Applied Energy 266 (2020) 114716

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A life cycle cost model for floating offshore wind farms

C. Maienza[a,*], A.M. Avossa[a], F. Ricciardelli[a], D. Coiro[b], G. Troise[c], C.T. Georgakis[d]

[a] Department of Engineering, University of Campania "Luigi Vanvitelli", Via Roma 9, 81031 Aversa, Italy
[b] Department of Industrial Engineering, University of Naples "Federico II", Italy
[c] Seapower scrl, Italy
[d] Department of Engineering, Aarhus University, Denmark

HIGHLIGHTS

- Floating offshore wind turbines are the next frontier in the wind energy sector.
- Life cycle assessment is crucial to the planning of floating offshore wind farms.
- A cost model is developed for life cycle assessment of offshore wind farms.
- CAPEX, OPEX and DECEX are considered in the model.
- A case study of a wind farm located in Southern Italy is developed.

ARTICLE INFO

Keywords:
Wind energy
Offshore wind farms
Floating turbines
Life cycle cost assessment
Economic key parameters

ABSTRACT

Over the last few decades, there has been a renewed interest in the offshore wind sector. In particular, floating wind turbines represent the next frontier in the wind power industry. Currently, only research prototypes exist, and few studies are available on their possible investment cost. Therefore, a cost assessment for this technology is necessary to ascertain whether it is economically sustainable. This paper develops a life cycle cost model for floating offshore wind farms, bringing together the most up-to-date data and parametric equations from databases and literature. The cost model considers the key parameters of the wind power economy, namely CAPEX, OPEX, DECEX and LCOE. The proposed model should be helpful for future decision-making, as the wind energy industry is in constant evolution. An application to an offshore floating wind farms is also carried out, in which the three main types of floaters are considered, namely the Semi-Submersible Platform, the Spar Buoy and the Tension Leg Platform. An average LCOE of 9.74 €c/kWh was found, at the lower bound of the typical range applying to fixed base offshore wind farms, and higher than typical values applying to onshore wind farms.

1. Introduction

Recent years have seen a considerable effort towards the development of offshore wind turbine technology, where alongside shallow water turbines, floating turbines have made their appearance; these represent the next challenge in the wind power industry. The offshore wind sector has reached a global installed capacity of more than 18.8 GW at the end of 2017, almost 84% of which is located in European waters [1]. According to [2] offshore wind power is expected to reach 20% of the total installed power by 2020, having started from to 2% in 2005, corresponding to 34 GW [3]. These figures also reflect the decrease in the costs of offshore wind farms, and the expected shortage of suitable onshore areas for wind generation, especially for densely populated countries or areas prone to high environmental risks [4]. This brought the vision of floating offshore wind energy generation, which has now entered into a prototyping stage. The advantages of floating wind generation are the availability of an almost unlimited resource, together with lower visual and acoustic impact. Moreover, in the deep water environment a larger producibility can be achieved due to higher winds with lower turbulence, the latter being also beneficial to fatigue life [5]. On the other hand, floating offshore wind turbines have the disadvantage of higher complexity and of higher installation, maintenance and decommissioning costs; this is due to restricted site access because of possible harsh weather conditions, expensive installation procedures and high grid connection costs. These aspects make the capital cost of floating wind turbines about twice as large as in

* Corresponding author.
E-mail addresses: carmela.maienza@unicampania.it (C. Maienza), albertomaria.avossa@unicampania.it (A.M. Avossa), francesco.ricciardelli@unicampania.it (F. Ricciardelli), coiro@unina.it (D. Coiro), g.troise@seapowerscrl.com (G. Troise), cg@eng.au.dk (C.T. Georgakis).

https://doi.org/10.1016/j.apenergy.2020.114716
Received 28 October 2019; Received in revised form 17 February 2020; Accepted 21 February 2020
Available online 24 March 2020

shallow waters, where installation is technically and economically consolidated.

In the current literature, few works on the assessment of offshore turbines life cycle costs are available. Most of these show the final result of the cost estimates of wind installations but do not show the calculation model for all the components. Furthermore, almost all of the procedures apply to shallow-water installations and not to floating ones. Guidelines for the assessment of investment cost for shallow-water offshore wind generation are shown in [6], with special attention to the cost associated with different grid connection typologies. An example of economic estimates for shallow-water wind turbines off the Portuguese coast is shown in [7]. The methodologies for the assessment of life cycle costs related to shallow-water offshore installations are highlighted in [8,9]. In particular, they develop a methodology for a life cycle techno-economic assessment for the prediction of costs of shallow-water offshore wind farms, considering technical aspects associated with the installation and maintenance of the asset. In [10], a cost estimate of the different components of an offshore wind power installation, both shallow-water and floating is presented.

Currently, only research prototypes of floating turbines exist. In particular, *Hywind* is the first prototype wind farm using Spar Buoy (SB) platforms; it is located in the North Sea, off the Scottish coast, featuring five turbines with total installed power of 30 MW [11]. *WindFloat* is a single Semi-Submersible Platform (SSP) prototype, located in the Atlantic Ocean off the Portuguese coast [12]. Finally, *Gicon* is a single Tension Leg Platform (TLP) prototype to be installed in the Baltic Sea [13]. Other prototypes are currently being considered for installation.

Indeed, an economic analysis is fundamental to highlight the possible greater potential of floating offshore wind farms, and to support their technical values and sustainability.

Only very few studies are available on criteria for the possible investment costs of floating wind turbines. In [14,15] the costs related to floating wind turbines are shown, considering SSPs, SBs and TLPs. A general methodology to calculate the life cycle cost of floating offshore turbines is developed by Castro-Santos and co-workers. In [16] the methodology is shown and applied to a specific case study in Spain which considers SSPs, SBs and TLPs; in [17] a methodology is defined, which allows evaluating the main mooring and anchoring costs; in [18] the synthesis of the methodology presented in [16] is given; finally, in [19] the procedure is shown to calculate the installation costs of floating offshore wind farms. Though general in principles, this methodology appears to be related in some aspects to the specific application; as a matter of fact the calibration of some of the relevant quantities do come from a particular case. It is concluded that an optimized cost assessment procedure for floating offshore wind turbines would be beneficial when ascertaining economic sustainability.

The aim of this paper is to define a direct approach for the preliminary calculation of the cost of floating offshore wind farms; this is done by integrating existing methodologies with new optimized cost criteria. In particular, cost items common to shallow-water offshore technology are borrowed from the relevant literature, and applied to floating offshore technology. Specific aspects of the floating offshore technology are also taken from the existing literature and merged with the other existing information. There results a self-contained modular procedure which lends itself to refinement and generalization.

The approach should be useful for future decision-making, and can be applied to both SSP, SB, and TLP floaters. A case study located in Southern Italy will be shown as an example.

The paper is expected to push the research of renewable energy one step forward. In particular, it strengthens the scientific research and bridges gaps of floating offshore wind sector.

The paper is organized as follows. In Section 2, the cost assessment model is presented, whose details are given in Appendix A. In Section 3, the model is applied to an offshore floating wind farm project. In Section 4, the results obtained from the model are presented and finally, in Section 5 conclusions are drawn.

2. Cost assessment model

The key parameters of wind power economics are taken into account to carry out a life cycle cost assessment of offshore wind farms. These parameters are the Capital Cost (CAPEX), the Operation and Maintenance Cost (O&M - OPEX) and the Decommissioning Cost (DECEX) [20]. CAPEX is the largest contributor to the life cycle cost of wind farms and includes all investment costs covered before the commercial operation date. OPEX comprises all expenditures incurred after the commercial operation date, but prior to decommissioning, that are necessary to operate the project and guarantee turbine efficiency [21]. CAPEX can be as large as 80% of the total cost of the wind farm project over its entire lifespan and includes the costs of turbine, substructures (platform, mooring and anchoring), and transmission system (cables and substations) [22].

O&M costs sum up to about 20% to 30% of the total costs of a wind farm project. In general, O&M costs are split into fixed and variable. Fixed costs include administrative costs, insurance, grid access fees and service contracts for scheduled maintenance, while variable costs include scheduled and unscheduled maintenance not covered by fixed contracts, replacement parts and materials [23]. Finally, DECEX covers costs of the last stage of wind farm lifespan, and sums up around 1–3% [24]. It includes all the expenditures for cleaning the area or possible repowering of the wind farm. Often, after the dismantling of offshore installations some materials, such as the steel of floating platforms or the aluminium of electrical cables can be sold becoming scrap revenue. In this way, this process implies an income which will be deducted from the costs [25]. The split of CAPEX, OPEX and DECEX is shown in Fig. 1.

In general, some costs depend and others do not depend on the type of offshore installation, and in particular on whether it is shallow-water or floating. Wind turbine, substations and cables do not depend on the type of offshore installation, whereas substructures depend on it. The latter can be fixed or compliant towers for shallow water installation, and can be SSPs, SBs and TLPs for deep water installation. Furthermore, pile foundations are used for the first, whereas a variety of anchoring and mooring systems are used for the latter.

The calculations have been validated by comparing them to real economic data available for offshore existing wind farms. The cost

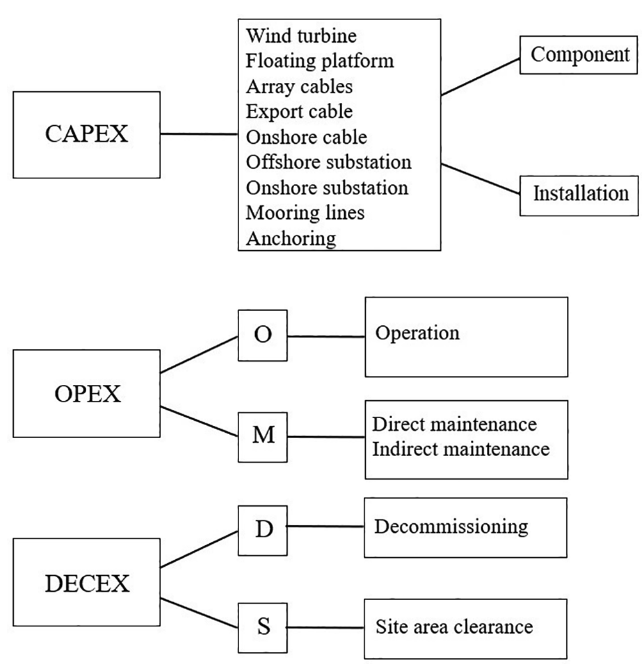

Fig. 1. Economic parameters and corresponding subcomponents of a floating wind farm.

components are evaluated through three different approaches: (i) analytically from knowledge of the details and breakdown of the specific cost under consideration, (ii) as a percentage, and (iii) proportional to the installed power.

In the following subsections, the main expressions of CAPEX, OPEX and DECEX calculations are presented; in Appendix A all the details of the different contributions are given.

2.1. CAPEX calculations

The contributions to CAPEX are mainly calculated analytically and/or as a function of the installed power of the wind farm. Component and installation costs are considered separately, mainly because the former is only moderately dependent on the site of installation, whereas the latter strongly depends on it.

