Comparative cost study between bottom-fixed and floating wind farms. Case applied to Fuerteventura Island.

Pablo Yánez Rosales[a], Julieta Schallenberg Rodríguez[b], Beatriz del Río Gamero[c]

[a] Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, España, pablo.yanez@ulpgc.es, Corresponding Autor
[b] Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, España, julieta.schallenberg@ulpgc.es
[c] Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, España, Beatriz.delrio@ulpgc.es

Abstract:

In many continental areas, the high density of wind farms and the scarcity of areas with optimal conditions to develop the wind energy is diminishing the expansion of wind turbines installations. Additionally, this problem is aggravated in islands characterized by orographically limitations. All this boosts the wind energy sector to develop offshore technology, whose forecasts estimate a decrease in costs. In this paper, Fuerteventura Island (Canary Islands, Spain) has been selected as scenario to analyze offshore wind farms costs, differentiating between floating and bottom-fixed technologies. For that, the total costs has been divided in Development Expenditure (DEVEX), Capital Expenditure (CAPEX), Operational Expenditure (OPEX) and Decommissioning Expenditure (DECEX) taking into account two principal variables such as distance to the coast and bathymetry. The results show that about 63% – 65% of total cost throughout the life of the park correspond to CAPEX, while 30% – 32% are operational costs. In terms of CAPEX, the cost would be in the range of 3,0 – 3,1 M€/MW in bottom fixed wind farms and 4,1 – 4,4 M€/MW in floating wind farms.

Keywords:

Offshore wind energy, Life cycle costs, bottom-fixed wind farm, floating wind farm, Canary Islands

1. Introduction

The generation of electricity from renewable sources is currently the main objective of decarbonization of the electricity sector worldwide. Despite the efforts made in recent years by institutions and companies, only 38% of annual penetration has been achieved (wind, solar and hydropower generation) in the EU electricity production in 2021 [1], 27% in the China electricity consumption in 2020 [2] and 20% in the US electricity generation in 2021 [3]. Although some countries have a high percentage of electricity production without emissions, such as Sweden (97%) Canada (82%) or Denmark (82%) [1, 4], other countries are far away from the international targets, such as Poland (20%) or Italy (37%).

In terms of renewable strategies, EU has set the target of achieving 32% of gross final energy consumption in 2030 [5], and no net emissions of greenhouse gases by 2050 [6]. In 2020 in EU, the renewables account for only 21.8% in terms of gross final energy consumption [7]. Other national targets are those of the United States (80% by 2030, although forecasts establish of 33% - 50% [8]), Canada (90% by 2030 [9]), or Japan (36% - 38% by 2030 [10]), among others.

Several renewable technologies has been developed, but wind energy remains the main renewable source for the electricity generation, more than doubling the photovoltaic generation in most countries [1–3]. However, the growing social rejection due to the possible impact generated, the availability of locations with worse wind resource or the scarcity of territory for its implementation (especially in isolated systems and archipelagos) have led to search for new locations where the effect is less: the sea.

Thus, two predominant technologies have been developed for offshore wind farms: bottom-fixed and floating systems. Currently, the widely used technology is the first of them. This technology is very limited, it is only feasible in shallow waters (50 - 70 m [11–15]). In addition, this technology has another disadvantage in many offshore areas of the world, since shallow waters are located at a short distance from the coast, which means a high visual impact on the coast. For this reason, in recent years a much more versatile technology has appeared: floating wind power, which makes it possible to install offshore wind farms at greater depths, and therefore further away from the coast. While Schallenberg-Rodríguez et al. [16] states that these wind farms can be installed at depths of less than 500 - 700 m, others authors such as Casto-Santos et al. [17–19] state the bathymetric limit at 1,000 m, or up to 1,300 m [12]. However, only prototypes in the depth range of 67 - 140 m have been installed to date [14, 20].

Although both are offshore wind farms, the technology used to attach them to the seabed is very different, which has a significant impact on the cost of the farms. Thus, the literature review revealed that in the published studies, the life cycle cost of both technologies for the same region is not jointly analyzed [12, 16, 17, 21–34].

