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O&M-aware techno-economic assessment for floating offshore wind farms: A geospatial evaluation off the North Sea and the Iberian Peninsula

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ABSTRACT

The development of accurate techno-economic models is crucial to boost the commercialisation of floating offshore wind farms. However, conventional techno-economic models oversimplify operation and maintenance (O&M) aspects, neglecting key maintenance factors, such as component failure rates, metocean conditions, repair times, maintenance vessels and ports. To address this limitation, this paper presents an O&M-aware techno-economic model that comprehensively incorporates the most relevant maintenance factors and evaluates their impacts on site-identification across the North Sea and the Iberian Peninsula based on diverse O&M strategies. Results reveal that operational expenditure can contribute significantly to the levelised cost of energy, ranging from 22% to 50% in the North Sea and 19% to 46% in the Iberian Peninsula. Furthermore, results demonstrate that suitable sites vary based on O&M strategy: preventive strategies favour areas with abundant wind resources like northern Scotland, Norway and Galicia, whereas corrective strategy prioritise sites with less severe metocean conditions, such as southern Scotland and extensive regions in the Mediterranean Sea, including the Gulf of Roses and the Alboran Sea. Finally, the downtime of turbines, an aspect traditionally neglected in techno economic frameworks, emerges as a key factor for accurate techno-economic assessment and site-identification.

1. Introduction

While the global consensus on transitioning from fossil fuels to renewable energy is growing, the associated challenges of energy security, macroeconomic aspects, and supply issues are also becoming increasingly evident [1]. In this complex context, policymakers are adopting legislative initiatives, such as the Inflation Reduction Act in the USA [2] and REPowerEU in the EU [3], in order to develop, deploy and scale up conventional and still immature renewable technologies. In fact, according to the International Energy Agency, over 45% of the total CO_2 emissions reduction by 2050 will be driven by emerging technologies under development, including Floating Offshore Wind (FOW) [4].

Pre-commercial FOW farms, such as Hywind Scotland [5], Hywind Tampen [6], Kincardine [7], and WindFloat [8], currently demonstrate the technical feasibility of floating turbines. Despite these advancements, the FOW technology remain commercially unviable, being more expensive than other established renewable energy technologies, such as onshore wind or bottom-fixed offshore wind [9,10]. Accordingly, achieving the commercialisation and integration of FOW technology into the energy market requires improving cost-effectiveness [11].

The levelised cost of energy ($LCoE$) is a widely accepted metric for evaluating and comparing the cost-effectiveness of different energy generation technologies [12]. In addition to its applicability for benchmarking, $LCoE$ estimates are also relevant in the context of offshore wind auction bid prices [13]. This underscores the importance of accurately estimating the $LCoE$ for FOW farms. The $LCoE$ is inherently site-specific, as the energy production, capital expenditures ($CapEx$) and operational expenditures ($OpEx$) are associated with the specific location of a farm [14]. Therefore, the identification of suitable sites through geospatial assessment of $LCoE$ is essential for the commercialisation of FOW projects [15]. In fact, this is especially critical for FOW farms, given the novelty of the sector and the potential for operation in unexplored deep waters (>50 m) far from shore (>90 km) [16,17].

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Operating at far-offshore sites enables stronger and more consistent winds, potentially reducing the $LCoE$ of FOW farms [18]. However, the greater distance from shore also leads to harsher metocean conditions and longer travel times, thereby decreasing accessibility and maintainability, and potentially increasing the $LCoE$ [19]. In this context, the initial $OpEx$ estimations for FOW farms, derived from bottom-fixed offshore wind farms, typically account for 25%–30% of the $LCoE$ [10]. Nevertheless, uncertainties are still large in these estimations, and the challenging conditions and complexity associated with operating at far-offshore sites might exceed these $OpEx$ estimations [20]. For that reason, there exists an increasing awareness about operation and maintenance (O&M) needs among commercial-scale FOW project promoters [21]. Hence, incorporating O&M factors into the techno-economic assessment is crucial for accurately evaluating the $LCoE$ and identifying suitable sites for FOW farms [20].

A comprehensive O&M assessment within the $LCoE$ mapping should consider the most important O&M factors, such as distances, component failure rates, repair times, metocean conditions, maintenance vessels and ports, and their interdependencies with system attributes, including reliability, maintainability, accessibility and availability [20,22]. The consideration of all these factors and attributes within the techno-economic framework is defined in this paper as an O&M-aware techno-economic assessment. In contrast, O&M-agnostic techno-economic models refer to the studies that disregard these O&M factors and attributes.

The comprehensive O&M framework consists of four main aspects that must be carefully considered. Reliability represents the capability of the FOW turbine to produce energy in the presence of failures [22]. Accessibility represents the feasibility of accessing the turbine to conduct a maintenance task [23]. Maintainability is related to accessibility and refers to the ability to undergo offshore maintenance tasks, which is modelled through different repair processes for each FOW component [20]. Finally, availability, encompassing reliability, maintainability and accessibility, refers to the proportion of time the FOW turbine remains operational over the full life time [24]. Consequently, the availability of the FOW turbine directly impacts the total energy production and cost, as no energy is produced during the downtime of the turbines [20].

In addition, the techno-economic model should also exhibit computational efficiency to enable rapid estimations of $LCoE$ for two main reasons:

- Given the precommercial stage of the FOW sector and the potential for operation in unexplored deep waters, it is a key factor for FOW promoters and governments to evaluate a large number of potential deployment sites.
- Given the uncertainty inherent in the floating wind sector, largely due to the novelty of the technology and low operational experience of these turbines, it is imperative to perform comprehensive sensitivity evaluation to understand the impact of different factors on the final $LCoE$. This uncertainty is particularly pronounced in the O&M of floating wind farms. For example, it is crucial to evaluate the effects of failure rates, repair times, operational limits of vessels, and associated costs on the $LCoE$. Given the wide range of values each parameter can take, numerous possible scenarios may arise. Analysing all these potential scenarios is pivotal for strategic decision-making under uncertainty.

Consequently, techno-economic models for evaluating the $LCoE$ of FOW farms should be both O&M-aware and computationally-efficient.

1.1. Literature review

The most important techno-economic models presented in the literature and their main characteristics are summarised in Table 1. Among these models, several O&M-agnostic techno-economic models are presented for mapping the $LCoE$ for different FOW turbine technologies in pre-defined and broad geographical areas, such as the North-West of Spain [25], Portugal [26], the European Atlantic Ocean [15,27], Ireland [28] and the Mediterranean Sea [29]. These studies comprehensively estimate the $CapEx$, which includes the costs of pre-operational phases along the FOW farm projects, encompassing development and consenting, manufacturing, transmission, and installation stages.

However, these studies oversimplify the articulation of O&M aspects in the techno-economic framework by using a constant farm availability indicator derived from bottom fixed offshore wind. This assumption ignores the specific geographical characteristics of each farm, such as metocean characteristics and distance to port, which may lead to incorrect implications of O&M actions in terms of turbines' downtime. The geographical dependence of turbine availability and the considerable impact of O&M procedures on the operation and, thus, the energy production of FOW farms, is demonstrated to influence the site-identification [37].

Furthermore, [25–27] estimate the $OpEx$ deterministically as a function of failure rates, overlooking crucial O&M factors such as distances, repair times, metocean conditions, and vessel characteristics. Similarly, [15,28,29] oversimplify the formulation of $OpEx$ by representing it as a fixed term plus an additional distance-dependent parameter. This formulation is based on cost models presented in the literature, where the techno-economic assessment of different offshore wind farms is carried out considering different geographical locations, types of turbines and farm sizes [38,39]. As these factors have a substantial impact on the overall $OpEx$, its general formulation for FOW farms is overly simplistic.

The National Renewable Energy Laboratory (NREL) introduces a comparable O&M-agnostic techno-economic model with spatial variation capabilities for mapping the $LCoE$ [30]. However, turbine downtime, like in other O&M-agnostic techno-economic models, is not computed but rather specified as input data [30]. Additionally, $OpEx$ is deterministically estimated, relying on factors such as distance to port and mean significant wave height (H_s). Including only the mean H_s value in the estimation of $OpEx$ can be considered conservative, as it does not consider variations in wave conditions such as frequency and extreme events.

In this context, the O&M model, provided by the Energy Research Centre of the Netherlands (ECN) offers a more comprehensive estimation of $OpEx$, encompassing turbine downtime, distance to port, failure rates, repair times, metocean conditions, and both corrective and preventive maintenance strategies in the analysis [31]. However, the tool is specifically designed for bottom-fixed offshore wind turbines, does not incorporate the computation of $CapEx$ and $LCoE$, and operates as a deterministic model in which only mean values are considered [31]. Incorporating probabilistic models to account for uncertainties associated with factors such as failure rates, repair times, and metocean conditions is crucial for providing a more comprehensive and accurate estimation of $OpEx$, and ultimately contributing to a more robust assessment of the $LCoE$.