2.1.1. Floating wind farm components

The total components cost C_C consists of the individual cost of the wind turbine C_T, floating platform C_P, transmission system $C_{TS,1}$, $C_{TS,2}$ and $C_{TS,3}$ and finally mooring and anchoring systems, C_M and C_A.

Wind turbine. The cost of the wind turbine is usually expressed as a function of rated power. It does not depend on the type of installation.

Using a linear regression model on the available dataset containing prices of wind turbines with rated power between 2 and 10 MW, the cost (M€) of a wind turbine is given by:

$$C_T = (1.6 \cdot p_T - 1.9) \cdot n_T \tag{1}$$

where p_T is the installed power (MW) of one turbine, and n_T is number of turbines in the farm.

Floating platform. The cost of platforms largely depends on type (Semi-Submersible, Tension Leg, Spar Buoy, etc.), a general expression has been introduced in [18]:

$$C_P = \left(\sum_{i=1}^{3} C_{P,i}\right) \cdot r_P \cdot n_T \tag{2}$$

In Eq. (2) $C_{P,1}$ is the material cost (i.e. steel), which depends on the mass of platform, the unit cost of steel and on the live, dead and internal surface of platform. $C_{P,2}$ is the direct labour cost, which includes preparation, prefabrication and construction of the platforms (i.e. painting and corrosion protection); the direct labour cost depends on the mass of the platform, on the unit cost of direct labour and on the live, dead and internal surface of platform. $C_{P,3}$ is the activities cost (i.e. employee salaries, engineering equipment), which depends on direct labour cost, on material cost and on the mass of platform; a reasonable value is considered to be 5% of the sum of $C_{P,1}$ and $C_{P,2}$ [18]; finally, r_P accounts for industrial profit.

See Appendix A for $C_{P,1}$, $C_{P,2}$ and r_P.

Transmission system. The offshore portion of the transmission system includes array cables, offshore export cable and offshore substation; the onshore portion of the transmission system comprises the onshore cable and the onshore substation. The array cables collect power from the wind turbines and deliver it to the offshore substation or directly to the export cable. The export cable connects the wind farm to an onshore connection substation, and it is divided into offshore export cable and onshore export cable. Therefore, the transmission system cost C_{TS} is [9]:

$$C_{TS} = \sum_{i=1}^{3} C_{TS,i} \tag{3}$$

In general, the total cost of cables, $C_{TS,1}$ is calculated as the product of the unit price of the cable, c_i (€/m in Eq. (4)) and total length of each type of cable, l_i, (m in Eq. (4)). Moreover, the cost of protective equipment (such as J-tube seals, passive seals, bend restrictors etc.) C_{sp}, needed to protect the cables, is added to the total cost of cables. Hence [9]:

$$C_{TS,1} = \sum_{i=1}^{3} (c_i \cdot l_i) + C_{sp} \tag{4}$$

In Eq. (4) i indicates the cable type, that is: Medium Voltage (MV) array cables ($i = 1$), High Voltage (HV) offshore export cables ($i = 2$) and High Voltage (HV) onshore export cables ($i = 3$). In particular, there are two types of HV currents: Alternating Current (HVAC) and Direct Current (HVDC). HVDC systems are used in deep waters with a distance to shore larger than 50 km, as the transmission capability of HVAC reduces with distance because of dielectric losses. HVDC transmission capability instead is independent of distance [26,27]. Therefore, direct current often provides the best technical and economic solution for power transmission to the shore, without being prohibitively expensive in terms of CAPEX [21].

See Appendix A for l_1 and C_{sp}.

Offshore substations stabilize the voltage of power produced offshore, reduce electrical losses and transmit electricity to land. They are generally needed when the installed power of the wind farm is larger than about 100 MW and/or when the farm is very far from shore. In [8] it is suggested that the cost of an offshore substation is calculated as the sum of a fixed cost and a cost proportional to the total installed power. In fact, the variation from linear relationship is negligible and therefore the following simplified expression (M€) can be used, bringing the same results:

$$C_{TS,2} = 0.11 \cdot n_T \cdot p_T \tag{5}$$

Unlike the offshore substation, whose presence depends on some variables, the onshore substation is a fixed component of the wind farm. In the common case of floating installations, in which both onshore and offshore substations are present, the cost of the onshore substation is given as half the cost of the offshore substation [8]:

$$C_{TS,3} = \frac{C_{TS,2}}{2} \tag{6}$$

Mooring and anchoring systems. The cost of mooring lines C_M depends on their mass per unit length, m_M (kg/m in Eq. (7)), on their length, l_M (m in Eq. (7)), on their unit cost, c_M (€/kg in Eq. (7)), on the number of mooring lines, n_M and on the number of turbines n_T. According to these criteria the cost of mooring lines can be defined as [18]:

$$C_M = m_M \cdot l_M \cdot c_M \cdot n_M \cdot n_T \tag{7}$$

The cost of anchors C_A depends on their mass, m_A (kg in Eq. (8)), on the unit cost of anchors, c_A (€/kg in Eq. (8)), on the number of anchors (coincident of the number of mooring lines), n_M, and on turbines n_T [17]. Then, anchoring cost can be given by:

$$C_A = m_A \cdot c_A \cdot n_M \cdot n_T \tag{8}$$

Finally, the cost of both mooring and anchoring systems are strictly affected by the type of floater. In general, steel chains are used for SSPs and SBs, and synthetic fibre (nylon, polypropylene and polyester) ropes moorings are used for TLPs [10,28].

2.1.2. Installation

The total installation cost C_I consists of the individual costs for the installation of the wind turbine C_{IT}, of the floating platform C_{IP}, of the mooring lines and anchoring C_{IMA}, and of the transmission system C_{ITS}. Each installation procedure involves costs depending on a number of variables, e.g. the number of lifts, the crane capacity, the installation time, the type of vessel and number of travels, and the type of assembly of turbine, on whether the assembly is carried out entirely in the port, or partly at sea [21]. The choice of the installation procedure also depends on whether the shipyard allows enough area for storage, and has enough draft for the floater [29]. As the installation procedure varies greatly depending on substructure, distance to port and characteristics of the port, in the following the calculation of installation costs is

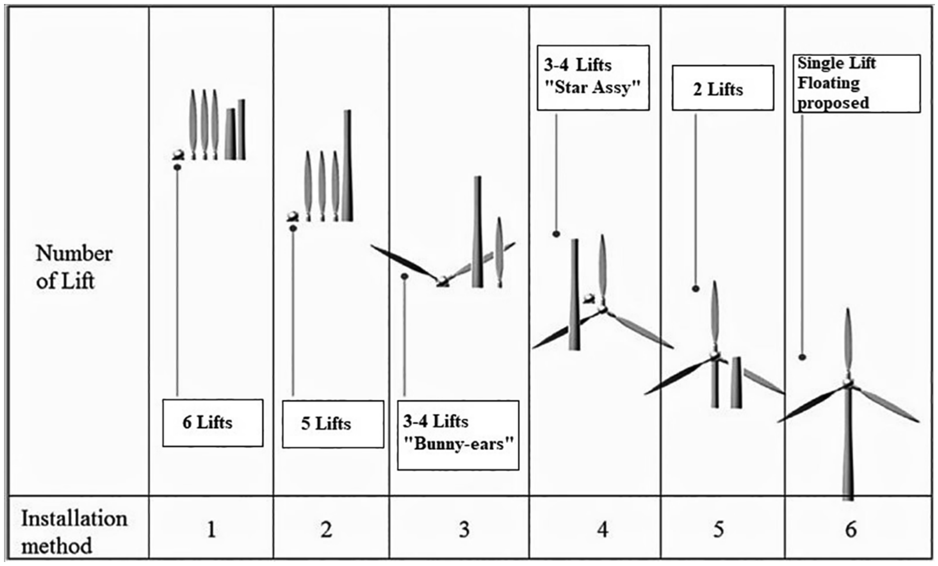

Fig. 2. Different installation methods of wind turbine. Edited from: Ahn et al., 2017.

carried out analytically.

Wind turbine installation. The components of turbine are traditionally at least seven, namely two tower sections, the nacelle, the hub and the three rotor blades. Components can be assembled with different methods, as sketched in Fig. 2. Installation method #6, best suits floating offshore turbines. Multiple turbines can be towed concurrently, increasing transport efficiency by reducing the number of travels and possibly that of towing vessels, for large wind farm installations. The installation cost of a wind turbine is calculated considering the stages in its installation method: the port procedure, whose cost is $C_{IT,1}$, represents the first installation stage, ending with the loading of wind turbine on the vessel; it is followed by transportation, whose cost is $C_{IT,2}$, and ends with the installation at sea, whose cost is $C_{IT,3}$. Then, the total installation cost C_{IT} is given as [19]:

$$C_{IT} = \sum_{i=1}^{3} C_{IT,i} \tag{9}$$

See Appendix A for $C_{IT,1}$, $C_{IT,2}$ and $C_{IT,3}$.

Floating platform installation. The installation process of floater depends on the type of substructure. In general, the installation of SSPs is carried out by tugging the floater to the offshore site; on the other hand, the use of tug and barge vessels and floating cranes with or without storage is required for installation in the case of SBs and TLPs (Fig. 3)). The reason for the different installation procedures derives from the lower draft of SSP substructures as compared to that the other platforms. Also in the case of floating platforms, the installation cost C_{IP} depends on port procedure costs $C_{IP,1}$, on transportation costs $C_{IP,2}$ and on the offshore installation costs of the platform $C_{IP,3}$ [19]:

$$C_{IP} = \sum_{i=1}^{3} C_{IP,i} \tag{10}$$

See Appendix A for $C_{IP,1}$, $C_{IP,2}$ and $C_{IP,3}$.

