have been calculated taking into account an Activity-Based Cost (ABC) model, such as the cost of direct labour, the direct materials and the cost of activities. On the other hand, values as the probability of failure of the mooring and anchoring have been obtained using a Montecarlo simulation. As the table shows, the $P_{failure}$ will be zero in all the platform models because the calculation of the mooring and anchoring weight has been developed considering a high safety factor.

Table 2: Platform parameters.

Concept	Nomenclature	Value			Units	Reference
		Model A	Model B	Model C		
Number of mooring lines of each platform	LP	6	8	3	-	[13], [21], [46]
Mass of the platform	m_P	695,985	964,771	988,797	kg	Calculated considering dimensions
Weight of anchoring	w_a	3,150	8,100	8,100	kg	
Weight of mooring	w_m	1,572	2,192	1,852	kg	
Cost of direct labour	C_{DL}	897,529	1,254,126	1,273,495	€	ABC calculation
Cost of direct materials	C_{DM}	819,418	849,707	866,988	€	
Cost of activities	C_A	90,365	110,728	112,657	€	
Speed of the vessel	v_{vessel}	3.60 (tug)	3.14 (heavy lift crane)		m/s	[27]
Fleet of the vessel	C_{vessel}	22,502	116,000		€/day	
Failure probability of mooring and anchoring	$P_{failure}$	0	0	0	-	Calculated using Montecarlo simulation

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In addition, several considerations will be assumed as constant for all the types of floating platforms: there will be an offshore substation; a HVDC (High Voltage Direct Current) string configuration of the electrical cable will be taken into consideration; the dismantling will be carried out by "tree fall", in which the pieces of the wind turbine and the platform will be cut down; no cohesive soil; there is no accommodation platform; wind turbine tower will be assembled onshore; preventive maintenance will be carried out with a helicopter; the mooring and anchoring installation are developed with an Anchor Handling Vehicle (AHV); and the installation of the substation will be developed with a cargo barge and a heavy lift vessel. Furthermore, the selection of the mooring material and the type of anchoring will be dependent on the depth of the location. In this sense, chain and pilots will be considered for shallow waters (less than 40 m), and synthetic mooring and plate anchor will be taken into account for deep waters (more than 40 m).

However, the installation process of the floating devices will depend on the type of substructure chosen. In this context, the installation of the semisubmersible platform will be developed tugging the platforms and the process necessary to install the TLP and the spar will use a cargo barge and an offshore heavy lift crane. One of the main reasons is because the semisubmersible substructure has an inferior draft in comparison to the others.

5. Results

Several types of results will be analysed according to each type of floating platform considered: the percentage of the costs, the value of the cost of each phase of the life-cycle and the value of the total cost in each point of the coast.

Firstly, the percentage of the cost of each life-cycle phase will be useful to determine in the future the main stages to consider when a floating offshore wind farm is to be developed. It has been calculated as equation (11) indicates and where C_i is the cost of each "i" phase of the life-cycle.

$$\%C_i = \frac{C_i}{LCS_{FOWF}} \qquad (11)$$

However, as results indicate these percentages depend on the type of platform chosen. In the semisubmersible model, the highest percentage is the manufacturing cost (61.7%), the maintenance cost (30.9%) and the installation cost (5.4%). However, in the TLP model these values vary: manufacturing (53.0%), maintenance (24.5%) and installation (16.1%). As shown, the installation cost of the TLP is higher than the semisubmersible because the cost of the cargo barge and the offshore lift crane is higher than the cost of the tug. Furthermore, the spar substructure has very similar values to the Model A: manufacturing (63.6%), maintenance (29.2%) and installation (5.3%). This last value is less than the cost of installation the Model B because more spar platforms can be transported using the same cargo barge. Thus, fewer trips of the vessel and, therefore, less cost associated. Consequently, the main phases in the life-cycle of a floating offshore wind farm will be, in this order, the manufacturing, the installation and the maintenance of its components.

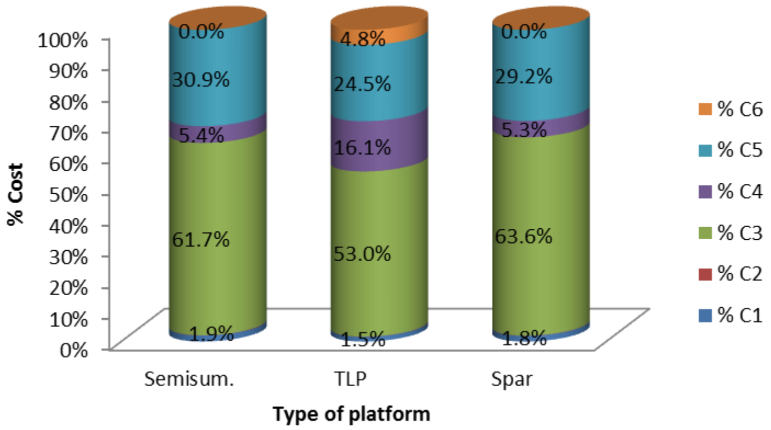


Fig. 8. Percentage of the costs for each floating platform model.