The main reason that these O&M factors are ignored in existing $LCoE$ mappings is the lack of a computationally-efficient and accurate O&M model. The articulation of reliability, maintainability, accessibility and availability attributes, along with their interdependencies, in existing techno-economic models is mostly achieved through Monte Carlo-based O&M models [32–35]. These models use repeated random sampling methods to approximate the failure and repair processes of the FOW farm [34]. However, their main disadvantage lies in the high computational burden, as numerous iterations are required to achieve convergence in the results [34]. For example, the O&M-aware techno-economic assessment for a single geographical location requires at least two days of computation [35,40]. In this regard, NREL presents a discrete event simulation model named WOMBAT, which reduces computational burden by skipping periods in the simulation wherein no events occur [36]. Nonetheless, further reduction of the computational

Table 1
The main features of literature techno-economic models.

		[25–27]	[15,28,29]	[30]	[31]	[32–34]	[35]	[36]	This Paper
LCoE modelling		✓	✓	✓	✗	✗	✓	✗	✓
CapEx modelling		✓	✓	✓	✗	✗	✓	✗	✓
O&M	**Model** [a]	Det.	Det.	Det.	Det.	Prob. (MC)	Prob. (MC)	Prob. (MC)	Prob. (Markov)
	Downtime computation	✗	✗	✗	✓	✓	✓	✓	✓
	OpEx:								
	Distance	✗	✓	✓	✓	✓	✓	✓	✓
	Failure Rates	✓	✗	✗	✓	✓	✓	✓	✓
	Repair times	✗	✗	✗	✓	✓	✓	✓	✓
	Metocean [b]	✗	✗	✗[c]	✓	✓	✓	✓	✓
	Vessels [d]	✗	✗	✗	✓	✓	✓	✓	✓
	Corrective	✓	✗	✗	✓	✓	✓	✓	✓
	Preventive	✓	✗	✗	✓	✓	✓	✓	✓
Technology [e]		FOW	FOW	FOW	BFOW	FOW	FOW	FOW	FOW
Computational efficient		✓	✓	✓	✓	✗	✗	✗	✓

[a] Deterministic models (Det.) and probabilistic models (Prob.). Probabilistic models can be further categorised into Monte Carlo (MC) simulations and Markov chains (Markov) with analytical solutions.

[b] Consideration of metocean conditions for weather window computation, including significant wave height and wind speed.

[c] The computation of $OpEx$ based on the mean significant wave height. It does not include an assessment of weather windows and their influence on accessibility and subsequent $OpEx$ implications.

[d] Consideration of maintenance vessels and their operational limits for weather window computation.

[e] Floating offshore wind (FOW) and bottom-fixed offshore wind (BFOW).

burden is still necessary to achieve at least subminute simulation times for conducting extensive sensitivity assessments and to better understand the uncertainty associated with model parameters [36].

To address this issue, a computationally-efficient O&M model based on Markov chains is proposed with the same level of fidelity, but a significantly lower computational burden in [20]. The evaluation of a single grid point requires just a few seconds, allowing the study of the whole geographical area [20]. In fact, this computationally-efficient O&M model is employed for mapping the impact of O&M on the energy production of FOW farms in the North Sea and the Iberian Peninsula [37]. Assessing the impact of O&M on energy production is the first step in understanding the cost efficiency of FOW farms. However, a comprehensive site-identification should not be limited to energy production alone, but should also encompass cost evaluation, including $OpEx$ and $LCoE$. Additionally, [37] conducts O&M assessment based on a corrective maintenance strategy. It is essential to understand the impact of corrective maintenance. However, it is equally important to incorporate preventive maintenance actions into the overall techno-economic assessment, as it is expected to have a significant role in enhancing the cost-effectiveness of FOW farms [10].

A common limitation in the techno-economic modelling of $OpEx$ lies in the reliability data of FOW turbines. Reliability data from past and current wind turbines is scarce due to the sensitive nature of the information [41]. To the best of the authors' knowledge, the only available data on failure rates of offshore wind turbines are provided in [42]. These failure rates are complemented by floating platform, mooring and cable failure rates in [35]. In this respect, failure data provided in [35] is frequently used as a reference failure rate database in the FOW domain.

1.2. Motivation and contribution

The techno-economic assessment of FOW farms is significantly influenced by the uncertainty associated with input parameters, including costs, failure rates, repair times and maintenance strategies. Moreover, considering the wide range of potential deployment sites for FOW farms, it is necessary to include broad spatial areas in the analysis. In this sense, a computationally-efficient techno-economic model that enables (i) a sensitivity analysis of different input parameters and (ii) coverage of wide spatial areas is necessary.

To the best of authors' knowledge, the techno-economic models presented in the literature do not sufficiently integrate O&M factors to enable such sensitivity analysis and broad geospatial assessment. Hence, this research addresses this gap by making two main contributions:

(i) A novel and computationally-efficient O&M-aware techno-economic model is presented, enabling the assessment of $LCoE$ across broad geographical areas and incorporating the most significant O&M factors within the assessment.
(ii) A comparative study evaluating the impact of O&M factors and the selected maintenance strategies on the final $LCoE$ is presented across the North Sea [43] and the Iberian Peninsula [44,45]. Using the O&M-aware techno-economic model suggested in this study, the variation of appealing sites for FOW farms based on O&M strategy has been evaluated.

To evaluate the contribution of the present study compared to the state-of-the-art, a baseline study is designed covering the North Sea and the Iberian Peninsula. This baseline study is based on the state-of-the-art techno-economic frameworks that have been applied in the European Atlantic Ocean [15], Ireland [28] and the Mediterranean Sea [29].

The remainder of the paper is organised as follows: Section 2 describes the O&M-aware techno-economic model, Section 3 defines the evaluated scenarios to assess the influence of considering O&M factors in the techno-economic assessment, Section 4 provides the main results and discussion, and Section 5 draws the main conclusions of the study.

2. O&M-aware techno-economic model

The O&M-aware techno-economic model calculates the $LCoE$ through three main steps: (i) defining the specific characteristics of the FOW farm; (ii) computing the $CapEx$ [€] using the approach described in [15]; and (iii) determining the $OpEx$ [€] and annual energy production (AEP) [MWh] through the computationally-efficient O&M model

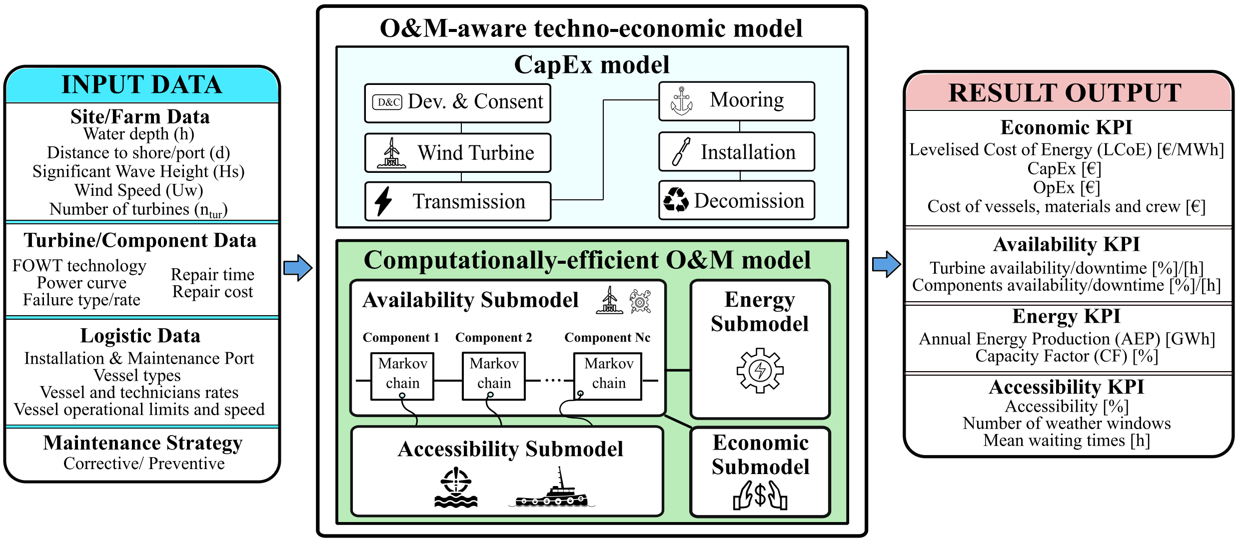


Fig. 1. The flowchart of the O&M-aware techno-economic model.

Table 2
Main information of the selected geospatial regions [37].