For this reason, the main goal of this research will be to propose an easy methodology to estimate the life cycle cost of any wind farm, bottom-fixed or floating system. For this purpose, only in areas suitable for the installation of offshore wind farms the total cost will be analyzed.

All of the above are detailed in Section 2. In Section 3, the proposed methodology is applied to a practical case, Fuerteventura (Canary Islands, Spain) and the results are explained. Finally, Section 4 summarizes the conclusions.

2. Methodology

To estimate the total lifetime cost of bottom-fixed and floating wind farms, a detailed breakdown of the cost has been realized, according to DEVEX, CAPEX, OPEX and DECEX.

2.1. Development Expenditure (DEVEX)

Typical DEVEX is mainly composed of project management, the payment of licenses, the elaboration of different studies and the engineering costs. In the case of bottom-fixed turbines, Dicorato et al. [32] proposes a project development cost of 46.8 k€/MW, within the price range 45.6 – 48 k€/MW of some already installed parks. Nielsen P. estimates the DEVEX around 4% of the CAPEX [35]. BGV collects an annual DEVEX around 3.3% of the CAPEX [36], Martin et al. proposes a 5 – 7% DEVEX range [37] and González-Rodríguez estimates an annual cost of 3.5% of the CAPEX [30]. While the floating parks, Schallenberg-Rodríguez and Martinez et al. estimate the annual development cost around 4% of the CAPEX [38, 39]. An average CAPEX of 4% for bottom-fixed and floating wind farms is assumed.

2.2. Capital Expenditure (CAPEX)

CAPEX is the most relevant cost throughout a wind farm's lifetime. The fixation of the seabed is the main difference between bottom-fixed (foundation) and floating (floating substructure, mooring & anchoring system) wind farms costs. However, the other components of wind farms are common: the cost of the turbine, the electrical network and the substations.

2.2.1. Turbine costs

The cost of the wind turbine is the most relevant within the investment costs of an offshore wind farm. The turbine costs will be differentiating among manufacturing/acquisition costs, transportation costs and installation costs.

2.2.1.1. Manufacturing/Acquisition Cost

There are numerous authors who propose different cost functions to estimate the price of a wind turbine [28, 30, 32, 33, 36, 37, 40]. However, most of the functions are for wind turbines in the range 2-5 MW, which are the most installed since the construction of offshore wind farms began. Therefore, these functions are not valid for the calculation. From costs of many authors [18, 30, 32, 40–42], Eq. (1) calculates the manufacturing cost (C_{man_t}, in millions of euros) for turbines with power greater than 5 MW, in function of the turbine power (P, in MW). The unit costs are in the range 1.2 – 1.35 M€/MW, according to González-Rodríguez or Dicorato et al., among other researches [28, 30, 32, 33, 36, 40].

$$C_{man_t}(M€) = 7.6431 \ln(P) - 5.7165 \qquad 5 \leq \mathrm{P} \leq 10\ MW \tag{1}$$

2.2.1.2. Installation cost

The installation cost (C_{inst_t}) depends on the number of parts and assemblies that need to be transported to the location of the wind turbine, the time to assembly and the cost of the vessel (C_{vessel}) to install the turbine [41]. The time required to install the wind turbine ($\mathrm{T_{inst}}$) in its final location is calculated from Equation 2. The parameters that take part in its calculation are the number of assemblies (n), the height to which each piece must be raised ($\mathrm{h_{piece}}$), the crane speed to raise each piece (V_{crane}) , the assembly time (t_{ass}) and the daily cost of the jackup (C_{jackup}), according to [41, 42].

$$C_{inst} = n \times \left(2 \times \frac{h_{piece}}{V_{crane}} + t_{ass}\right) \times C_{jackup} \tag{2}$$

2.2.1.3. Transportation cost

Equation (3) calculates the cost of the transportation of the wind turbine to the final position, in line with [41, 42]. This cost depends on the sea conditions, the distance between the port from where the wind turbine is towed and its location (d_{port}), and the daily cost of vessel, principally. All the parameters and their normal values are exposed in Table 1, according to other authors [18, 41, 42].

$$C_{transp_t} = F \times \left[t_{load} + 2 \times \left(\frac{d_{port}}{V_{vessel}} + t_{app}\right)\right] \times C_{vessel} \tag{3}$$

Table 1. Transportation parameters.