Mooring and anchoring installation. The installation cost of mooring and anchoring C_{IMA} is calculated considering a specialized vessel in this field, the Anchor Handling Vehicle (AHV); installation takes into account the AHV cost, $c_{IMA,1}$ (€/day in Eq. (11)), the cost of direct labour, $c_{IMA,2}$ (€/day in Eq. (11)), the number of moorings n_M and, finally, the installation rate $r_{IMA,1}$ (anchors/day in Eq. (11)) as [16]:

$$C_{IMA} = (c_{IMA,1} + c_{IMA,2})\cdot\frac{n_M}{r_{IMA,1}} \tag{11}$$

Transmission system installation. For the installation of the transmission system, a Cable Laying Vessel (CLV) is generally used. A combination between tug and barge vessels is also an option [30]. In the following the use of CLV is considered for the calculations. In particular, the installation cost of array cables $C_{ITS,1}$ depends on the daily rate of CLV, $c_{ITS,1}$ (€/day in Eq. (12)), on the installation rate of the 20 kV electric cable, $k_{ITS,1}$ (m/day in Eq. (12)), on the array cables length, l_1 (m in Eq. (12)) and on the number of array cables, n_1 as follows [19]:

$$C_{ITS,1} = \frac{c_{ITS,1}}{k_{ITS,1}}\cdot l_1\cdot n_1 \tag{12}$$

Similarly, the export cable installation cost $C_{ITS,1,}$ depends on $c_{ITS,1}$ (€/day in Eq. (13)), on the installation rate of the 220 kV electric cable, $k_{ITS,2}$ (m/day in Eq. (13)), on the export cable length, l_2 (m in Eq. (13)) and on the number of export cables, n_2 as follows [19]:

$$C_{ITS,2} = \frac{c_{ITS,1}}{k_{ITS,2}}\cdot l_2\cdot n_2 \tag{13}$$

The installation cost of the onshore cables is given as the product of the unit installation cost, $c_{ITS,3}$ (€/m in Eq. (14)), of the length of single cable, l_3 (m in Eq. (14)) and of the number of cables n_3; thus [19]:

$$C_{ITS,3} = c_{ITS,3}\cdot l_3\cdot n_3 \tag{14}$$

The offshore substation can be either floating or submerged, and the former case is considering in the following. This brings a similar calculation scheme to that already discussed for the floating platforms. As a consequence the corresponding cost depends on the number of substation platforms $n_{ITS,4}$, on shipyard costs $C_{ITS,4,1}$, on transportation cost $C_{ITS,4,2}$, and on the cost of installation at sea $C_{ITS,4,3}$. It is evaluated as follows [19]:

$$C_{ITS,4} = C_{ITS,4,2} + (C_{ITS,4,1} + C_{ITS,4,3})\cdot n_{ITS,4} \tag{15}$$

See Appendix A for $C_{ITS,4,1}$.

The installation procedure of onshore substation depends on the characteristics of the foundation soil. Therefore, the installation cost depends on the cost of soil preparation, $C_{ITS,5,1}$, on the cost of foundation, $C_{ITS,5,2}$, and on the installation cost using cranes, $C_{ITS,5,3}$ (all expressed in € in Eq. 16) [19]. This cost can be calculated as:

$$C_{ITS,5} = \sum_{j=1}^{3} C_{ITS,5,j} \tag{16}$$

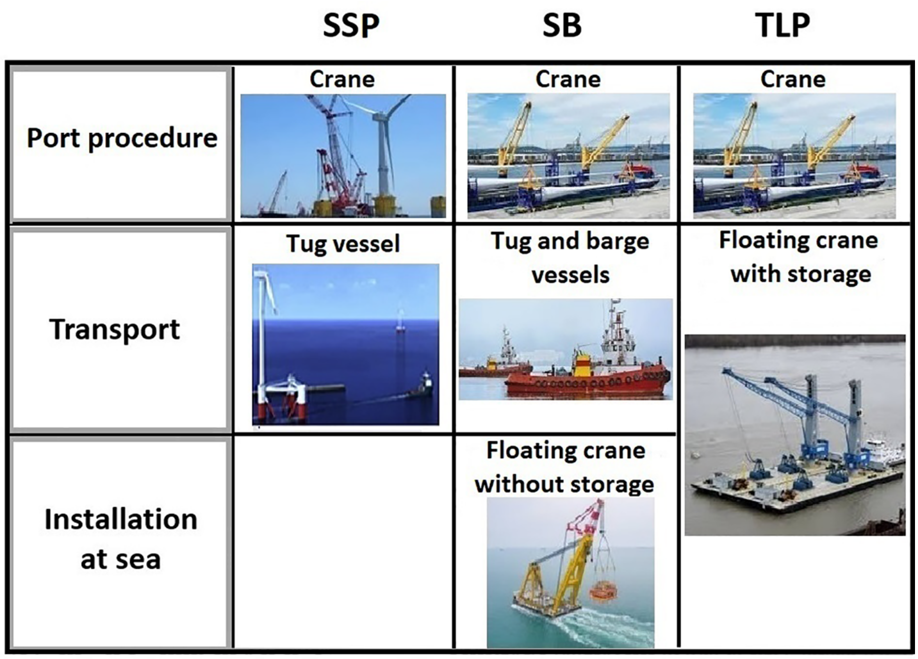

Fig. 3. Different installation methods of floating platforms.

2.2. OPEX cost calculations

The contributions to OPEX are also calculated analytically and/or as a function of the installed power of the wind farm.

Operational expenditures. Operational expenditures, C_O (€ in Eq. (17)), comprise the cost of seabed rental, $C_{O,1}$, insurance, $C_{O,2}$, and grid access fees, $C_{O,3}$. Thus, operational expenditures can be given by [8]:

$$C_O = \sum_{i=1}^{3} C_{O,i} \tag{17}$$

See Appendix A for $C_{O,1}$, $C_{O,2}$ and $C_{O,3}$.

Maintenance expenditures. Maintenance expenditures, C_{MD}, are split into direct and indirect costs. Direct costs are given as the sum of preventive, C_{MD1}, and corrective maintenance, C_{MD2}:

$$C_{MD1} = \sum_{i=1}^{m} p_i \cdot r_{f,i} \cdot C_{MD,1,i} \tag{18}$$

$$C_{MD2} = \sum_{i=1}^{m} [(1 - p_i) \cdot r_{f,i} \cdot C_{MD,2,i}] \tag{19}$$

See Appendix A for $C_{MD,2,i}$.

The former includes all actions aimed at avoiding failure of a component and its downtime, and represents a fixed cost; on the other hand, the latter refers to actions taken after a breakdown has happened [31]. Moreover, direct costs have a minimum value corresponding to the optimal solution, as sketched in Fig. 4.

In Eqs. (18) and (19) $C_{MD,1,i}$ is the direct cost associated with preventive maintenance of the $i-th$ component; $C_{MD,2,i}$ is the cost associated with the corrective maintenance action of the $i-th$ component; $r_{f,i}$ is the annual failure rate of the turbine component; $p_i \in [0, 1]$ is the probability that failure of $i-th$ component can be anticipated, therefore its occurrence avoided.

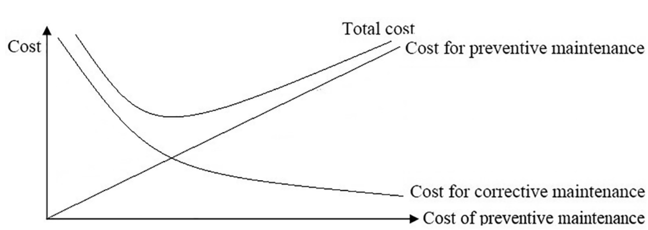

Fig. 4. Balance between preventive and corrective maintenance.

The direct cost associated with any maintenance activity is lower if this is performed in a preventive form, than it is done as corrective maintenance.

Indirect maintenance expenditures include fixed costs faced to guarantee repair services. According to [8], these expenses can be given by:

$$C_{MI} = \sum_{i=1}^{3} C_{MI,i} \tag{20}$$

where $C_{MI,1}$, $C_{MI,2}$, $C_{MI,3}$ are the port fees, vessel hiring fixed costs and maintenance planning and managing costs, respectively. In particular, port fees must be paid for the storage of spare parts and for the use of dock facilities. Furthermore, vessels need to be rented for maintenance activities. Finally, coordination activities take place onshore, such as weather forecasting and repair activity planning [8].

2.3. DECEX cost calculations

DECEX includes the expenditures for decommissioning and site clearance. Contributions to DECEX are generally calculated as a percentage of installation procedures costs. After decommissioning, the site must be cleared according to approved regulations. Hence, site clearance involves the removal of all assets of the offshore wind farm from the site area.

Decommissioning and site clearance. Decommissioning is the cost related to the final stage of a wind project lifetime (25–30 years). All the components of the farm are dismantled: wind turbines, floating platforms, mooring lines, anchoring and transmission system. In the case of floating wind farms, impact on seabed is lower than for fixed offshore wind farms; therefore, decommissioning costs are lower. Decommissioning costs are calculated as the sum of percentages of installation costs and components costs, and can be expressed as follows:

$$C_D = \sum_{i=1}^{4} C_{D,i} + C_{SC} \tag{21}$$

where $C_{D,1}$ is the dismantling costs of the complete floating system, $C_{D,2}$, $C_{D,3}$ and $C_{D,4}$ are the dismantling costs of cables, of substations and of mooring and anchoring systems; C_{SC} is the site clearance cost.

Literature values of $C_{D,1}$, $C_{D,2}$, $C_{D,3}$ and $C_{D,4}$ will be assumed, equal to 70%, 10%, 90% and 90% of the corresponding installation costs, respectively [10,28].

The site clearance cost, C_{SC}, will be calculated multiplying the area to be cleared, A, by the clearance cost per unit area, c_{SC} [8]:

$$C_{SC} = A \cdot c_{SC} \tag{22}$$

In Eq. (22), A is the area to be cleared, to be calculated based on geometry of the farm.

2.4. Levelized cost of energy calculation

The Levelized Cost of Energy (LCOE) is used to compare the cost of energy coming from different sources (e.g. wind, solar, natural gas). It represents the net present value of the unit cost of electricity produced. In this particular case, LCOE corresponds to the ratio between the average price at which the energy produced over the entire life of the wind project must be sold to exactly match all the costs incurred for construction, management and decommissioning of the farm. It is given by the ratio between the levelized cost of the wind project (CAPEX, OPEX and DECEX) and the Annual Energy Production (AEP), that corresponds to the total energy production over the lifetime of the wind project [32]:

$$LCOE = \frac{CAPEX + OPEX + DECEX}{AEP} \tag{23}$$

LCOE strongly depends on different input parameters such as the capacity factor, distance to shore, water depth etc. and has therefore to be regarded as a site specific value. Moreover, with the use of LCOE it is possible to optimize the design of the wind farm by analysing key aspects during the planning and pre-design phase [32].

Finally, LCOE can be reduced by incentives, such as tax exemptions or tax credits and by the system positioning, optimized for maximum energy output.

3. Cost model application

The proposed cost model is applied to a case study located in Southern Italy. In particular, the farm is placed in a marine area where the mean wind speed Weibull parameters are $a = 7.7$ m/s and $k = 1.574$ (corresponding to an average mean wind velocity of 6.94 m/s). In Table 1 and Fig. 5 some details of farm and the wind rose are shown respectively.

The farm is arranged in two rows and it covers a total area of around 16 km^2 (Fig. 6). Turbines are placed at a distance of seven rotor diameters from each other. The chosen arrangement of wind turbines is a trade-off between the conflicting needs of maximising producibility and minimising wake losses.

The cost model is applied to three different platform solutions (SSP, SB and TLP). The choice of 5 MW turbines stems from the availability of well-established data.

Tables 2,3 show the general properties of the wind turbine and floating platforms, respectively.

Table 1
Wind farm characteristics.