Region	Lower Left		Upper Right	
	Long.	Lat.	Long.	Lat.
North Sea	3.5° W	51° N	9° E	59° N
Iberian Peninsula	11° W	34.75° N	6° E	45° N

presented in [20]. The flowchart describing the O&M-aware techno-economic model is represented in Fig. 1. In this respect, the $LCoE$ is defined as follows [15],

$$LCoE(x,y) = \frac{\sum_{i=1}^{T} [CapEx(x,y) + OpEx(x,y)] \cdot (1+r)^{-i}}{\sum_{i=1}^{T} AEP(x,y) \cdot (1+r)^{-i}}, \tag{1}$$

where (x,y) represent the geographical coordinates, r is the discount rate defined over the range [0,1], and T the project lifetime [years].

2.1. Main characteristics of the offshore wind farm

The $LCoE$ values are associated with specific characteristics of FOW farms. In the present study, a FOW farm is assumed to be deployable at each grid point across the North Sea and the Iberian Peninsula. Accordingly, the geographical boundaries of the North Sea and the Iberian Peninsula are defined in Table 2.

The operational lifespan of the FOW farms is set at 20 years ($T = 20$) with a 10% discount rate ($r = 10\%$), as defined in [15]. One hundred semi submersible FOW turbines ($n_{tur} = 100$), each with a capacity of 10 MW and four mooring lines, are considered in each FOW farm, resulting in a total installed capacity (P_{farm}) of 1 GW each farm. The power curve of the turbine is based on the DTU 10-MW wind turbine, which has a cut-in wind speed of 4 m/s, rated power at 11.4 m/s, and cut-out speed of 25 m/s [46]. For each FOW farm, electricity transmission is assumed to rely on high-voltage alternating current (HVAC) cables for a distance less than 56 km between the farm and shore, and the high-voltage direct current (HVDC) alternative above that distance [15].

The two main input parameters for the estimation of the $CapEx$ are the minimum distance to shore ($d_{shore}(x,y)$) and the water depth ($h(x,y)$) [47]. The minimum distance for each ocean coordinate is determined by calculating Haversine distances to all coastline coordinates and selecting the shortest one as in [20]. The bathymetry data for the North Sea and the Iberian Peninsula are obtained from ETOPO Global Relief Model of the NOAA database at one arc-minute resolution [48], as depicted in Figs. 2(a) and 2(b), respectively.

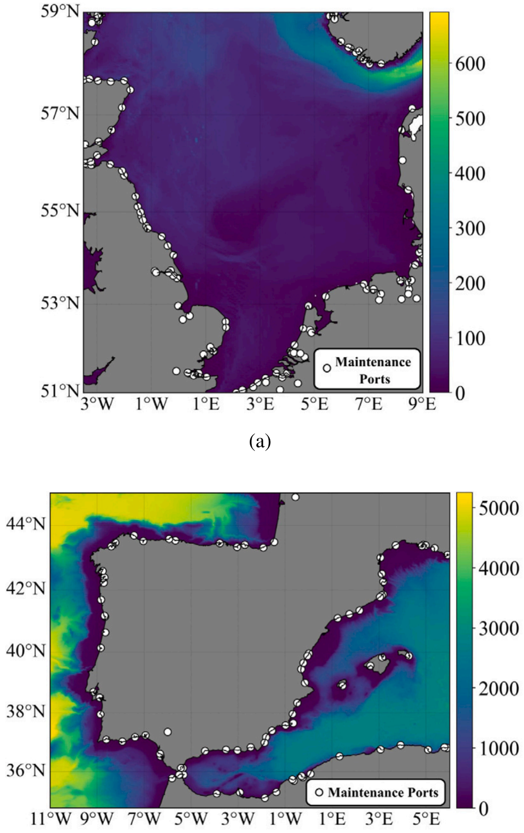
H_s and wind speed (U_w) time-series data at a 100 m height are obtained from the ERA5 reanalysis products by the European Centre for Medium-Range Weather Forecasts [49]. The data are acquired using the minimum time and spatial resolution available in ERA5, which includes hourly measurements from year 2000 to 2019 and a grid resolution of 0.25° in both longitude and latitude.

The annual failure rates, onsite repair times and repair costs for all the most relevant components of the semi-submersible FOW turbine are obtained from [35] and presented in Table A.1. Failures requiring onsite repair times up to 8 h or less are classified as minor repairs, actions requiring a repair time between 8 to 24 h are referred to as medium repairs and repair events exceeding 24 h are deemed as major repairs, following the definition presented in [37].

A set of maintenance vessels for minor, medium, and major repairs have been selected, including a Crew Transfer Vessel (CTV), a Field Support Vessel (FSV), and a Heavy-Lift Vessel (HLV) [35], respectively. The speed and operational limits of the vessels are obtained from [35] and presented in Table 3. In this context, a conservative approach is applied when defining operational limits, with the same limits established for both the transit from port to turbine and the execution of onsite repair tasks. Furthermore, it is assumed that all vessels begin and end their journeys at the port.

Among the challenges that FOW industry faces today, major component replacements represent a crucial aspect, demanding efficient maintenance strategies to minimise turbine downtime. Considering these challenges, numerous O&M experts are developing different heavy maintenance solutions for FOW turbines. To date, the suggested heavy maintenance solutions can be classified into towing and onsite replacement maintenance strategies [21,50]. The towing maintenance strategy has demonstrated its effectiveness as a technically viable solution at the Kincardine FOW farm in Scotland, where two major maintenance operations have already been conducted on two semi-submersible FOW turbines since 2022 [51]. However, considering the extended turbine downtime experienced in Kincardine, it is anticipated that onsite replacement solutions will be essential for future commercial-scale FOW projects [21,52]. Accordingly, the O&M-aware techno-economic model developed in this paper assumes that the HLV has the capability to execute onsite replacement operations.

Additionally, O&M ports have been determined using the World Port Index [53]. The identified ports for the North Sea and the Iberian Peninsula are marked with white dots in Figs. 2(a) and 2(b). For each grid point representing a potential FOW farm of 1 GW, the closest port is selected following the same procedure based on Haversine distances and used in the determination of the closest point on shore [37]. Port



(a)

(b)

Fig. 2. Water depth [m] and maintenance ports in: (a) the North Sea, and (b) the Iberian Peninsula.

Table 3
Characteristics of selected maintenance vessels [20,55,56].

	CTV	FSV	HLV
Vessel speed [knots]	24	10	12.5
H_s limit [m]	2.5	1.8	1.5
U_w limit [m/s]	30	30	25
Day rate [€/day]	1988	10 792	170 400
Mobilisation cost [€]	1136	2840	30 672
Fuel consumption [mt/h]	0.24	0.2	0.55
Fuel cost [€/mt]	300	300	450
Required technicians	2	4	6

Abbreviations: CTV = Crew Transfer Vessel, FSV = Field Support Vessel, HLV = Heavy Lift Vessel.
Note 1: Wind speed limit is given at hub height.
Note 2: Costs were given in 2019 currency values. The average conversion rate from GBP to EUR of 1.136 was used [35].

selection can also be influenced by the depth of the port and the suitability of the seabed [54]. However, conducting a comprehensive analysis of all these factors is beyond the scope of this paper given the large number of FOW farms considered.

2.2. Capital expenditures model

Capital expenditures refer to the costs incurred before the operational phase of FOW turbines, including costs of the following: development and consenting services ($C_{D\&C}$), the turbine and substructure (C_{tur}), the transmission ($C_{trans}(x,y)$), the mooring ($C_{moor}(x,y)$), the installation ($C_{inst}(x,y)$), and the decommissioning ($C_{dec}(x,y)$) [15].

Table 4
Parameters to compute installation costs for a FOW farm consisting of 100 turbines [15].

	HVAC	HVDC
$n_{exp}(x,y)$	3	2
C_{exp} [M€/km]	2.336	1.168
n_{off}(x,y)	3	2
C_{off} [M€]	39	142.75
n_{on}(x,y)	–	1
C_{on} [M€]	–	84.35

Abbreviations: HVAC = High Voltage Alternating Current, HVDC = High Voltage Direct Current.

Therefore, the $CapEx$ can be computed as,

$$CapEx(x,y) = C_{D\&C} + C_{tur} + C_{moor}(x,y) + C_{trans}(x,y) + C_{inst}(x,y) + C_{dec}(x,y)\,. \tag{2}$$

Environmental, seabed and met-station surveys along with project management and development services are included in $C_{D\&C}$ [15]. In this respect, $C_{D\&C}$ is defined at 210 k€/MW based on UK government data for offshore wind projects [15,57].