Parameter	Description	Value	Unit
F	Sea condition factor (1 = calm sea)	1 – 1.4	-
t_{load}	Loading time of wind turbine parts on the vessel	2	h
t_{app}	Approach time to the wind turbine location	1	h
V_{vessel}	Average vessel speed	12	km/h
C_{vessel}	Daily cost of the vessel	150,000 - 500,000	€/day

The total cost of the turbines in a wind farm (C_t) will be calculated according to Eq. (4), where N is the number of wind turbines in the wind farm.

$$C_t = N \times (C_{man_t} + C_{inst_t} + C_{transp_t}) \quad (4)$$

2.2.2. Foundation (only for bottom-fixed wind farms)

The foundation is a fundamental element in the cost of bottom-fixed wind farms. The cost could represent 34% on average [43], although it will depend on the technology used to fix the wind turbines. This research will only consider the cost of monopile/jacket type foundations, as they are the most widely installed at present. The manufacturing cost of both is very similar [27]. Equation (5), in line with Dicorato or Shafiee et al. [27, 32], calculates the manufacturing cost (C_{man_f}) of the foundation (cost adjusted with the inflation to 2022).

$$C_{man_f}(M€) = \frac{400,000}{10^6} \times \mathrm{P} \times [1 + 0.02 \times (d - 8)] \times \left[1 + 0.8 \times 10^{-6} \left(h \times \left(\frac{D}{2}\right)^2 - 10^5\right)\right] \quad (5)$$

Where

- P Rated power of the turbine (MW)
- d Depth of the seabed (m)
- h Hub height (m)
- D Rotor diameter (m)

The installation and transportation costs are calculated according Eq. (2) and Eq. (3), as well as for the turbine costs.

2.2.3. Floating substructure (only for floating wind farms)

There are several technologies with an advanced level of development, such as spar-buoy, Tension Leg Platform (TLP) and semi-submersible platforms. Table 2 shows some estimated costs of these technologies. The installation and transportation costs are calculated according Eq. (2) and Eq. (3), as well as for the turbine costs.

Table 2. Unit costs of different floating substructure types, updated to 2022

Floating substructure type	Unit cost (M€/MW)	Source
Semisubmersible	0.6 – 1.7	[31]
Semisubmersible	1.41	Own calculations
TLP	0.58	[29]
TLP	0.60	Own calculations
Spar-buoy	1.14	[31]
Spar-buoy	1.46	Own calculations

2.2.4. Mooring & Anchoring (only for floating wind farms)

The cost of fixing a floating wind turbine will depend on the cost of mooring and anchoring, depending on the bathymetry, the rated power of the turbine and the seabed stratification.

2.2.4.1. Mooring

The different types of moorings can be grouped into two different classifications: according to the material (steel or synthetic fiber) and the configuration (chains/catenaries or tension legs). [44–46]. It will be considered only the tensioned synthetic fiber, due to the reduced environmental impact compared to chains and the lower cost for greater depths [44]. Equation (6) calculates the acquisition cost of the mooring system for each turbine ($C_{m_{acq}}$). [45, 47] have studied different unit mooring costs ($C_{u_m}, in\ M€/m$) according to the material and configuration.

$$C_{m_{acq}}(M€) = 1.05 \times (p - h_{subs} - h_{anc}) \times C_{u_m} \times c \quad (6)$$

Where:

p	Mean depth (m)
h_{subs}	Floating substructure height underwater (m)
h_{anc}	Anchor height on the seabed (m)
c	Number of moorings per floating substructure (between 3 – 8, depending on the floating substructure type, according to [48])