	Unit	Value
Number of turbines	–	25
Total wind farm power	MW	125
Distance from wind farm to port	km	165
Distance from wind farm to shore	km	16
Water depth	m	130–140

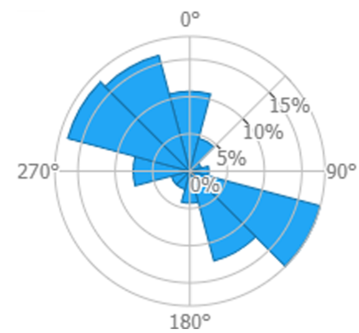

Fig. 5. Wind rose at offshore site. Source: Global Wind Atlas.

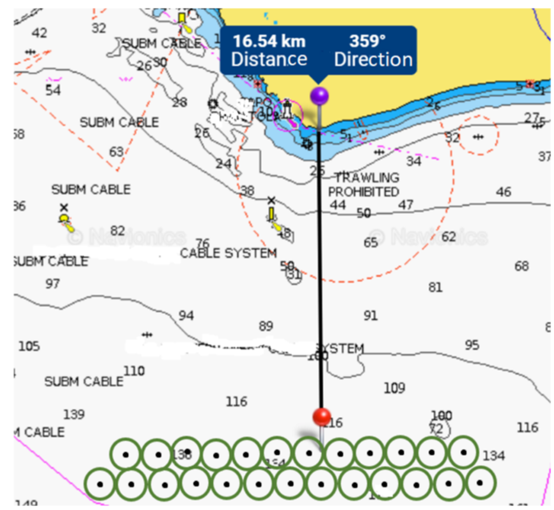

Fig. 6. Layout of the offshore wind farm. Edited from Navionics.

Table 2
Wind turbine characteristics.

	Unit	Value
Turbine power	MW	5
Hub height	m	90
Rotor diameter	m	126
Blade length	m	61.50
Tower diameter	m	6,00
Cut-in speed	m/s	3
Rated speed	m/s	11.4
Cut-out speed	m/s	25

Table 3
Floating platform characteristics.

	Unit	SSP	SB	TLP
Mass of platform	*ton*	696	989	965
Maximum freebord of platform	m	12	–	–
Draft of platform	m	10	120	45
Inferior pontoon diameter	m	2	–	3
Maximum horizontal dimension of platform	m	76	9.40	54
Mass of anchoring	*ton*	3.15	3.15	8.1
Number of mooring lines per platform	–	6	3	8
Mass of each mooring lines	*ton*	22.1	31.0	0.58
Length of mooring	m	450	390	85

Steel chains are used for the mooring lines of SSP and SB platforms whereas synthetic fibre ropes are used for the TLP platforms. The formers have a weight of 177 kg/m; the latter has a weight of 10.68 kg/m. Foundations with plate anchors were considered for the SSP, SB and TLP platforms.

The cost model application was made considering the following design parameters: wind speed, distance from coast, distance from port and water depth. In addition, site constraints such as available and protected areas have been considered. The site has been chosen based on its mean wind climate. The distance from the coast has been chosen such to locate the farm within national waters and to minimize visual impact. Finally, the closest port has been chosen among those having the required infrastructures.

Regarding the installation phases, different methods have been considered. In particular, for SSPs onshore installation with the use of a crane and wet transportation of the assembled wind turbine and floater using a tug vessel, was considered. For SBs, dry transport of the wind turbine and wet transport of the floater was considered, with an offshore assembly; to this purpose, an onshore crane, a tug and a barge vessel and a floating crane without storage are used. Finally, for TLPs a floating crane with a storage area is used for transport of both the turbine and floater, and for their offshore installation.

Transmission system installation requires the use of a CLV for the cables, of a rock-dumping vessel for the scour protection, of a crane, of a tug and/or a barge vessel for the offshore substation, and of a crane for the onshore substation. Installation of anchoring and mooring systems requires the use of an AHV.

Regarding maintenance activities, eight technicians were considered for fixing and/or replacing damaged parts (corrective maintenance), and four technicians·day, three times a year for preventive maintenance. More details concerning the incidence of corrective and preventive maintenance can be found in [33,16].

The cost of cables, the daily rate of vessels and the cranes used during the installation procedures, the labour cost, and the general parameters regarding the installation activities are shown in Tables 4–7, respectively. These values have been taken from [16,9,33] where detailed lists of sources are given. In particular, the cost of cables is derived as an average of those of different manufacturers. The daily rate of vessel and cranes, the labour cost and the parameters regarding the installation activities are derived from different technical and economic assumptions. These are based on quotes from consultants and contractors in the marine sector, about the construction and installation process, and the costs of labour and equipment. Further details can be found in [34–36].

4. Results

The results obtained through the application of the cost model to the case study wind farm are shown in Table 8. The final costs are especially influenced by the types of substructure chosen (floating platform, mooring lines and anchoring), by the installation methods and, finally, by the distance from the port/shipyard and from the coast to the installation site. The costs of turbine, array cables, offshore export cable, onshore export cable, cables installation, offshore and onshore substations, and the total OPEX are the same in the three cases, as they are independent of the type of substructure. On the other hand, other costs in fact depend on substructure.

There results that the use of a SSP is the most cost-effective solution, whereas the TLP turns out to be the most expensive solution (Table 8).

Taking as a reference the SSP solution, there results that higher cost of the SB solution (+17 M€) derives from the floating platform (+41 M€), from the installation of the turbine (+1.6 M€) and from the installation of the floating platform (+1.5 M€). However, there is a lower cost of mooring lines (−17 M€) and of their installation (−4.2 M€) (Table 9). Still referred to the SSP solution, there results that the

Table 4
Unit costs of cables.

	Unit	Value
Array cable	€/m	279
Offshore Export cable	€/m	336
Onshore cable	€/m	83

Table 5
Rates of vessels and cranes used for transport and installation of the wind farm.

	Unit	Value
Tug vessel	€/day	22,500
Barge vessel	€/day	35,000
Cable Laying Vessel	€/day	91,000 (Array), 114,000 (Export)
Anchor Handling Vehicle	€/day	48,900
Rock-dumping vessel	€/day	13,800
Crane at port	€/h	833
Floating crane without a storage area	€/day	116,000
Floating crane with a storage area	€/day	811,900

Table 6
Labour cost details.

	Unit	Value
Hourly labour rate for CAPEX activities	€/h	27
Technician daily cost for corrective maintenance	€/day	200

Table 7
General parameters regarding the installation of Wind Turbine (WT) and Floating Platform (FP).

	Unit	SSP	SP	TLP
Number of lifts at port/shipyard of the WT/FP for their loading in the vessel	–	1	1	1
Number of lifts at sea	–	0	1	1
Time required for the lift at port/shipyard	h	3	3	3
Time required for the lift at sea	h	–	3	3
Time between movements while the offshore WT/FP is being installed	h	8	8	8
Speed of tug and barge vessels	m/s − kts		3.6 (1.86)	
Speed of floating crane	m/s − kts		3.09 (1.59)	

Table 8
Economic calculations results based on the different floating platform (M€).

		SSP	SB	TLP
CAPEX	Turbine		151.2	
	Floating platform	95.6	136.9	131.0
	Array cables		6.58	
	Offshore export cable		5.37	
	Onshore cable		0.833	
	Offshore substation		13.8	
	Onshore substation		6.89	
	Mooring lines	30.3	13.2	1.26
	Anchoring	0.945	0.473	3.24
	Turbine installation	0.625	2.27	7.05
	Floating platform installation	4.34	5.86	23.6
	Array cables installation		20.0	
	Offshore export cable installation		9.12	
	Onshore cable installation		6.00	
	Offshore substation installation		4.38	
	Onshore substation installation		1.04	
	Mooring & Anchoring installation	8.47	4.24	11.3
OPEX	Operation		12.6	
	Direct maintenance		82.9	
	Indirect maintenance		1.50	
DECEX	Decommissioning	20.7	19.5	41.6
	Site clearance area		0.903	
	Total	**482.97**	**500.46**	**541.63**

Table 9
AEP, wake loss and LCOE of floating offshore wind farms.

	Unit	Value		
AEP	MWh		316314	
Wake loss	%		5.26	
LCOE	€/MW*h*	SB	SSP	TLP
		94,17	91,97	106,70

higher cost of the TLP solution (+59 M€) derives mainly from the floating platform (+35 M€), from decommissioning (+21 M€), from the installation of the floating platform (+19.3 M€) and from the installation of the turbine (+6.4 M€). In this case, there is a lower cost of the mooring lines (−29 M€) (Table 8).

More details on the cost differences are given below. The installation of turbine and floating platform is less expensive in the case of SSPs, as these components are assembled at port and tugged together to the offshore site by a single vessel trip. On the other hand, for the SB and TLP solutions more travels are required to bring the floater and the turbine to the offshore site. Moreover, the installation of the TLP is the most expensive due to its complex mooring and anchoring systems. This makes decommissioning also more expensive as its cost is proportional to the installation cost.

The percentages of CAPEX, OPEX and DECEX for each type of wind turbine installation are shown in Fig. 7. CAPEX covers the largest percentage in all cases, ranging from 74% to 77%. OPEX is almost independent of the type of installation, ranging between 19% and 20%. DECEX is observed to be much larger when TLPs are used, 10% as opposed to 4% for SPPs and SBs; this is to be ascribed to the larger dismantling costs, deriving from larger installation costs. In general, the results presented in terms of CAPEX and OPEX are in good agreement with the outcomes similar studies available in the literature [22]. On the other hand, values of DECEX are found to be larger than those available in the literature [24].

As final outcome LCOE is also estimated. To this purpose the AEP of the floating offshore wind farm was calculated using WAsP software. First of all, Map Editor was used to provide topographical inputs to the software. Then, wind data are derived from the Global Wind Atlas [37], for the particular hub height of 90 m.

Moreover, several farm design arrangements were considered, and the final layout was chosen such to minimize wake losses (Fig. 8). To this aim, the WAsP software uses the PARK model [38] to estimate the wake interaction between turbines and the related production losses for the given wind climate.

The results obtained in terms of LCOE reflect those found in terms of total costs, with an average value for the different types of wind farm installation similar to each other (Table 9). The little differences observed in the LCOE values reflect those of the total cost already pointed out in the previous section.

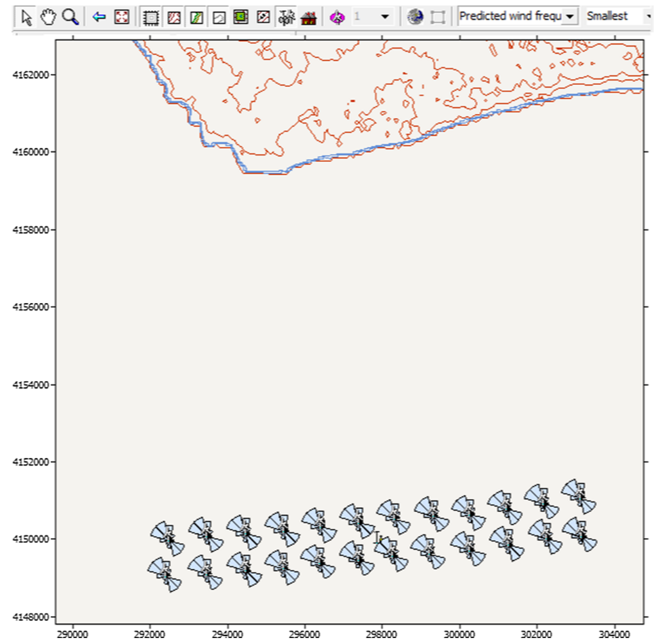

Fig. 8. Layout of floating wind farm. Source: WAsP software.