The cost of the turbine is approximated at 1.6 M€/MW [15,58] and the semi-submersible floater cost is set at 8 M€/turbine based on *WindFloat* data [58], both included in C_{tur}. Note that these two costs are represented by constant values, and the rest depend on the geographical location. For example, the semi-submersible floater comprises four mooring lines with drag embedment anchors, for which the manufacturing cost is expressed as a function of the water depth as follows [15],

$$C_{moor}(x,y) = n_{tur} \cdot n_{lines} \cdot [C_{anchor} + 50 \cdot C_{chain} + (1.5 \cdot h(x,y) + 410) \cdot C_{line}]\,, \tag{3}$$

where n_{tur} is the total number of turbines, n_{lines} the number of mooring lines per turbine, $h(x,y)$ the water depth at each geographical location, C_{anchor} the cost of an anchor estimated at 123 k€ [58], and C_{line} and C_{chain} respectively represent the costs of the mooring line and chain per unit length approximated at 48 €/m and 270 €/m [38].

The cost for transmitting the generated power from turbines to shore is included in $C_{trans}(x,y)$, which is computed as [15],

$$C_{trans}(x,y) = d_{shore}(x,y) \cdot n_{exp}(x,y) \cdot C_{exp} + n_{off}(x,y) \cdot C_{off} + n_{on}(x,y) \cdot C_{on} + d_{inter} \cdot C_{inter}\,, \tag{4}$$

where $d_{shore}(x,y)$ is the distance to shore, $n_{exp}(x,y)$ and C_{exp} are the number and costs per unit of distance of the export cable, respectively, $n_{off}(x,y)$ and C_{off} the number and cost per offshore substation, respectively; $n_{on}(x,y)$ and C_{on} the number and cost per onshore substation, respectively; and d_{inter} and C_{inter} the length and cost per unit of distance of the inter array cable, respectively. The values of these parameters are shown in Table 4.

The cost of installing turbines assuming a tug boat can be expressed as [59],

$$C_{inst_{tur}}(x,y) = \frac{n_{tur}}{n_{tur_{trip}}} \cdot [T_{inst} + 2 \cdot \frac{d_{port}(x,y)}{V_{tug}}] \cdot C_{tug}\,, \tag{5}$$

where $d_{port}(x,y)$ is the distance to port, $n_{tur_{trip}}$ the number of turbines carried per trip, set to five turbines; T_{inst} duration of the installation, set to two days; V_{tug} the towing speed, set to 10.8 knots; and C_{tug} the charter cost of the vessel per day, set to 2000€ [15].

The costs of installing the mooring system ($C_{inst_{moor}}$) is estimated at 240 k€ per turbine [58] and the installation cost of export cables ($C_{inst_{exp}}(x,y)$) is approximated at 637k€/km [15]. The costs of installing inter-array cables ($C_{inst_{inter}}(x,y)$) is considered one-third of the export cable installation cost [60]. Finally, installing the offshore substation ($C_{inst_{off}}$) is set to 20 M€ for the wind farm [38]. Hence, the total installation cost for the wind farm ($C_{inst}(x,y)$) is given as the sum of all these costs,

$$C_{inst}(x,y) = C_{inst_{tur}}(x,y) + C_{inst_{moor}}(x,y) + C_{inst_{exp}}(x,y) + C_{inst_{inter}}(x,y) + C_{inst_{off}} \ . \tag{6}$$

Decommissioning is the final phase of an offshore wind farm project and can be considered as the opposite of the installation stage [61]. In this regard, the decommissioning cost is commonly estimated as a percentage of the installation costs assuming that the duration of decommissioning operations is lower than the duration of installation operations [15],

$$\begin{aligned} C_{dec}(x,y) = {} & 0.7 \cdot C_{inst_{tur}}(x,y) \\ & + 0.9 \cdot [C_{inst_{moor}}(x,y) + C_{inst_{off}}] \\ & + 0.1 \cdot [C_{inst_{exp}}(x,y) + C_{inst_{inter}}(x,y)] \ , \end{aligned} \tag{7}$$

where 0.7, 0.9 and 0.1 are the normalised values related to the required installation time [62].

2.3. Computationally-efficient O&M model

The computationally-efficient O&M model consists of energy, economic, availability and accessibility submodels, as represented in Fig. 1. The interdependencies between these four submodels are captured by means of reliability block diagram (RBD) and Markov chains [20]. The main KPIs computed in the computationally-efficient O&M model are related with energy production and cost. In this respect, the farm level AEP is defined as,

$$AEP(x,y) = n_{tur} \cdot \frac{A_{tur}(x,y)}{T} \cdot \int_0^T P(U_w(x,y,t)) \, dt \ , \tag{8}$$

where $A_{tur}(x,y)$ is the average availability of the FOW turbine, $P(U_w(x,y,t))$ the power curve of the turbine, $U_w(x,y,t)$ the wind speed at time instant t, and dt the continuous integration. The availability model computes $A_{tur}(x,y)$ by means of RBDs considering a series configuration as follows,

$$A_{tur}(x,y) = \prod_{i=1}^{n_c} A_{c_i}(x,y) \ , \tag{9}$$

where n_c is the number of components per turbine and $A_{c_i}(x,y)$ the average availability for component i [20].

Similarly, the farm level $OpEx(x,y)$ is defined in the economic submodel as [20],

$$OpEx(x,y) = n_{tur} \cdot \sum_{i=1}^{n_c} [C_{corr}(n_{CM_i}) + C_{prev}(n_{PM_i})] \ , \tag{10}$$

where $C_{corr}(n_{CM_i})$ and n_{CM_i} are the cost and number of corrective maintenance tasks for component i, respectively, and $C_{prev}(n_{PM_i})$ and n_{PM_i} the cost and number of preventive maintenance tasks for component i, respectively. It should be noted that, both n_{CM_i} and n_{PM_i} are dependent on the global coordinates (x,y), although these dependencies are not explicitly defined in Eqs. (10)–(12) to maintain conciseness.

The corrective and preventive maintenance costs for each component can be further defined as [20],

$$C_{corr}(n_{CM_i}) = C_{v_{CM}}(n_{CM_i}) + C_{t_{CM}}(n_{CM_i}) + C_{m_{CM}}(n_{CM_i}) \ , \tag{11}$$

$$C_{prev}(n_{PM_i}) = C_{v_{PM}}(n_{PM_i}) + C_{t_{PM}}(n_{PM_i}) + C_{m_{PM}}(n_{PM_i}) \ , \tag{12}$$

where $C_{v_{CM}}(n_{CM_i})$ and $C_{v_{PM}}(n_{PM_i})$ are the vessel costs associated with corrective and preventive maintenance tasks, respectively; $C_{t_{CM}}(n_{CM_i})$ and $C_{t_{PM}}(n_{PM_i})$ the technician costs for these two, respectively; and $C_{m_{CM}}(n_{CM_i})$ and $C_{m_{PM}}(n_{PM_i})$ the material costs, respectively. Vessel, technician and material costs are further detailed in [20].

The function of each component is modelled by a continuous-time Markov chain. In this respect, $A_{c_i}(x,y)$, n_{CM_i} and n_{PM_i} are dependent on steady-state probability distributions of Markov chains. Two component level maintenance strategies are considered, each with its own Markov representation: a fully corrective and a combined corrective and preventive strategy [20].

- In the fully corrective maintenance strategy, the maintenance tasks are only performed after a component failure has been detected. By addressing turbine failures reactively, unnecessary preventive maintenance tasks and associated costs can be avoided. However, upon turbine failure, the maintenance crew must wait in port until metocean conditions become favourable and then proceed to carry out the necessary maintenance intervention. This results in wind turbine downtime, a period during which no energy is produced.
- The combined corrective and preventive maintenance strategy intends to perform preventive maintenance tasks before failure occurrences. However, given that failure occurrence instants are stochastic and therefore not fully predictable, there is the possibility that preventive maintenance cannot be performed before the failure instant. In that case, corrective maintenance must be performed to repair the failed component. However, corrective maintenance tasks can be practically neglected with appropriate preventive maintenance schedule, which is defined based on a maintenance reliability threshold [20]. In this sense, the threshold is defined at 95%, which effectively avoids corrective maintenance tasks and minimises turbine downtime [20]. Consequently, the combined corrective and preventive maintenance strategy acts mostly as a *fully* preventive maintenance strategy [20]. On the following, the latter strategy is referred to as *fully* preventive maintenance strategy. Furthermore, it should be noted that the accessibility dependency is not considered for preventive maintenance tasks, as the schedule of maintenance tasks is usually more manageable than in corrective tasks [63]. Hence, the *fully* preventive maintenance strategy assumes perfect knowledge of all components' health, reliant on an ideal condition monitoring system [64].

The definitions of $A_{c_i}(x,y)$, n_{CM_i} and n_{PM_i} for each Markov chain representation are further detailed in [20].

3. Evaluated scenarios

To assess the impact of considering O&M factors thoroughly in the techno-economic evaluation, three scenarios are designed: (i) a baseline, (ii) a conservative O&M and (iii) an ideal O&M, as shown in Fig. 3 and further detailed in this section. The $CapEx$ is the same for all scenarios and is calculated as detailed in Section 2.2. The difference between these scenarios lies in the underlying O&M approach.