2.2.4.2. Anchoring

Anchors can be classified according to their geometry, configuration with moorings, way of attachment to the seabed, etc. The 5 main types of anchors for floating turbines are the following: gravity-based anchor (GBA), driven pile anchor (DPA), suction pile anchor (SPA), plate anchor (PA) and drag-embedded anchor (DEA) [18, 44, 45]. The manufacturing cost of the anchor system in the turbine (C_{man_a}) is calculated from Eq. 7, in line with [48].

$$C_{man_a} = C_{m_a} \times W_{m_a} \times F \times n \quad (7)$$

Where:

C_{m_a}	Unit cost of the material (€/kg)
W_{m_a}	Mass of the material needed (kg)
F	Manufacturing difficulty factor (1 – 3)
n	Number of anchors for one turbine (between 3 – 8, depending on the floating substructure type, according to [48])

2.2.4.3. Installation and transportation cost

Transportation cost is calculated according Eq. (2), as well as for the turbine costs. In the case of installation cost, it will depend mainly on the type of vessel required for the installation, as well as the process (suction or gravity). Table 3 shows the estimated cost range of anchor and mooring (tension leg system), according to Castro-Santos et al. [48] with updated prices to 2022.

Table 3. Installation cost of mooring & anchoring

Anchor & Mooring	Cost of each mooring & anchor (k€)
TL + GBA / PA / DEA	200 – 310
TL + SPA / DPA	225 – 360

2.2.5. Electrical grid

The electrical grid is composed of 4 types of cables: Inner-array cable (IAC), to connect the wind turbines to each other and the offshore substation; Export Cable (EXC), to connect the offshore substation and the mainland; Onshore Cable (ONC), that will connect the EXC with the onshore substation; and Overhead Power Line (OPL), will connect the onshore substation with the general transmission grid [24, 30, 32, 49]. In the case that it is not necessary to install an offshore substation, the IAC will be connected directly to the ONC [27].

To calculate the cost of the electrical grid, Equation (8) is suggested, in function of the length of the cable (L_c) and the acquisition & installation cost of the cable ($C_{ac\,\&\,ins_c}$). Some typical costs are listed in Table 4.

$$C_c = \sum_{i=1}^{a} L_c \times C_{ac\,\&\,ins_c} \quad (8)$$

Where:

a	Type of cable

Table 4. Unit costs and parameters of the cables by type.

Cable	Tension (kV)	Diameter (mm)	Total Cost (€/m)	References

IAC	30	500	834	[32, 50]
IAC	30	800	1,189	[30]
EXC	220	1,000	1,850	[30]
ONC	30	500	700	[50–52]
ONC	220	1,000	864	[30, 51]
OPL	66	-	160	[53–55]
OPL	220	-	233	[56]

2.2.6. Substation

Substations in offshore wind farms can be onshore, offshore, or both [27, 32]. Depending on the size of the wind farm, an offshore substation will be required. In the case of the onshore substation, the farm may discharge directly to a grid substation, or it may require its own onshore substation.

2.2.6.1. Onshore substation

In order to estimate the cost of the onshore substation as a function of wind farm power, the cost of different substations already built was analyzed. Eq. (9) and Eq. (10) calculate the cost of the onshore substation ($C_{s_{on}}$), in function of apparent power (P_a). The results of these equations are in line with González-Rodríguez and Dicorato et al. [30, 32].

$$C_{S_{on}}(M€) = 2 \cdot 10^{-5} \times P_a + 0{,}0308 \times P_a + 1{,}7841 \qquad P_a \leq 250\ MVA \tag{9}$$

$$C_{s_{on}}(M€) = 7{,}9178 \times \ln(P_a) - 33{,}298 \qquad P_a > 250\ MVA \tag{10}$$

2.2.6.2. Offshore substation

In the case of offshore substations, Shafiee et al. [27] propose an expression to calculate the offshore substation cost ($C_{s_{off}}$), shown in Eq. 11 from active power (P_{ac}) of the substation and with updated costs.

$$C_{s_{off}}(M€) = 0{,}6708 + 0{,}1241 \times P_{ac} \qquad P_{ac} > 100\ MW \tag{11}$$