5. Conclusions

The analysis of the current literature shows that a complete and widely applicable model for the evaluation of the life cycle costs of floating offshore wind farms is not available. This paper proposes a simplified and easily applicable model, lending itself to preliminary evaluations in feasibility studies and in the decision-making processes. It can be easily implemented in a spreadsheet and the different cost components can be modified to meet alternative criteria, in case more accurate evaluation methods become available.

The proposed model considers the key parameters of the wind power economy, namely CAPEX, OPEX, DECEX and LCOE, in the estimation of life cycle costs applying to different types of floaters, namely founded on Semi-Submersible Platforms, Spar buoy, and Tension leg Platform. The model was applied to a case study in Southern Italy, located in a site characterized by a rather high mean wind speed and limited distance from the main ports. The total life cycle costs for Semi-Submersible Platform, Spar Buoy and Tension Leg Platform solutions have been evaluated; this shows that the Semi-Semisubmersible Platform solution is the most cost-effective. Most of the economy derives from the lower cost of the floater and its installation at sea. On the other hand, the Tension Leg Platform solution turns out to be the most expensive, also due to higher installation and decommissioning costs.

As further outcome, the LCOE for each wind farm installation was also calculated. The results show that LCOE is comparable among the three different solutions considered; the little differences observed

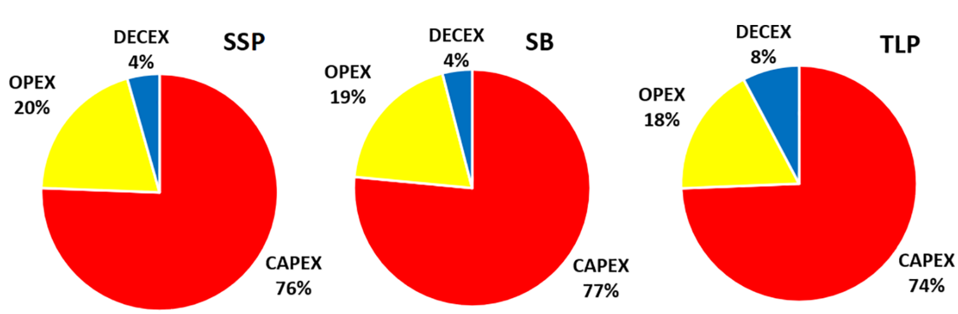

Fig. 7. Split of CAPEX, OPEX and DECEX for SSP, SB and TLP.

reflect the slightly different values of CAPEX, OPEX and DECEX. An average value of LCOE of 9.74 $€c/kWh$ was found; this is at the lower bound of the typical range of 9 to 18 $€c/kWh$ applying to fixed base offshore wind farms, and is higher than typical values of 5 to 8 $€c/kWh$ applying to onshore wind farms.

CRediT authorship contribution statement

C. Maienza: Conceptualization, Methodology, Software, Writing - review & editing, Project administration. **A.M. Avossa:** Conceptualization, Validation, Formal analysis, Data curation, Writing - review & editing, Supervision. **F. Ricciardelli:** Conceptualization, Validation, Formal analysis, Data curation, Writing - review & editing, Supervision. **D. Coiro:** Writing - review & editing, Supervision. **G. Troise:** Writing - review & editing, Supervision. **C.T. Georgakis:** Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Some of the results presented in this paper have been produced using equipment founded by the Italian Ministry for University (MIUR), in the framework of the research project GELMINCAL (Project number PONa3_00308). Founding is acknowledged.

The Italian Ministry for University (MIUR) is also acknowledged for founding the PhD Scholarship of the first author (PON 2014-2020 - DOT 1349551).

Appendix A

Floating platform. The material cost of floating platform is estimated as [16]:

$$C_{P,1} = \sum_{j=1}^{3} C_{P,1,j} \tag{24}$$

$C_{P,1,1}$ is the cost of steel used for the platform; $C_{P,1,2}$ includes the cost of material used in the preparation and painting of the platform surface; $C_{P,1,3}$ comprises the material cost of auxiliary equipment used (mainly ballast).

The direct labour cost of the floating platform is calculated considering the hours of labour $h_{L,i}$ and the hourly cost of labour c_L [16]:

$$C_{P,2} = \sum_{i=1}^{3} h_{L,i} \cdot c_L \tag{25}$$

c_L is taken into account as a fixed cost; $h_{L,1}$ includes the preparation, prefabrication and construction of the platform and it is dependent on the mass of platform; $h_{L,2}$ comprises the preparation (priming and blasting), painting and corrosion control on the surface of platform; $h_{L,3}$ are the installation hours of the auxiliary equipment of platforms.

Industrial profit r_P is equal to [16]:

$$r_P = (1 + TAE)^{t_P} \tag{26}$$

Where TAE is given by:

$$TAE = Euribor + 4.5\% \tag{27}$$

Euribor is the rate at which Euro interbank term deposits are offered by one prime bank to another prime bank within the Economic and Monetary Union (EMU) zone. Finally, t_P represents the construction period of a single platform (years in Eq. (26)).

Cables. The total length of array cables l_1 is given considering the rotor diameter, d (m in Eq. (28)), the water depth of the installation site, w_δ (m in Eq. (28)) and the number of wind turbines, n_T:

$$l_1 = (7 \cdot d + w_\delta) \cdot (n_T - 1) \tag{28}$$

The length of the offshore export cable, l_2, is assumed equal to the distance between the centre of the wind farm and the shore. Finally, the length of the onshore export cable, l_3, is equal to the distance from the onshore substation to the grid connection point.

Scour protection is estimated considering the total effective days for its installation, t_{sp} (days in Eqs. (29), (30)), the daily rate of rock-dumping vessel, $c_{sp,1}$ (€/day in Eq. (29)) and mobilization cost of operations, $C_{sp,2}$ (€ in Eq. (29)) [9]:

$$C_{sp} = t_{sp} \cdot c_{sp,1} + C_{sp,2} \tag{29}$$

where t_{sp} is calculated as:

$$t_{sp} = \frac{t_{sp,net}}{k_t} \tag{30}$$

$t_{sp,net}$ represents the total time for scour installation (days in Eq. (30)) and finally, k_t accounts the loss coefficient due to downtime (assumed equal to 0.75).

Wind turbine installation. Port procedure cost $C_{IT,1}$ are split into two parts consisting of hiring of port or shipyard surface costs, and loading and lifting costs. These costs depend on the hired surface of port or shipyard installations for the installation procedure of one wind turbine, $A_{IT,1}$ (m^2 in Eqs. (31), (38)), on the time of hiring of port or shipyard installations for the installation process of one wind turbine, $t_{IT,1}$ (days in Eq. (31)), on the hiring cost of the storage surface, c_s (€/(m^2 day) in Eq. (31)), on the number of turbines, n_T, on the time required to load the wind turbine in the vessel, t_{LT} (h in Eq. (31), (39)) and finally, on the cost of port crane, c_c (€/h in Eq. (31)) [19]:

$$C_{IT,1} = A_{IT,1} \cdot t_{IT,1} \cdot c_s + n_T \cdot t_{LT} \cdot c_c \tag{31}$$

In particular, $t_{IT,1}$ depends on platform type (SB, SSP or TLP) and can be estimated as the storage or waiting time of the components at port during the installation phases. It is equal to zero for SSPs because turbine is installed together with the floating platform, while it is expressed as function of times $t_{A,1}$, $t_{A,2}$ and $t_{A,3}$ in the case of SBs, and of times $t_{A,3}$ and $t_{A,4}$ in the case of TLPs. The times $t_{A,1}$, $t_{A,2}$, $t_{A,3}$, $t_{A,4}$ refer to the barge, tug, crane and floating crane, respectively. These are strictly related to the time spent for the installation stages, and depend on various parameters such as: the distance from port to the offshore location, d_p (m in Eqs. (33), (34), (37)), the speed of barge and tug vessels, v_t (m/s in Eqs. (33), (34)), the speed of floating crane, v_{t1} (m/s in Eq. (37)), the number of wind turbines per travel $n_{BT,1,2,3}$, the time between movements while the offshore wind turbine is being installed, t_{iT} (h in Eq. (35)), the time required to load the wind turbine on the vessel, t_{LT} (h in Eq. (33), (37)), the downtime k_t, and, finally, the time for installing the wind turbine offshore with lifts, t_{imT} (h in Eq. (35)).

In the case of SB, $t_{IT,1}$ is given as:

$$t_{IT,1} = t_{A,1} + t_{A,2} + t_{A,3} \tag{32}$$

where

$$t_{A,1} = \frac{(\frac{2}{3600}\cdot\frac{d_p}{v_t} + n_{BT,1}\cdot t_{LT})\cdot\frac{1}{k_t}\cdot\frac{n_T}{n_{BT,1}}}{24} \tag{33}$$

$$t_{A,2} = \frac{(\frac{2}{3600}\cdot\frac{d_p}{v_t})\cdot\frac{1}{k_t}\cdot\frac{n_T}{n_{BT,2}}}{24} \tag{34}$$

$$t_{A,3} = \frac{(t_{iT} + t_{imT})\cdot\frac{1}{k_t}\cdot n_T}{24} \tag{35}$$

In the case of SSPs, $t_{IT,1}$ is equal to zero, and the corresponding hiring of port or shipyard surface costs is also zero.

In the case of TLPs $t_{IT,1}$ is given by:

$$t_{IT,1} = t_{A,3} + t_{A,4} \tag{36}$$

where

$$t_{A,4} = \frac{(\frac{2}{3600}\cdot\frac{d_p}{v_{t1}} + n_{BT,3}\cdot t_{LT})\cdot\frac{1}{k_t}\cdot\frac{n_T}{n_{BT,3}}}{24} \tag{37}$$

The hired surface of port or shipyard installations for the installation procedure of wind turbines $A_{IT,1}$ is calculated considering the blade length, l_b (m in Eq. (38)), the blade diameter, d_b (m in Eq. (38)) and the tower diameter, d_t (m in Eq. (38)):

$$A_{IT,1} = 3\cdot n_T\cdot\left[l_b\cdot d_b + \pi\cdot(\frac{d_t}{2})^2\right] \tag{38}$$

Finally, the time required to load the wind turbine in the vessel t_{LT} is given by the number of liftings for the complete loading of wind turbine in the vessel n_{LT} and the time required to each lift of the wind turbine component, t_{LIT} (h in Eq. (39)):

$$t_{LT} = n_{LT}\cdot t_{LIT} \tag{39}$$

The transportation cost of wind turbine $C_{IT,2}$ and its installation cost at sea $C_{IT,3}$ depend on the installation scenario. Moreover, the installation at sea of the wind generator is affected by the numbers of tug and barge vessels used n_t and n_b, by their daily costs, c_t and c_b (€/day in Eq. (40)), and by their mobilization costs C_{tm} and C_{bm} (€ in Eq. (40)), respectively.