The baseline scenario is the reference case-study based on state-of-the-art techno-economic frameworks employed in the identification of FOW sites [15,28,29]. Therefore, the baseline scenario is used as the reference for comparison purposes. Factors such as downtime, failure rates, repair times, metocean conditions, vessels and maintenance strategies are not taken into account in this baseline scenario, as detailed in Table 1, resulting in an O&M-agnostic framework.

In contrast, the conservative and the ideal O&M scenarios are developed based on the O&M-aware techno-economic model of the present paper, where all the relevant O&M factors are considered. The distinction between the conservative and ideal O&M scenarios lies in the selected O&M strategy. In this respect, the definition of the conservative and ideal O&M scenarios allows for a quantitative assessment of the $LCoE$ variations, and, subsequently, the analysis of its qualitatively impact on site-identification. Fig. 4 illustrates both the selected O&M scenarios as the upper and lower limits of the downtime and $LCoE$, and their representation in terms of site identification.

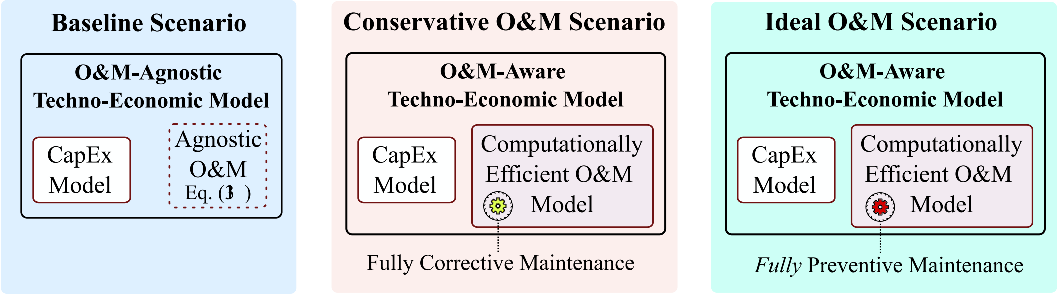


Fig. 3. The three evaluated scenarios in this paper. The three scenarios evaluated share the same $CapEx$ model. The conservative and the ideal O&M scenarios are designed based on the O&M-aware techno-economic model presented in this paper.

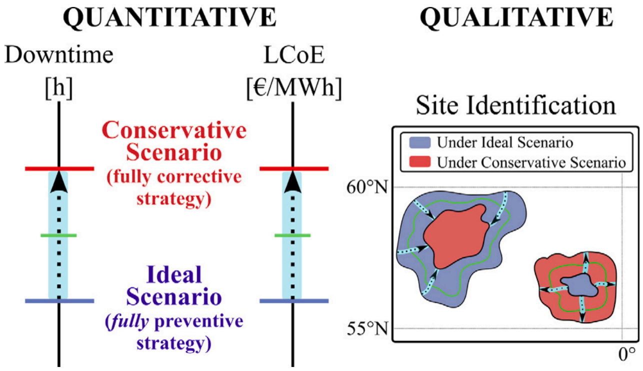


Fig. 4. The conservative and ideal O&M scenarios establish the upper and lower limits of turbine downtime and $LCoE$, respectively. The identified sites for FOW farms can vary depending on the scenario. By comparing these contrasting scenarios, the potential impact on site-identification concerning the O&M strategy can be assessed.

3.1. Baseline scenario

In the baseline scenario, $OpEx$ is defined linearly as a function of the distance-to-shore, as outlined in state-of-the-art O&M-agnostics techno-economic frameworks [15,28,29],

$$OpEx(x,y) = P_{farm} \cdot T \cdot [k_p + k_d \cdot d_{shore}(x,y)] \,, \tag{13}$$

where k_p and k_d are constant parameters defined as 138 k€/(MW year) and 40 €/(MW year km), respectively. Note that in the baseline scenario, the AEP estimation is performed solely considering the wind resource, neglecting turbine downtime (*i.e.*, turbine availability is 100%) [15,28,29].

3.2. Conservative O&M scenario

A conservative O&M scenario is designed based on the O&M-aware techno-economic model presented in this paper, where AEP and $OpEx$ are computed again by Eqs. (8) and (10), respectively. The conservative scenario represents a worst-case scenario because it is based on the fully corrective maintenance strategy. It should be noted that no operator in practice would rely solely on corrective maintenance interventions. Nevertheless, corrective maintenance tasks constitute a substantial part of the $OpEx$ for bottom-fixed offshore wind farms [65]. Therefore, it is expected that corrective maintenance will also play a major role in FOW farms. Furthermore, adopting a conservative scenario for decision making helps mitigate to financial and technical risks by establishing the upper limit of the turbine downtime and $LCoE$.

3.3. Ideal O&M scenario

An ideal O&M scenario is also designed based on the O&M-aware techno-economic model presented in this paper, where AEP and $OpEx$ are computed as described in Eqs. (8) and (10), respectively. The ideal O&M scenario is based on the *fully* preventive maintenance strategy, which minimises turbine downtime and $LCoE$, as explained in Section 2.3. In this sense, given that the *fully* preventive maintenance strategy involves the monitoring of the health of all critical components, this scenario can be deemed optimistic, especially considering the current maturity of the FOW sector. However, the FOW sector is emphasising on enhancing component monitoring systems for the early detection of potential issues, especially given the challenges of operating offshore [66]. Therefore, the ideal O&M scenario represents a best-case scenario and establishes the lower limit of the turbine downtime and $LCoE$.

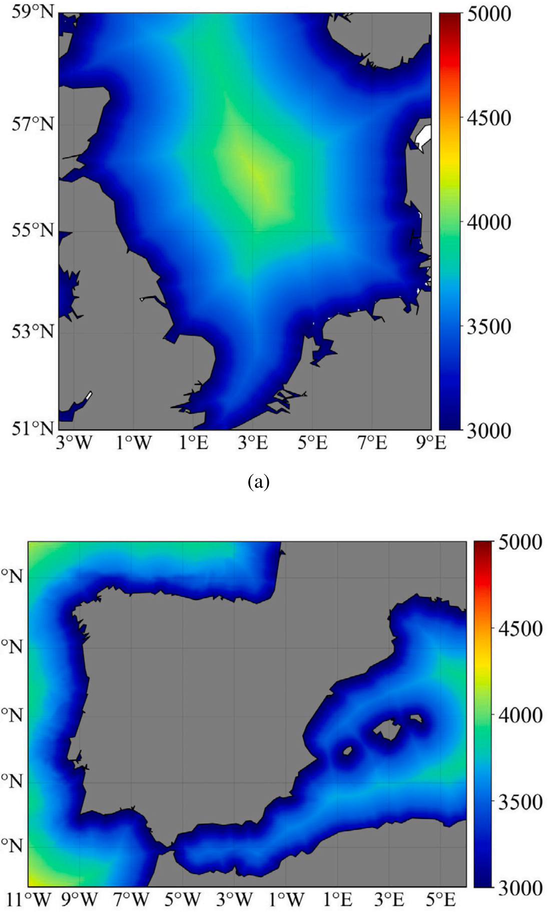
4. Results and discussion

4.1. Capital expenditures

The $CapEx$ for the North Sea and the Iberian Peninsula is represented in Figs. 5(a) and 5(b). The $CapEx$ ranges from 3000 M€ in locations closer to the shore to approximately 4500 M€ at more distant locations in the North Sea and the Iberian Peninsula. This variation in $CapEx$ is primarily influenced by the distance to shore in the North Sea, considering that the water depth is relatively uniform across the whole area, as depicted in Fig. 2(a). In contrast, $CapEx$ variability is mainly driven by the water depth in the Iberian Peninsula, due to the narrow continental shelf, as observed in Fig. 2(b). These $CapEx$ values align with [15], thereby serving as a verification for the $CapEx$ modelling in this paper.

4.2. Operational expenditures

The $OpEx$ across the North Sea and the Iberian Peninsula is represented in Figs. 6 and 7, respectively for the baseline, conservative and ideal O&M scenarios. In the baseline scenario, the $OpEx$ ranges from 1160 M€ to around 1280 M€ in the North Sea and the Iberian Peninsula, as depicted in Figs. 6(a) and 7(a), respectively. In the conservative O&M scenario the $OpEx$ is at least 83% and 75% (*i.e.*, x1.83 and x1.75, respectively) higher than the baseline in the North Sea and the Iberian Peninsula, as observed in Figs. 6(b) and 7(b). In contrast, in the ideal O&M scenario, the $OpEx$ estimation is at least 28% lower (*i.e.*, x0.72) compared to the baseline in the North Sea and the Iberian Peninsula, as depicted in Figs. 6(c) and 7(c), respectively. These results demonstrate that the variability of $OpEx$ depends directly on the maintenance strategy, highlighting the potential for cost reduction of applying preventive maintenance interventions.



(a)

(b)

Fig. 5. The $CapEx$ [M€] for: (a) the North Sea, and (b) the Iberian Peninsula.