Secondly, if the cost of each life-cycle phase is analysed (Fig. 9), observation concludes that the cost of conception and design are identical for all the types of platforms: 6.79 M€ and 0.24 M€ respectively. Semisubmersible platform has the lower manufacturing cost (215.38 M€), followed by the 235.45 M€ and the 235.80 M€ of the TLP and spar respectively. According to the installation cost, the cheapest process is the semisubmersible installation. The maintenance cost is very similar to all the platforms: approximately 108 M€. However, the cost of the last life-cycle phase, the dismantling, presents very cheap values for the semisubmersible because, although the quantity of steel is less, the quantity of copper is higher because the length of the electrical cable is higher (less draft), then the income from the sale of these materials will be superior. Moreover, the spar device has dismantling values inferior to the TLP because it has more steel mass from the platform and the number of trips is also inferior in comparison to the other case.

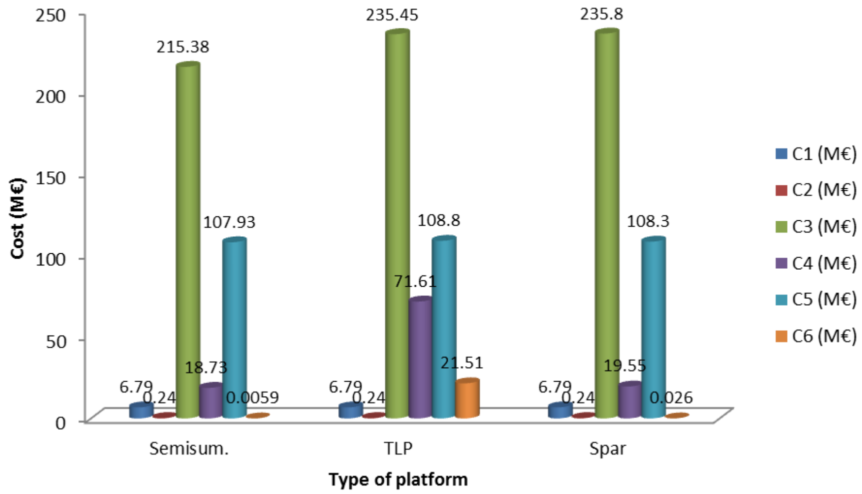
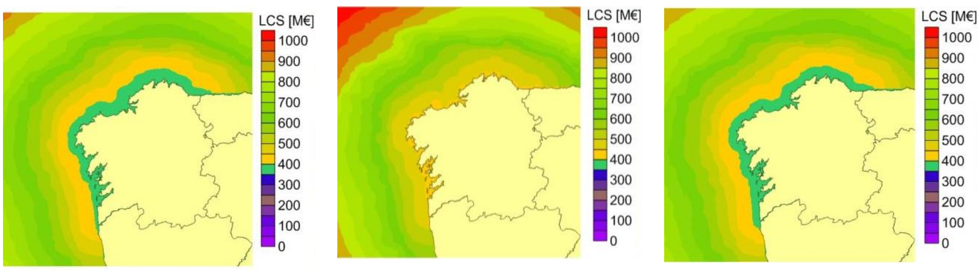


Fig. 9. Cost (millions of euros) depending on the floating offshore wind platform selected.

Finally, the value of the total cost for each point of the offshore geography will be represented taking into account the tool developed. In this context, costs go from 349.08 M€ to 949.14 M€ in Model A, from 444.40 M€ to 1071.01 M€ in Model B and from 370.71 M€ to 929.15 M€ in Model C, as Fig. 10 shows:



(a) (b) (c)

Fig. 10. LCS_{FOWF} (millions of euros) depending on the floating offshore wind platform selected: semisubmersible (a), TLP (b) and spar (c).

6. Conclusions

The present study has formulated the costs involved in a floating offshore wind farm taking into account the six phases of its life-cycle: definition, design, manufacturing, installation, exploitation and dismantling. Furthermore, their main dependences, whose influences will be developed in future studies, have been defined: wave height, speed of the current, wave period, scale parameter, shape parameter, depth, distance to shore, distance from farm to shipyard, distance from farm to port, among others.

Results have been analysed for the specific place of Galicia, which is located in the North-West of Spain, an area where offshore wind resource is high. In this sense, several types of values have been analysed: the percentage of the costs, the value of the cost of each phase of the life-cycle and the value of the total cost on each point of the coast. Furthermore, all of these issues have been considered for each type of floating offshore wind platform: semisubmersible, TLP and spar.

Results allow us to become aware of the most important costs and minimize these costs in the future, improving the competitiveness of floating wind farms. Furthermore, the results of the percentage for a floating offshore wind farm for the CAPEX (Capital Expenditure) costs do not differ substantially from conclusions reached by Bussel, Snyder and Musial for fixed offshore wind farms. They consider that the sum of definition cost, design cost, manufacturing cost, installation cost and dismantling cost represents between 70% [47] and 78% [38] [48] of the total costs, values that in the floating offshore devices will be from 69.1 % to 75.5%.

On the other hand, if the present prototypes are borne in mind [13], the floating offshore wind farm considered with 21 semisubmersible platforms is cheaper than other with spar or TLP platforms, with an approximate cost of 349 M€. However, the main costs will be related to manufacturing, maintenance and installation, in this order, for all the types of floating platforms.

Future studies will be used to determine, taking into account these costs, some economic indicators, which will help the investor to know the viability of the project.

8. Acknowledgments

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