2.3. Operational Expenditure (OPEX)

The main costs related to OPEX (Operational Expenditure) are logistics costs, preventive costs, maintenance of the facilities and possible repairs or replacement of wind farm elements. Several authors as [27, 29, 57, 58] designate an OPEX in the range of 25% – 35% of the total cost of the offshore wind farms. On the one hand, some authors as [16, 31, 59] estimate an OPEX in the range of 70 - 115 k€/MW per year for bottom-fixed wind farms. On the other hand, [39, 59] assume an annual OPEX of 131 k€/MW. It will be assumed an annual OPEX for bottom-fixed of 100 k€/MW, according to Scheu et al. [57] and 131 k€/MW for floating wind farms.

2.4. Decommissioning Expenditure (DECEX)

Some researchers estimate a DECEX in the range 1.8% – 2% [31, 36] in terms of LCoE, and in the range of 114 – 175 k€/MW [30]. However, the sale of recycle materials could be profitable for the company [39, 59]. It will be assumed a cost of 120 k€/MW in the decommissioning phase.

3. Practical case: Fuerteventura

The methodology described in the previous section was applied to one island: the island of Fuerteventura, part of the Canary Archipelago (Spain). Fuerteventura is the second largest island of the archipelago (1,660 km^2), with a population of 120,021 inhabitants [60].This population is distributed across 6 municipalities, where all population centers are concentrated on the east coast and the interior of the island, leaving the west coast practically unpopulated. In 2019, Fuerteventura had an electricity demand of 643.7 GWh, with a maximum instantaneous demand of 113 MW [61]. Since then, both electricity demand and instantaneous peak power have decreased. Likewise, the installed power exceeded 280 MW.

In order to apply the methodology described in Section 2, a previous zoning study has been carried out. For this purpose, the methodology described by [16] has been followed, which includes the environmental, territorial and technical restrictions to know which areas are suitable for the installation of offshore wind farms. The technical restrictions assumed for sizing offshore wind farms are shown in Table 5.

Table 5. Technical restrictions and assumptions to locate the potential offshore areas

Technical restrictions	Value	Source
Bathymetry (bottom-fixed wind farm)	50 m	[11, 62]
Bathymetry (floating wind farm)	500 m	[16]
Minimum wind speed at 80 m	6.5 m/s	[16, 63]
Diameter of the turbine (D)	165 m	-
Crosswind distance	4 D	[25]
Downwind distance	10 D	[64]

After applying all the constraints, the proposed offshore wind farms are shown in Figure 1. Two bottom-fixed wind farms and two floating wind farms will be studied. The main characteristics of each park analyzed are shown in Table 6. Each wind farm has been set as far away from the coast as possible to reduce the visual impact on the proposed areas, a fundamental factor on an island with more than 2.7 million tourists.

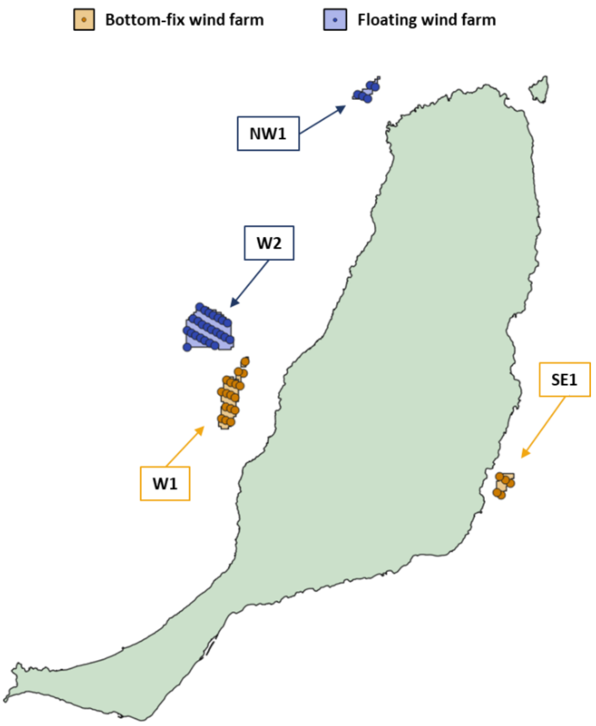

Figure 1. Location of the potential offshore wind farms in Fuerteventura

Table 6. Main parameters of each offshore wind farm

Park	Technology	Average distance from the coast (km)	Power (MW)	Number of turbines	Average depth (m)
W1	Bottom-fixed	6	170	17	50
SE1	Bottom-fixed	2.5	50	5	40
NW1	Floating	5	50	5	350
W2	Floating	11	240	24	170