Moreover, contrary to the assumption in the baseline, these results demonstrate that the $OpEx$ does not consistently increase along with the distance to shore across all regions. In this respect, the $OpEx$ is related to the distance to shore as follows:

(i) An increase in the distance to shore entails longer vessel trips and, therefore, higher fuel consumption, vessel use and labour hours, resulting in, higher $OpEx$.

(ii) An increase in the distance to shore also requires wider weather windows. This, in turn, reduces accessibility [19]. A reduction in accessibility leads to increased difficulties in performing required maintenance tasks, especially for tasks that require longer time, which in turn delays subsequent maintenance tasks, as the grouping of tasks is not considered. Consequently, the total number of performed maintenance tasks in the analysis horizon decreases, resulting in a reduction in the $OpEx$. Nevertheless, it should be noted that such a reduction of the $OpEx$ is not a positive sign, since the decrease in accessibility also leads to increased turbine downtime, consequently reducing the AEP.

Therefore, the overall $OpEx$ depends on the trade-off between the rise in costs per vessel trip and the reduction in accessibility. The reduction in accessibility is particularly notable in regions characterised by harsh metocean conditions, such as Galicia and Portugal, where turbine availability can decrease by up to 25% [37]. For that reason, the $OpEx$ does not consistently increase with the distance to shore in Galicia and Portugal, as depicted in Fig. 7(b). In other regions of the Iberian Peninsula and the North Sea, the accessibility decreases less [37]. Consequently, the $OpEx$ increases with the increase of the distance from shore, as observed in Figs. 6(b) and 7(b).

In the ideal O&M scenario depicted in Fig. 7(c), such a reduction in $OpEx$ is not observed in Galicia and Portugal. This is attributed to the omission of accessibility dependence in the preventive maintenance tasks.

The above results underscore that $OpEx$ is heavily dependent on diverse factors, including metocean conditions, distances, failure rates, repair times, operational limits of vessels, maintenance strategies, and their interdependencies. Defining these interdependencies is achievable only through a comprehensive O&M model and not through a single equation [Eq. (13)], as traditionally done by techno-economic models.

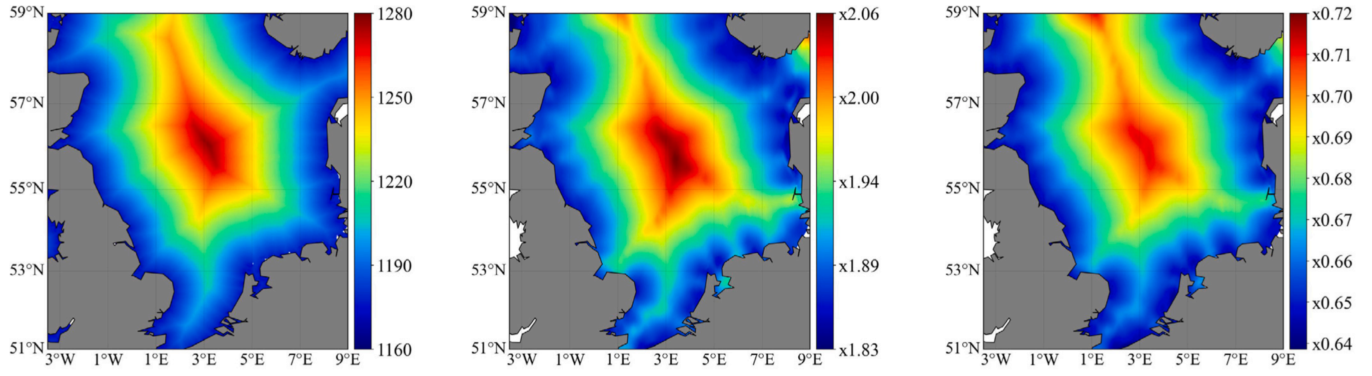
4.3. Levelised cost of energy

The $LCoE$ for the North Sea and the Iberian Peninsula in the baseline scenario, conservative O&M scenario, and ideal O&M scenario are represented in Figs. 8 and 9. The $LCoE$ in the baseline scenario, following $CapEx$ and $OpEx$ characteristics, ranges from 90 €/MWh in locations closer to the shore to approximately 130 €/MWh at the centre of the North Sea, as observed in Fig. 8(a). In contrast, higher values of $LCoE$ are observed in the Iberian Peninsula, as observed in Fig. 9(a), most likely due to a lower wind resource compared to the North Sea. The lowest $LCoE$ values in the Iberian Peninsula are observed in Galicia and Portugal with values of approximately 110 €/MW h. In the Mediterranean Sea, identifying the best locations are in the Gulf of Roses and the Alboran Sea with the $LCoE$ values of approximately 150 €/MW h.

Nevertheless, these estimations of $LCoE$ change when O&M factors are considered. In the conservative O&M scenario, illustrated in Figs. 8(d) and 9(d), the $LCoE$ increases by at least 25% and 35% (*i.e*, x1.25 and x1.35) compared to the baseline across the North Sea and the Iberian Peninsula, respectively. This implies that the $LCoE$ can reach values higher than 150 €/MWh in most of the regions in the North Sea. Differences increase in the Iberian Peninsula, where the lowest $LCoE$ values reach approximately 200 €/MWh in Portugal and Galicia. In contrast, due to higher maintainability (*i.e.*, lower H_s) and, thus, lower turbine downtime, the best regions in the Mediterranean Sea, such as the Gulf of Roses and the Alboran Sea, show values of approximately 150 €/MWh. In the rest of the regions of the Iberian Peninsula, $LCoE$ values surpass 250 €/MWh. In the ideal O&M scenario, the *fully* preventive maintenance strategy can reduce the $LCoE$ with respect to the baseline by up to 20% and 6% (*i.e*, x0.80 and x0.94) in the North Sea and the Iberian Peninsula, respectively, as depicted in Figs. 8(e) and 9(e).

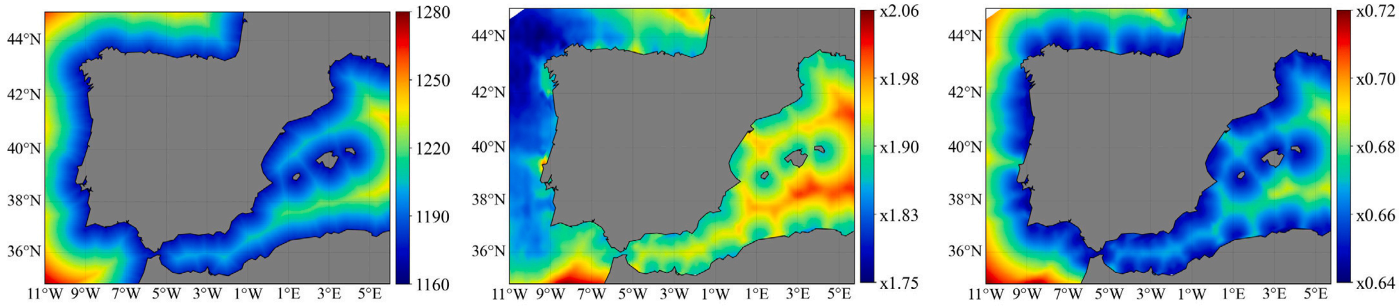
The percentages of $OpEx$ in relation to the $LCoE$ for the North Sea and the Iberian Peninsula are illustrated in Figs. 10 and 11, respectively. In both regions, the baseline estimation of the $OpEx$ ranges from 24% to 28% of the $LCoE$, as shown in Figs. 10(a) and 11(a) for the North Sea and the Iberian Peninsula, respectively. In contrast, in the conservative O&M scenario, the contribution of the $OpEx$ to $LCoE$ can vary between 44% to 50% in the North Sea and 38% to 46% in the Iberian Peninsula, as observed in Figs. 10(b) and 11(b). Finally, in the ideal O&M scenario, the $OpEx$ represents 22% to 25% of the $LCoE$ in the North Sea and 19% to 23% in the Iberian Peninsula, as observed in Figs. 10(c) and 11(c).

Overall, the analysis leads to the conclusion that the O&M agnostic baseline estimates are closer to an ideal O&M scenario than to a conservative one. However, to achieve this outcome, preventive maintenance interventions are necessary, demanding continuous and precise health monitoring of all components. Hence, this ideal O&M scenario can be regarded as optimistic, considering the current maturity of the FOW sector. For that reason, it can be argued that the O&M-agnostic techno-economic analyses in the literature may be underestimating the $LCoE$.



(a) (b) (c)

Fig. 6. The North Sea $OpEx$ [M€]: (a) Baseline scenario, (b) Conservative O&M scenario, and (c) Ideal O&M scenario.



(a) (b) (c)

Fig. 7. The Iberian Peninsula $OpEx$ [M€]: (a) Baseline scenario, (b) Conservative O&M scenario, and (c) Ideal O&M scenario.