In particular, the transportation cost of wind turbine in the case of SBs, and its installation cost at sea are estimated as [19]:

$$C_{IT,2} = n_t\cdot t_{A,1}\cdot c_t + n_b\cdot t_{A,2}\cdot c_b + C_{tm} + C_{bm} \tag{40}$$

$$C_{IT,3} = n_c\cdot t_{A,3}\cdot c_c + C_{cm} \tag{41}$$

where n_c is the number of cranes without a storage area for the installation at sea, c_c (€/h in Eq. (41)) is the daily cost of cranes and, finally, C_{cm} (€ in Eq. (41)) is the mobilization cost.

In the case of SSPs, the costs of transportation, $C_{IT,2}$, and installation at sea, $C_{IT,3}$, are equal to zero [19] and the hiring of port or shipyard surface costs and lifting costs are also zero.

Finally, for TLPs the costs of transportation and installation at sea are calculated according to the following expression [19]:

$$C_{IT,2} = n_{cs}\cdot t_{A,2}\cdot c_{cs} + C_{csm} \tag{42}$$

where n_{cs} is the number of floating cranes with a storage area used for transportation, c_{cs} (€/day in Eq. (42)) is its daily cost and, finally, C_{csm} (€ in Eq. (42)) represents its mobilization cost.

The cost of installation at sea $C_{IT,3}$ is calculated similarly to the SB case.

Floating platform installation. Port procedure cost $C_{IP,1}$ is also split in two parts, as well as the corresponding term considered in wind turbine installation. In particular, $C_{IP,1}$ is estimated taking into account the hired surface of port or shipyard installations for the installation procedure of floating platform, $A_{IP,1}$ (m^2 in Eqs. (43), (44), (46)), the time of hiring port or shipyard installations for the installation process of floating platform, $t_{IP,1}$ (days in Eq. (43)), the hiring cost of the storage surface, c_s (€/(m^2 day) in Eq. (43)), the number of turbines, n_T, the time required to load the floating platform on the vessel, t_{LP} (h in Eqs. (43), (45), (48)) and, finally, the cost of port crane, c_c (€/h in Eq. (43)) [19]:

$$C_{IP,1} = A_{IP,1}\cdot t_{IP,1}\cdot c_s + n_T\cdot t_{LP}\cdot c_c \tag{43}$$

Calculation of $A_{IP,1}$ comprises the surface for storing the floating platforms, A_{SP} (m^2 in Eq. (44)), and it is calculated as follows:

$$A_{IP,1} = A_{SP} + n_s\cdot(l_{TS} + l_{GIS})^2 \tag{44}$$

where n_s is the number of substation platforms, l_{TS} (m in Eq. (44)) is the electric transformer length, and l_{GIS} (m in Eq. (44)) is the Gas Insulated Switchgear *GIS* length.

t_{LP} is given by the number of liftings of the floating platform for its loading on the vessel, n_{LP}, and the time needed to lift the floating platform and install it, t_{LIP} (h in Eq. (45)):

$$t_{LP} = n_{LP} \cdot t_{LIP} \tag{45}$$

The transportation cost of floating platform $C_{IP,2}$ and its offshore installation cost $C_{IP,3}$ depends on the installation scenario. Consequently, different installation methods are considered and the specific calculations are listed below.

In the case of SBs $t_{IP,1}$ is estimated taking into account $t_{A,5}$, $t_{A,6}$ and $t_{A,7}$, that are the operation times of floating crane, barge and tug, respectively. These times depend on different parameters, as: the distance from port to the offshore location, d_p (m in Eqs. (47)–(49)), the speed of barge and tug vessels, v_t (m/s in Eqs. (48), (49)), the speed of floating crane, v_{t1} (m/s in Eq. (47)), the time for installing and lifting the floating platform offshore, t_{iP} (h in Eq. (47)), the time between movements while the floating platform is being installed, t_{imp} (h in Eq. (47)), the downtime k_t, the time required to load the floating platform in the vessel, t_{LP} (h in Eq. (48)) and, finally, the numbers of floating platforms per boat transported $n_{BP,1,2,3}$ for different types of vessel [19]. In particular:

$$t_{IP,1} = t_{A,5} + t_{A,6} + t_{A,7} \tag{46}$$

$$t_{A,5} = \frac{\left(\frac{2}{3600} \cdot \frac{d_p}{v_{t1}}\right) + (t_{iP} + t_{imp}) \cdot \frac{1}{k_t} \cdot n_T}{24} \tag{47}$$

$$t_{A,6} = \frac{\left(\frac{2}{3600} \cdot \frac{d_p}{v_t} + n_{BP,1} \cdot t_{LP}\right) \cdot \frac{1}{k_t} \cdot \frac{n_T}{n_{BP,1}}}{24} \tag{48}$$

$$t_{A,7} = \frac{\left(\frac{2}{3600} \cdot \frac{d_p}{v_t}\right) \cdot \frac{1}{k_t} \cdot \frac{n_T}{n_{BP,2}}}{24} \tag{49}$$

The hired surface of port or shipyard installations for the installation procedure of SB floaters A_{SP} is calculated considering l_f, d_P and l (m in Eq. (50)), that are the maximum freeboard, draft and length of SB platforms, respectively [19]:

$$A_{SP} = n_T \cdot (l_f + d_P) \cdot l \tag{50}$$

The transportation cost of SB floaters, $C_{IP,2}$, and its offshore installation cost, $C_{IP,3}$, are estimated as follows [19]:

$$C_{IP,2} = n_b \cdot t_{A,6} \cdot c_b + 2 \cdot n_t \cdot t_{A,7} \cdot c_t + C_{bm} + 2 \cdot C_{tm} \tag{51}$$

$$C_{IP,3} = t_{A,5} \cdot c_c + C_{cm} \tag{52}$$

where calculations include the numbers of tugs and barge vessels used n_b and n_t, their daily costs, c_b and c_t (€/day in Eq. (51)), their mobilization costs C_{bm} and C_{tm} (€ in Eq. (51)), the daily cost of cranes, c_c (€/day in Eq. (52)) and, finally, the mobilization cost of the crane, C_{cm} (€ in Eq. (52)). Within the calculation of $C_{IP,2}$ a transportation scenario with a barge and two tugs for each travel is considered.

In the case of SSPs, $t_{IP,1}$ is calculated considering the time for installing and lifting the SSP floating platform at sea, t_{iP} (h in Eqs. (53)), the number of wind turbines n_T, the number of substation platforms, n_s [19]:

$$t_{IP,1} = \frac{t_{iP}}{24} \cdot (n_T + n_s) + t_{A,8} \tag{53}$$

where:

$$t_{A,8} = \frac{\left(n_{BP3} \cdot t_{LT} + \frac{2}{3600} \cdot \frac{d_p}{v_t}\right) \cdot \frac{1}{k_t} \cdot \frac{n_T}{n_{BP,3}}}{24} \tag{54}$$

expresses the time of tug, which depends on the number of floating platforms transported by the boat $n_{BP,3}$, the time required to load the wind turbine on the vessel t_{LT}, the distance from port to the offshore location, d_p (m in Eq. (54)), the speed of tug vessel, v_t (m/s in Eq. (54)), the downtime k_t and, finally, on the number of wind turbines n_T.

The hired surface A_{SP} of port or shipyard installations for the installation procedure of SSP floater is given as follows:

$$A_{SP} = n_T \cdot \frac{l^2}{2} \cdot \sqrt{3} \tag{55}$$

where l represents the length of the SSP.

In the case of TLPs, $t_{IP,1}$ is estimated taking into account times $t_{A,6}$ and $t_{A,9}$ [19]:

$$t_{IP,1} = t_{A,6} + t_{A,9} \tag{56}$$

$$t_{A,9} = \frac{(t_{iP} + t_{imp}) \cdot \frac{1}{k_t} \cdot n_T}{24} \tag{57}$$

where $t_{A,6}$ is the time of use of the floating crane, calculated using an expression similar to the time of use of the barge vessel for SBs. $t_{A,9}$ is the time of use of the crane, that depends on the time needed for lifting and installing the TLP floater at sea, t_{iP} (h in Eqs. (57)), on the time between movements while the TLP floater is being installed, t_{imp} (h in Eqs. (57)), on the downtime k_t and, finally, on the number of wind turbines n_T.

The hired surface of port or shipyard installations for the installation procedure of TLP floaters, $A_{IFP,1}$, is calculated as follows:

$$A_{SP} = n_T \cdot (l_f + d_P + d_{ip}) \cdot l \tag{58}$$

where l_f, d_P and d_{ip} are the maximum freeboard, the draft and the inferior pontoon diameter of TLP floater, respectively.

The transportation cost of TLP, $C_{IP,2}$, and its offshore installation cost, $C_{IP,3}$, are estimated in the following expressions [19]:

$$C_{IP,2} = n_{cs} \cdot t_{A,6} \cdot c_{cs} + C_{csm} \tag{59}$$

$$C_{IP,3} = t_{A,9} \cdot c_{cs} + C_{csm} \tag{60}$$

where n_{cs} is the number of floating cranes with a storage area used for transportation of TLPs, c_{cs} (€/day in Eq. (59), (60)) is its daily cost and, finally, C_{csm} (€ in Eqs. (59), (60)) represents its mobilization cost.

Offshore substation installation. The calculation of port or shipyard activities, $C_{ITS,4,1}$, also comprises the hired surface of port or shipyard to be used for the installation procedure of the offshore substation, $A_{ITS,4,1}$ (m^2 in Eqs. (61), (62)), the hiring time of port surface or shipyard for storing the offshore substation, $t_{ITS,4,1}$ (h in Eq. 61), the hiring cost of the storage surface, c_s (€/m^2*day* in Eq. 61), the number of transformers, n_{TS}, the time needed to load the substation, t_{LOS} (h in Eqs. 61, 63) and, finally, the daily cost of port crane, c_c (€/day in Eq. (43)) [19]:

$$C_{ITS,4,1} = A_{ITS,4,1} \cdot t_{ITS,4,1} \cdot c_s + (n_{TS} \cdot 1 + 1 + 1) \cdot t_{LOS} \cdot c_c \tag{61}$$

In Eq. 61 $A_{ITS,4,1}$ and t_{LOS} are expressed as:

$$A_{ITS,4,1} = n_{TS} \cdot (A_{TS} + A_{GIS}) \cdot (1 + 1.5) \tag{62}$$

$$t_{LOS} = (n_{TS} \cdot 1 + 1 + 1) \cdot t_{LIOS} \tag{63}$$

where the calculation includes the plan area of transformer, A_{TS} (m^2 in Eq. 62) and the Gas Insulated Switchgear *GIS* plan area, A_{GIS} (m^2 in Eq. 62).