The results of applying the methodology discussed in Section 2 show that CAPEX is the major cost of offshore wind farms, as Figure 2 shows. Capital costs are estimated to be around 65% of the lifetime cost in the case of fixed-bottom wind farms, and 63% in floating wind farms. The OPEX is also considerable over the lifetime of the farms, in the range of 30% - 32% depending on the technology implemented. To bring the future operating costs to the present, a lifetime of 25 years and an interest rate of 5% has been assumed. The total costs of the wind farms are 4.8 M€/MW average for bottom-fixed wind farms and 6.5 M€/MW average for floating wind farms, which means that the cost of floating wind farms is 35% higher than that of bottom-fixed wind farms.

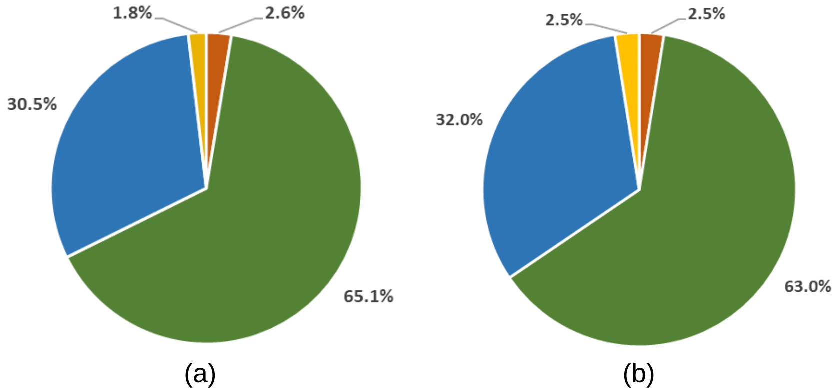

Figure 2. Distribution of total costs over the lifetime of offshore wind farms. a) bottom-fixed wind farms. b) Floating wind farms.

An in-depth analysis of the main cost of offshore wind farms (CAPEX) shows important differences between bottom-fixed wind farms and floating wind farms (Figure 3). While the cost of foundations of the former has an average cost of 1 M€/MW, the cost of fixation to the seabed of floating systems would be in the range of 2.1 - 2.3 M€/MW, which means increasing the cost of floating offshore wind farms by more than 30%, doubling the cost of fixation. Studying each farm separately, while the foundation costs do not vary significantly between W1 and SE1, the mooring & anchoring costs of W2 and NW1 wind farms present substantial differences due to the average depths of each farm.