4.4. The qualitative influence of O&M on site-identification

To evaluate the qualitative impact, sites with the lowest $LCoE$ are selected in the North Sea and the Iberian Peninsula under the baseline, conservative and ideal O&M scenarios. To that end, the top 10% most appealing sites, *i.e.*, the 10% of lowest $LCoE$, are identified from Figs. 8(a)–8(c) in the North Sea and Figs. 9(a)–9(c) in the Iberian Peninsula, respectively. Note that the analysis is restricted to sites with a water depth of at least 50 m to assess regions suitable for FOW farms.

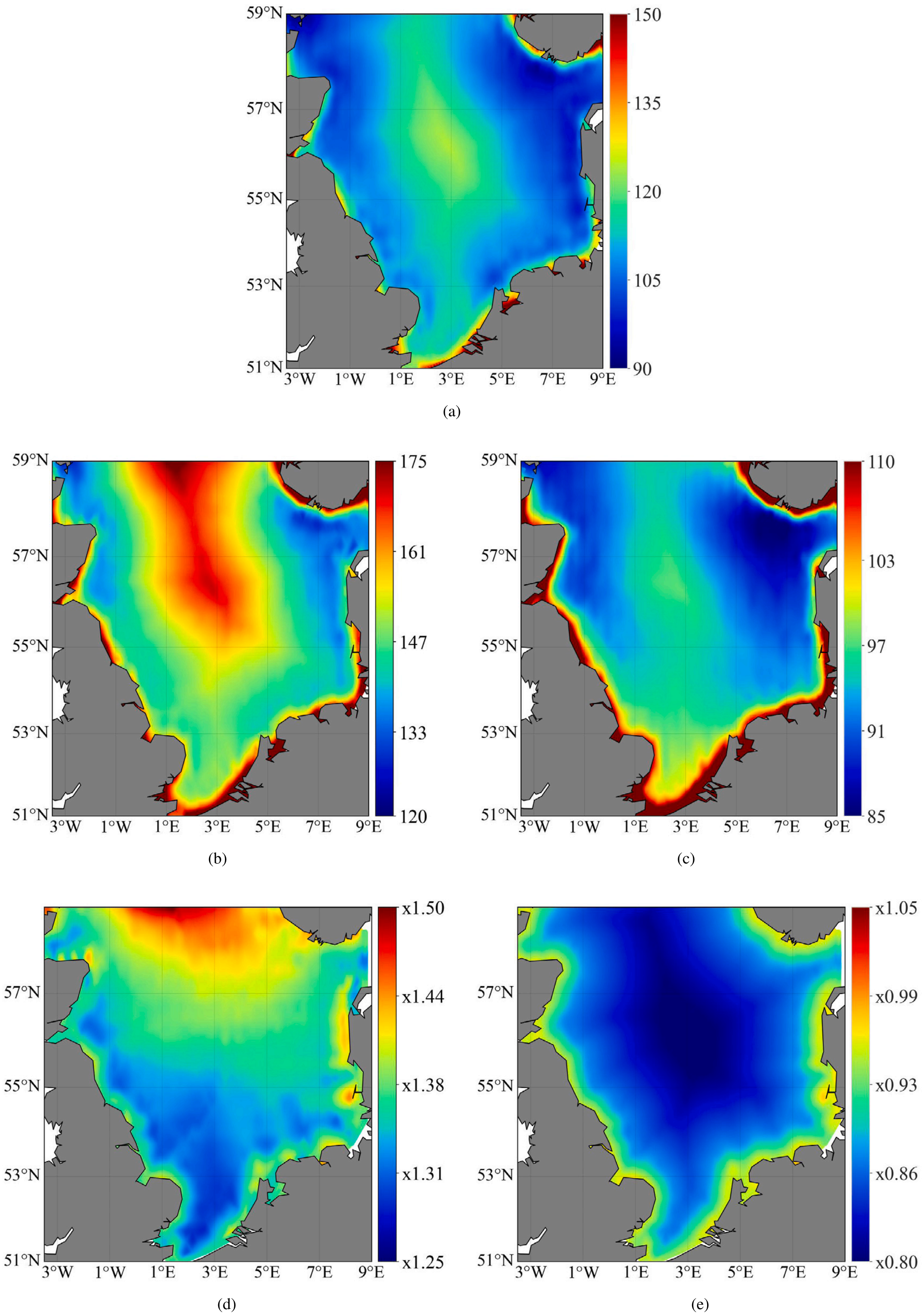
The suitable sites identified for FOW farms are shown in Figs. 12(a) and 12(b). However, the areas identified under the baseline scenario are not depicted in Figs. 12(a) and 12(b), as they practically overlap with those under the ideal O&M scenario. There is a quantitative difference between the baseline and ideal O&M scenarios in terms of $LCoE$, as observed in Section 4.3, but there is no significant qualitative distinction. In both scenarios, the lowest $LCoE$ is predominantly found in regions with abundant wind resource potential, such as Norway and northern Scotland in the North Sea, and Galicia and the Gulf of Roses in the Iberian Peninsula. This observation is further analysed in Fig. B.1, where the yellow regions indicating the top 10% most promising sites based solely on the potential of wind resources largely coincides with the aforementioned regions.

It is important to note that this similarity on identified sites between the baseline and ideal O&M scenarios happens due to different reasons. The baseline scenario relies on an O&M-agnostic techno-economic model, which neglects turbine downtime. Consequently, in the baseline scenario, the lowest $LCoE$ values always correspond to areas where the wind resource is most abundant [15]. In contrast, the ideal O&M scenario identifies these areas given the *fully* preventive maintenance strategy, which minimises turbine downtime in all potential areas, thereby highlighting regions with the greatest wind resource potential.

In contrast, the spatial distribution of suitable sites in the North Sea and the Iberian Peninsula varies significantly under the conservative O&M scenario, as observed in Figs. 12(a) and 12(b). In the conservative O&M scenario with a fully corrective maintenance strategy, the identified sites are those that combine (i) a significant wind resource potential and (ii) a less severe metocean conditions, which enables a significant increase in maintainability and, thus, a reduction in turbine downtime. In the North Sea, the identified regions include areas south of Scotland and sites along the coast of Norway closer to shore compared to the regions identified in the ideal O&M scenario. In the Iberian Peninsula, the Mediterranean Sea is prioritise over the European Atlantic Ocean. Suitable sites in Galicia are limited to near-shore locations, while attractive areas in the Alboran Sea and the Gulf of Roses have been identified in the Mediterranean Sea.

As the FOW industry becomes more capable of preventing failures with advanced condition monitoring systems and gains operational experience in FOW farms, the most attractive sites will be those with the highest wind resource potential, regardless of the harsh wave conditions. In the meantime, other areas with significant wind resource but less severe wave conditions seem to be more appealing.

The average KPIs of the identified regions highlighted in Figs. 12(a) and 12(b) are shown in Table 5. The average $LCoE$ in the ideal O&M scenario is 94.66 €/MWh and 114.16 €/MWh in the North Sea and the Iberian Peninsula, respectively, which results in a reduction of about 30%–40% compared to the conservative O&M scenario. This reduction is mainly due to the reduction in the $OpEx$. The $OpEx$ in the ideal O&M scenario is in average 42.19 €/MWh and 57.67 €/MWh lower in the North Sea and the Iberian Peninsula, respectively, compared to conservative O&M scenario. Additionally, turbine availability also affects the $LCoE$, with the availability increasing in about 6% with the ideal O&M scenario.