Transport cost, $C_{ITS,4,2}$ and installation cost, $C_{ITS,4,3}$, of the offshore substation are estimated considering the same calculations used for floating platforms installation. Finally, t_{LIOS} (h in Eq. (63)) represents the time required to lift the substation and load it on the vessel.

Operation and maintenance. The cost of seabed rental is related to the fees established by the local authorities of the Country where wind farm is placed. It is calculated considering the unit annual cost of the maritime state property, $c_{O,1}$ (€/m^2 in Eq. (64)) and the wind farm surface, $s_{O,1}$ (m^2 in Eq. (64)) as follows[8]:

$$C_{O,1} = c_{O,1} \cdot s_{O,1} \tag{64}$$

The insurance cost, $C_{O,2}$, is calculated by the insurance cost per unit, $c_{O,2}$ (€/MW in Eq. (65)) times the installed capacity (MW in Eq. (65)) [8].

$$C_{O,2} = c_{O,2} \cdot (n_T \cdot p_T) \tag{65}$$

Finally, the cost of transmission, $C_{O,3}$, is given by the transmission unit cost, $c_{O,3}$ (€/MW in Eq. (66)) times the installed capacity (MW in Eq. (66)) [8]:

$$C_{O,3} = c_{O,3} \cdot (n_T \cdot p_T) \tag{66}$$

The cost of corrective maintenance, $C_{MD,2,i}$ on the $i - th$ component is given by the sum of: (i) the cost of sub-assembly needing to be repaired or replaced, $C_{MD,2,i,1}$, (ii) the cost of equipping the maintenance crew, hiring service vessels and booking the spare parts, $C_{MD,2,i,2}$; (iii) the cost of transportation of maintenance crew to the wind farm, $C_{MD,2,i,3}$; (iv) the manpower cost for inspections and corrective maintenance tasks on the failed sub-assembly, $C_{MD,2,i,4}$; (v) the expected cost of production loss due to failure, $C_{MD,2,i,5}$.

$C_{MD,2,i,3}$, $C_{MD,2,i,4}$ and $C_{MD,2,i,5}$ are calculated as [33,39]:

$$C_{MD,2,i,3} = 2 \cdot d_{ps} \cdot c_{tu} \tag{67}$$

This cost depends on the distance between the wind farm and the port, d_{ps} (km in Eq. (67)) and on the transportation cost per unit distance, c_{tu} (€/*km* in Eq. (67)).

Manpower cost $C_{MD,2,i,4}$ is estimated considering the number of technicians required to repair the failure, n_{te}, the average labour-days needed for maintenance of $j - th$ component, n_{lbm} (1/*day* in Eq. (68)), the fixed daily labour rate, c_{lb} (€/day in Eq. (68)), the daily rate of manpower for eight working hours per day, c_m (€/day in Eq. (68)), the distance between the wind farm and the port, d_{ps} (km in Eq. (68)), the transportation time (round trip), t_t (day/km in Eq. (68)), expected time required to setup the maintenance actions, t_m (day in Eq. (68)) and, finally, the expected time required to repair or replace the failed sub-assembly, t_f, (day in Eq. (68)):

$$C_{MD,2,i,4} = n_{te} \cdot n_{lbm} \cdot c_{lb} \cdot (2 \cdot d_{ps} \cdot t_t + t_m + t_f) \tag{68}$$

The expected cost of production loss due to failure, $C_{MD,2,i,5}$, depends on the expected time required to equip the maintenance crew, t_e (day in Eq. (69)), the distance between the wind farm and the port, d_{ps} (km in Eq. (69)), the transportation time (round trip), t_t (day/km in Eq. (69)), the expected time required to setup the maintenance actions and to repair or replace the failed sub-assembly, t_m and t_f (day in Eq. (69)) and, finally, the fixed cost of production loss per unit downtime, c_{pl} (€/day in Eq. (69), (70)):

$$C_{MD,2,i,5} = (t_e + d_{ps} \cdot t_t + t_m + t_f) \cdot c_{pl} \tag{69}$$

$$c_{pl} = (n_T \cdot p_T) \cdot c_E \cdot f \tag{70}$$

In the Eqs. (69) and (70) c_E represents the unit cost of energy (€/MW in Eq. (70)) and f is the capacity factor of wind farm.

Appendix B. List of symbols

Table B1.

Table B1
List of symbols (WT = Wind Turbine; FP = Floating Platform; OS = Offshore Substation).

Symbol	Unit	Definition
Uppercase symbols		
A	km^2	Area of site clearance
AEP	MWh	Annual Energy Production
A_{GIS}	m^2	Plan area of Gas Insulated Switchgear (GIS)
$A_{IT,1}$	m^2	Hired surface of port/shipyard installations for WT installation process
$A_{IP,1}$	m^2	Hired surface of port/shipyard installations for FP installation process
$A_{ITS,4,1}$	m^2	Hired surface of port/shipyard for OS installation process
A_{SP}	m^2	Shipyard surface for storing the FP
A_{TS}	m^2	Plan area of transformer
C_A	€	Cost of anchors
$CAPEX$	€	Capital cost
C_{bm}	€	Mobilization cost of barge vessel
C_{cm}	€	Mobilization cost of cranes without a storage area
C_D	€	Decommissioning cost
$C_{D,1}$	€	Decommissioning cost of complete floating WT
$C_{D,2}$	€	Decommissioning cost of cables
$C_{D,3}$	€	Decommissioning cost of substations
$C_{D,4}$	€	Decommissioning cost of mooring and anchoring
C_{IMA}	€	Mooring and anchoring installation cost
C_{IP}	€	FP installation cost
$C_{IP,1}$	€	Cost of port activities to install the FP
$C_{IP,2}$	€	Cost of transportation to install the FP
$C_{IP,3}$	€	Cost of offshore installation of the FP
C_{IT}	€	Cost of WT installation
$C_{IT,1}$	€	Port procedure costs
$C_{IT,2}$	€	Transportation costs
$C_{IT,3}$	€	Cost of installation at sea
$C_{ITS,1}$	€	Array cables installation costs
$C_{ITS,2}$	€	Offshore export cable installation cost
$C_{ITS,3}$	€	Onshore export cable installation cost
$C_{ITS,4}$	€	Offshore substation installation cost
$C_{ITS,5}$	€	Onshore substation installation cost
$C_{ITS,4,1}$	€	Port activities to install offshore substation
$C_{ITS,4,2}$	€	Transportation cost to install offshore substation
$C_{ITS,4,3}$	€	Installation cost of offshore substation
$C_{ITS,5,1}$	€	Cost of soil preparation to install onshore substation
$C_{ITS,5,2}$	€	Cost of foundation to install onshore substation
$C_{ITS,5,3}$	€	Installation cost of the onshore substation using cranes
C_{MD}	€	Direct maintenance cost
$C_{MD,1,i}$	€	Preventive maintenance cost
$C_{MD,2,i}$	€	Corrective maintenance cost
C_{MI}	€	Indirect maintenance cost
$C_{MI,1}$	€	Port fees
$C_{MI,2}$	€	Vessel hiring costs
$C_{MI,3}$	€	Maintenance labour costs
$C_{MD,i,3}$	€	Cost of transportation of maintenance crew to the wind installation
$C_{MD,i,4}$	€	Manpower cost for inspections and corrective maintenance
$C_{MD,i,5}$	€	Expected cost of production loss due to the failure
C_O	€	Operation cost
$C_{O,1}$	€	Cost of seabed rental
$C_{O,2}$	€	Cost of insurance
$C_{O,3}$	€	Cost of grid access fee
C_P	€	Total FP cost
$C_{P,1}$	€	Material cost of FP
$C_{P,2}$	€	Direct labour cost of FP
$C_{P,3}$	€	Activities cost of FP
$C_{P,1,1}$	€	Cost of steel used for FP
$C_{P,1,2}$	€	Material cost for preparation of platform surface
$C_{P,1,3}$	€	Material cost of auxiliary equipment for platform
C_{SC}	€	Site clearance cost
C_{scm}	€	Mobilization cost of cranes with a storage area
C_{sp}	€	Scour protection cost
$C_{sp,2}$	€	Mobilisation cost of operations of scour protection
C_T	€	Wind turbine cost

(*continued on next page*)

Table B1 (*continued*)

Symbol	Unit	Definition
C_{tm}	€	Mobilization cost of tug vessel
$C_{TS,1}$	€	Total cost of cables
$C_{TS,2}$	€	Offshore substation cost
$C_{TS,3}$	€	Onshore substation cost
$DECEX$	€	Decommissioning cost
$Euribor$	%	Interbank interest rate
$LCOE$	€/MWh	Levelized cost of energy
$OPEX$	€	Operational cost
Lowercase symbols		
c_1	€/m	Unit price of array cables
c_2	€/m	Unit price of export cable
c_3	€/m	Unit price of onshore cable
c_A	€/kg	Unit cost of anchors
c_b	€/day	Daily rate of barge vessels
c_c	€/h	Cost of port crane
c_{cm}	€/day	Daily rate of cranes without storage area
c_{cs}	€/day	Daily rate of cranes with storage area
c_E	€/MW	Unit cost of energy
$c_{IMA,1}$	€/day	Daily rate of Anchor Handling Vehicle (AHV)
$c_{IMA,2}$	€/day	Cost of direct labour to install anchors and mooring lines
$c_{ITS,1}$	€/day	Daily rate of Cable Laying Vessel (CLV) to install onshore cable
$c_{ITS,3}$	€/day	Unit installation cost of onshore cable
c_M	€/kg	Unit cost of mooring lines
c_{lb}	€/day	Daily rate of corrective maintenance labour
c_L	€/h	Hourly labour rate for CAPEX activities
$c_{o,1}$	€/m^2	Maritime state property concession fee
$c_{o,2}$	€/MW	Unit insurance cost of wind farm
$c_{o,3}$	€/MW	Unit grid access fee
$c_{p,1}$	€/day	Daily rate of Rock-dumping vessel
c_{pl}	€/day	Unit cost for downtime
c_s	€/(m^2day)	Hiring cost of storage surface
c_{SC}	€/km^2	Site clearance cost per unit area
c_t	€/day	Daily rate of tug vessel
c_{tp}	€/h	Transport cost to port
c_{tu}	€/km	Cost of transportation for maintenance
d	m	Diameter of wind turbine
d_b	m	Blade diameter
d_P	m	Draft of FP
d_{ip}	m	Inferior pontoon diameter of FP
d_p	m	Distance from port to the offshore site
d_t	m	Tower diameter
d_{ps}	m	Distance from port to shipyard
f	%	Capacity factor of wind farm
$h_{L,1}$	h	Hours of labour for preparation, prefabrication and construction of FP
$h_{L,2}$	h	Hours of labour for preparation, painting and corrosion control of FP
$h_{L,3}$	h	Hours of labour for auxiliary equipment installation of FP
$k_{ITS,1}$	–	Parameter relevant to the installation of the 20 kV electric cable
$k_{ITS,2}$	–	Parameter relevant to the installation of the 220 kV electric cable
k_t	–	Loss coefficient due to downtime
l	m	Length of floating platform
l_1	km	Total length of array cables
l_2	km	Total length of export cable
l_3	km	Total length of onshore cable
l_b	m	Blade length
l_f	m	Maximum freebord of FP
l_M	m	Length of mooring lines
l_{TS}	m	Electric transformer length
l_{GIS}	m	Gas Insulated Switchgear GIS length
m_A	m	Anchoring mass
m_M	kg	Mooring lines mass
n_1	–	Number of array cables
n_2	–	Number of offshore export cables
n_3	–	Number of onshore cables
n_b	–	Number of barge vessels used to install WTs
$n_{BP,i}$	–	Number of FPs per travel
$n_{BT,i}$	–	Number of WTs per travel
n_c	–	Number of cranes without storage area
n_{cs}	–	Number of cranes with storage area
$n_{ITS,4}$	–	Number of substation platforms
n_{lbm}	1/day	Daily rate of component i maintenance
n_{LFP}	–	Number of liftings of the FP for its loading in the vessel