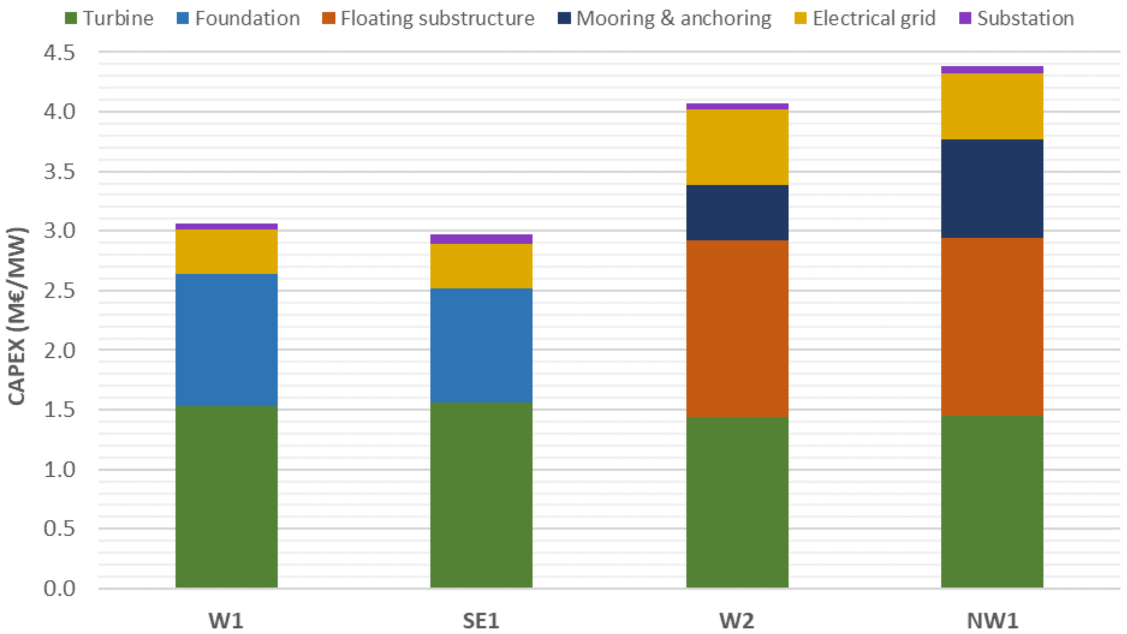

Figure 3. CAPEX of the offshore wind farms analyzed

Another of the main differences, although not so significant, are the electrical grid costs of each wind farm. While in the bottom-fixed wind farms the costs are around 0.4 M€/MW, in the floating wind farms the cost increases up to 50% with respect to the previous ones due to a greater distance from the coast and a greater depth. In addition, substation costs are relatively low due to the small size of the proposed farms, so the installation of offshore substations has not been considered [27].

The CAPEX of the bottom-fixed wind farms is estimated to be €3 M/MW, according to some researches [27, 36]. Likewise, the CAPEX of floating wind farms would increase to €4.2 M/MW, in line with Schallenberg-Rodríguez and Myhr et al. [16, 59].

4. Conclusions

Currently, electricity generation from renewable resources is a major challenge as a fundamental vector for the decarbonization of the planet. In this sense, wind energy, and specifically offshore wind energy, will play a decisive role in the energy transition. In isolated systems, the problem is accentuated, with greater dependence on fossil fuels, a weak power transmission grid and a shortage of land for the development of renewable energies. Therefore offshore wind energy can become a great alternative for the decarbonization of islands and isolated systems.

However, offshore wind energy has higher costs than onshore wind energy, mainly due to its fixation to the seabed and its distance from the power transmission grid. The objective of this research has been to analyze the lifetime costs of offshore wind farms, applied to an island system: the island of Fuerteventura (Canary Islands, Spain). For this purpose, the cost of the two predominant technologies for attachment to the seabed have been compared: bottom-fixed and floating technologies.

The results show that over the lifetime of the offshore wind farms, around 63% - 65% of the cost corresponds to capital costs (CAPEX), while another 30% - 32% corresponds to operation and maintenance costs (OPEX). The remaining costs correspond to development (DEVEX) and decommissioning (DECEX) costs. Analyzing only the CAPEX, the floating wind farms have a higher investment cost, exceeding 4.2 M€/MW, 30% higher than the bottom-fixed CAPEX (3 M€/MW on average). These costs are up to 4 times higher in the case of floating wind farms, compared with typical onshore CAPEX, and 3 times higher in the case of bottom-fixed wind farms. The main difference in costs between the two technologies lies in the fixation to the seabed. While floating technology has a cost of 2.1 - 2.3 M€/MW to support the turbine, the cost in bottom-fixed is around 1 M€/MW. Also, due to the depth and the distance from the coast, the costs of the electrical grid of the wind farm is 50% higher in floating wind farms than in bottom-fixed wind farms.

In conclusion, bottom-fixed wind farms have lower investment and operating costs than floating wind farms. Nevertheless, in islands with deep bathymetry such as the Canary Islands, the installation of bottom-fixed wind farms is very complicated, which leads to the development of floating solutions.

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