(*continued on next page*)

Table B1 (*continued*)

Symbol	Unit	Definition
n_{LT}	–	Number of liftings of the WT
n_M	–	Number of mooring lines
n_s	–	Number of substation platforms
n_T	–	Number of WTs
$n_{t,1}$	–	Number of tug vessels used to install WTs
$n_{t,2}$	–	Number of tug vessels used to install FPs
n_{te}	–	Number of technicians required to repair the failure
n_{TS}	–	Number of transformers
p_i	–	Probability of failure event
p_T	MW	Power of one wind turbine
$r_{f,i}$	–	Annual failure rate
r_P	%	Interest rate
$r_{IMA,1}$	t	Time to install using AHV vessel
$s_{o,1}$	m^2	Surface of wind farm
$t_{A,1}$	day	Time of barge vessel usage for WT installation
$t_{A,2}$	day	Time of tug vessel usage for WT installation
$t_{A,3}$	day	Time of crane usage for WT installation
$t_{A,4}$	day	Time of floating crane usage for WT installation
$t_{A,5}$	day	Time of floating crane usage for FP installation
$t_{A,6}$	day	Time of barge vessel or floating crane usage for FP installation
$t_{A,7}$	day	Time of tug vessel usage for FP installation
$t_{A,8}$		
$t_{A,9}$	day	Time of crane usage for FP installation
t_e	day	Expected time required to equip the maintenance crew
t_f	day	Expected time required to repair or replace the failed sub-assembly
t_{imP}	h	Time between movements while the FP is being installed
t_{imT}	h	Time for installing the WT offshore with lifts
t_{iP}	h	Time for installing and lifting the FP onshore
$t_{IP,1}$	day	Time of hiring port/shipyard installations for FP installation process
t_{iT}	h	Time between movements while the offshore WT is being installed
$t_{ITS,4,1}$	h	Time of hiring the port surface/shipyard for offshore substation installation
t_{IT1}	day	Time of hiring port/shipyard installations for WT installation process
t_{LIFP}	h	Time required to lift and install the FP
t_{LIOS}	h	Time required to load substation
t_{LIT}	h	Time required to lift and install the WT
t_{LOS}	h	Time required to load substation
t_{LT}	h	Time required to load the WT on the vessel
t_{LP}	h	Time required to load the FP on the vessel
t_m	day	Expected time required to setup the maintenance actions
t_P	years	Construction time of a single platform
t_{sp}	day	Time for scour protection installation
$t_{sp,net}$	h	Time for scour installation
t_t	day/km	Transportation time (round trip)
v_t	m/s	Speed of tugging
v_{t1}	m/s	Speed of floating crane
w_δ	m	Water depth at the installation site

References

[1] Lerch M, De-Prada-Gil M, Molins C, Benveniste G. Sensitivity analysis on the Levelized Cost of Energy for floating offshore wind farms. Sustain Energy Technol Assess 2018;30:77–90.

[2] Larsen HH, Petersen LS. Dtu international energy report 2014: Wind energy–drivers and barriers for higher shares of wind in the global power generation mix. Technical report; 2014.

[3] Kumar V. Optimization of offshore wind farm installation procedure with a targeted finish date Master's thesis Netherlands: Delft University of Technology; 2017.

[4] Avossa AM, Demartino C, Ricciardelli F. Assessment of the peak response of a 5 MW HAWT under combined wind and seismic induced loads. Open Construct Build Technol J 2017;11(1):441–57.

[5] Bilgili M, Yasar A, Simsek A. Offshore wind power development in Europe and its comparison with onshore counterpar. Renew Sustain Energy Rev 2011;15(2):905–15.

[6] Dicorato M, Forte G, Pisani M, Trovato M. Guidelines for assessment of investment cost for offshore wind generation. Renew Energy 2011;36(8):2043–51.

[7] Limpo J, Castro R, Sarmento A, Raventos A, Correia C. Contributions to an electrical and economic assessment of offshore wind energy in shallow waters: Application to a Portuguese site. J Ocean Wind Energy 2014;1(4):246–52.

[8] Shafiee M, Brennan F, Espinosa IA. A parametric whole life cost model for offshore wind farms. Int J Life Cycle Assess 2016;21(7):961–75.

[9] Ioannou A, Angus A, Brennan F. A lifecycle techno-economic model of offshore wind energy for different entry and exit instances. Appl Energy 2018;221:406–24.

[10] Bjerkseter C, Ågotnes A. Levelised Costs of Energy for offshore floating wind turbine concepts Master's thesis Norway: Norwegian University of Life Sciences; 2013.

[11] Statoil. Hywind Scotland pilot park. Technical report, Environmental Statement; 2015.

[12] George J. Windfloat design for different turbine sizes Master's thesis Portugal: UL–University of Lisbon; 2014.

[13] Kausche M, Adam F, Dahlhaus F, Großmann J. Floating offshore wind-economic and ecological challenges of a TLP solution. Renew Energy 2018;126:270–80.

[14] Heidari S. Economic modelling of floating offshore wind power: Calculation of levelized cost of energy. Master's thesis. Sweden: School of Business, Society and Engineering; 2017.

[15] Nilsson D, Westin A. Floating wind power in Norway-analysis of opportunities and challenges Master's thesis Sweden: Lund University; 2014.

[16] Castro-Santos L. Methodology related to the development of the economic evaluation of floating offshore wind farms in terms of the analysis of the cost of their life-cycle phases PhD thesis Spain: Universidade da Coruña; 2013.

[17] Castro-Santos L, Ferreño González S, Diaz-Casas V. Methodology to calculate mooring and anchoring costs of floating offshore wind devices. In: International Conference on Renewable Energies and Power Quality (ICREPQ), vol. 1; 2013.

[18] Castro-Santos L, Martins E, Guedes Soares C. Methodology to calculate the costs of a floating offshore renewable energy farm. Energies 2016;9(5):324.

[19] Castro-Santos L, Filgueira-Vizoso A, Lamas-Galdo I, Carral-Couce L. Methodology to calculate the installation costs of offshore wind farms located in deep waters. J Cleaner Prod 2018;170:1124–35.

[20] Ioannou A, Angus A, Brennan F. Parametric CAPEX, OPEX, and LCOE expressions for offshore wind farms based on global deployment parameters. Energy Sources,

Part B: Econ Plann Policy 2018;13(5):281–90.
[21] Maienza C, Avossa AM, Ricciardelli F, Scherillo F, Georgakis CT. A comparative analysis of construction costs of onshore and shallow- and deep-water offshore wind farms. In: XV Conference of the Italian Association for Wind Engineering: IN VENTO 2018. Springer, vol. 27; 2019. p. 440–53.
[22] Blanco MI. The economics of wind energy. Renew Sustain Energy Rev 2009;13(6–7):1372–82.
[23] IRENA. Renewable energy technologies: cost analysis series. Technical report; 2012.
[24] Topham E, McMillan D. Sustainable decommissioning of an offshore wind farm. Renew Energy 2017;102:470–80.
[25] Castro-Santos L, Diaz-Casas V. Life-cycle cost analysis of floating offshore wind farms. Renew Energy 2014;66:41–8.
[26] Lazaridis L. Economic comparison of HVAC and HVDC solutions for large offshore wind farms underspecial consideration of reliability Master's thesis Sweden: Royal Institute of Technology; 2005.
[27] NREL. Cost of wind energy review. Technical report; 2016.
[28] Myhr A, Bjerkseter C, Ågotnes A, Nygaard TA. Levelised Cost of Energy for offshore floating wind turbines in a life cycle perspective. Renew Energy 2014;66:714–28.
[29] Kaiser MJ, Snyder B. Offshore wind energy cost modeling: installation and decommissioning vol. 85. Springer Science & Business Media; 2012.
[30] Kaiser MJ, Snyder B. Offshore wind energy installation and decommissioning cost estimation in the us outer continental shelf. Technical report; 2010.
[31] Brons-Illing C. Analysis of operation and maintenance strategies for floating offshore wind farms. Norway: University of Stavanger; 2015.
[32] Ebenhoch R, Matha D, Marathe S, Muñoz PC, Molins C. Comparative Levelized Cost of Energy analysis. Energy Procedia 2015;80:108–22.
[33] Shafiee M, Dinmohammadi F. An fmea-based risk assessment approach for wind turbine systems: a comparative study of onshore and offshore. Energies 2014;7(2):619–42.
[34] Kosugi A, Ogata R, Kagemoto H, Akutsu Y, Kinoshita T. A feasibility study on a floating wind farm off japan coast. In: The twelfth international offshore and polar engineering conference. International Society of Offshore and Polar Engineers; 2002.
[35] Junco Ocampo F. Ship projects and artifacts. Configuration selection: Dimensions and coefficients. Ferrol: Escuela Politécnica Superior, Universidad de A Coruña; 2003.
[36] Wayman EN, Sclavounos PD, Butterfield S, Jonkman J, Musial W. Coupled dynamic modeling of floating wind turbine systems. Technical report, National Renewable Energy Lab. (NREL), Golden, CO (United States); 2006.
[37] Mortensen NG, Davis N, Badger J, Hahmann AN. Global wind atlas–validation and uncertainty. In: Wind Europe resource assessment workshop; 2017.
[38] Katic I, Højstrup J, Jensen NO. A simple model for cluster efficiency. European wind energy association conference and exhibition. A. Raguzzi; 1987.
[39] García IEM, Sánchez AS, Barbati S. Reliability and preventive maintenance. MARE-WINT. Cham: Springer; 2016. p. 235–72.