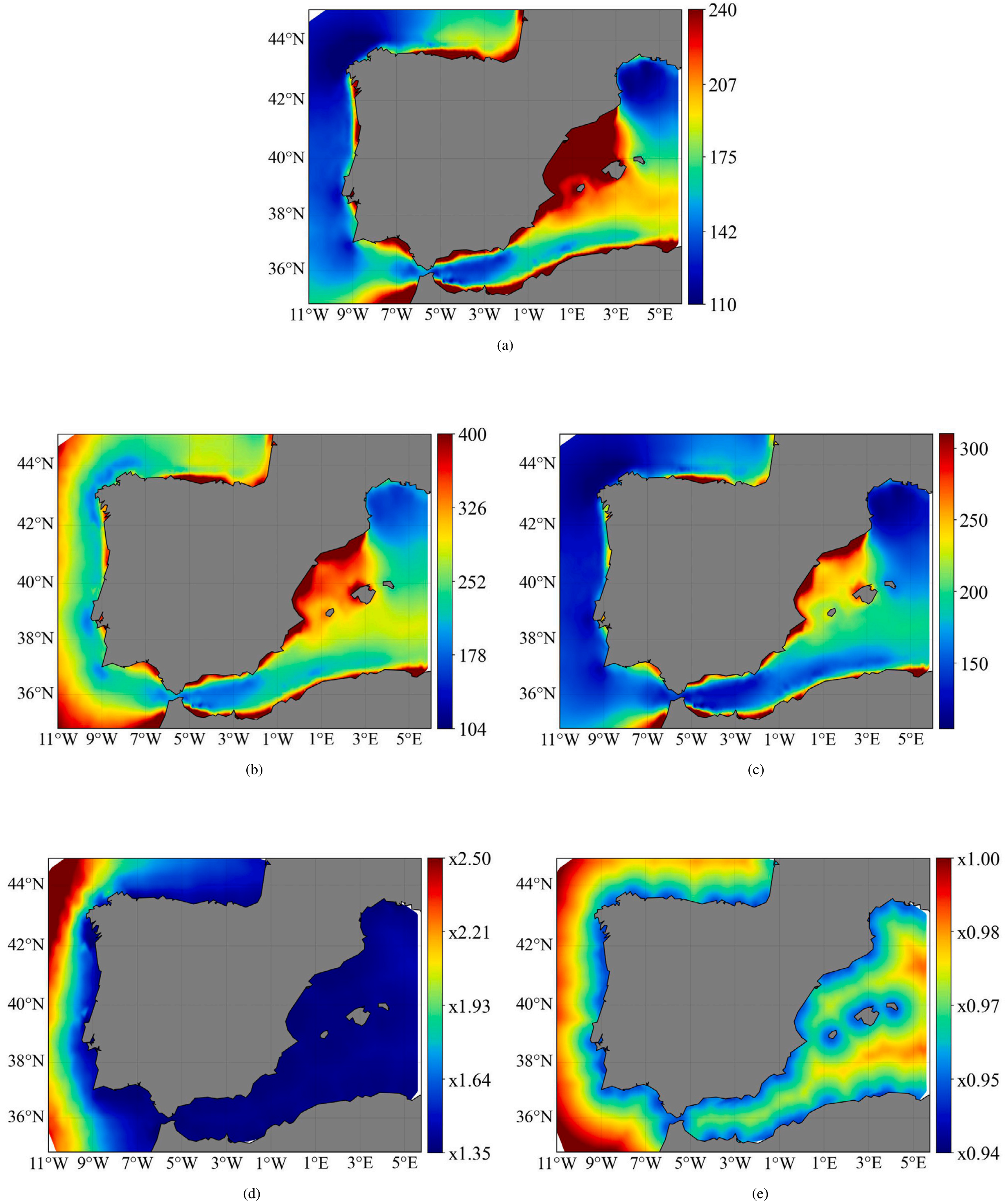


(a)

(b) (c)

(d) (e)

Fig. 8. The North Sea $LCoE$ in the: (a) Baseline scenario [€/MWh], (b) Conservative O&M scenario [€/MWh], (c) Ideal O&M scenario [€/MWh], (d) Conservative O&M scenario $LCoE$ with respect to the baseline, and (e) Ideal O&M scenario $LCoE$ with respect to the baseline.



(a)

(b) (c)

(d) (e)

Fig. 9. The Iberian Peninsula $LCoE$: (a) Baseline scenario [€/MWh], (b) Conservative O&M scenario [€/MWh], (c) Ideal O&M scenario [€/MWh], (d) Conservative O&M scenario $LCoE$ with respect to the baseline, and (e) Ideal O&M scenario $LCoE$ with respect to the baseline.

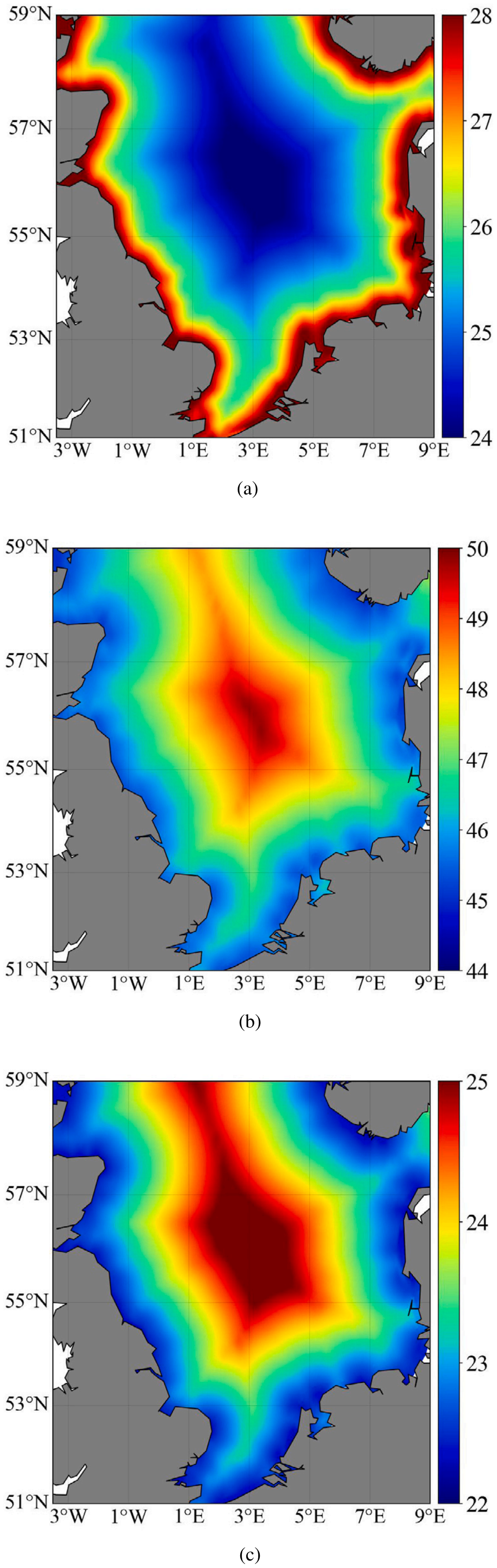


Fig. 10. The North Sea $OpEx$ representation [%] in the $LCoE$ with: (a) Baseline scenario, (b) Conservative O&M scenario, and (c) Ideal O&M scenario.

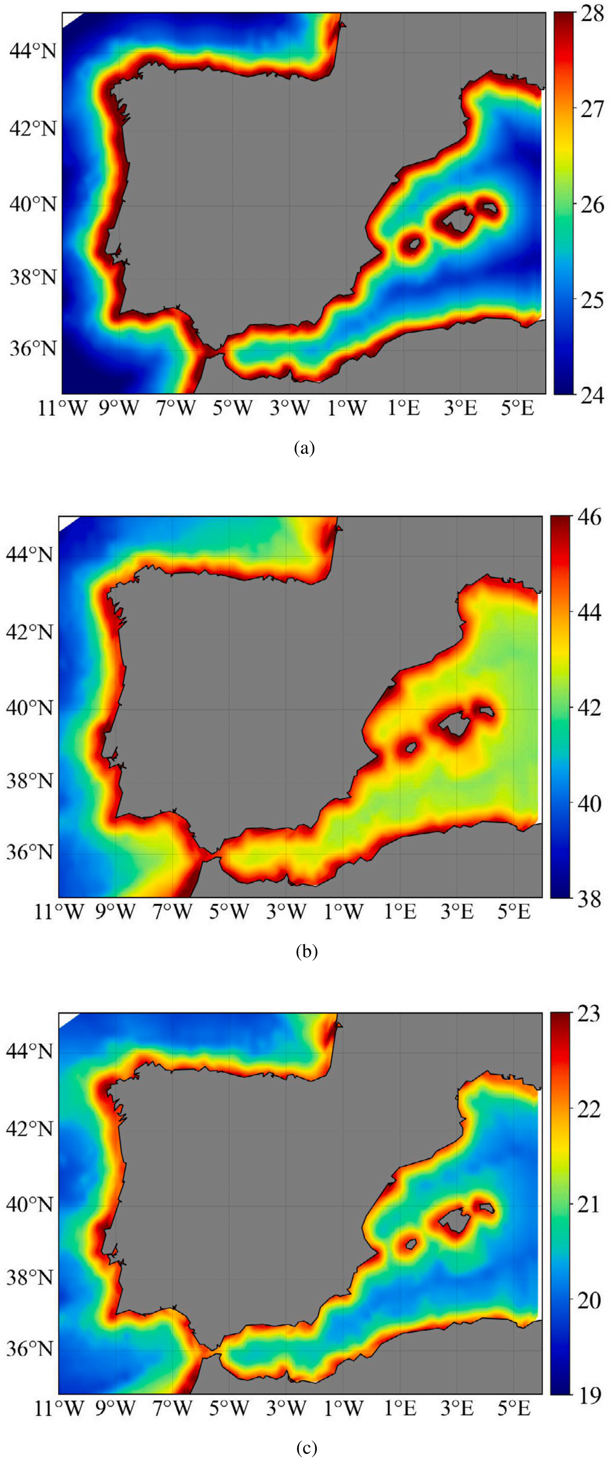
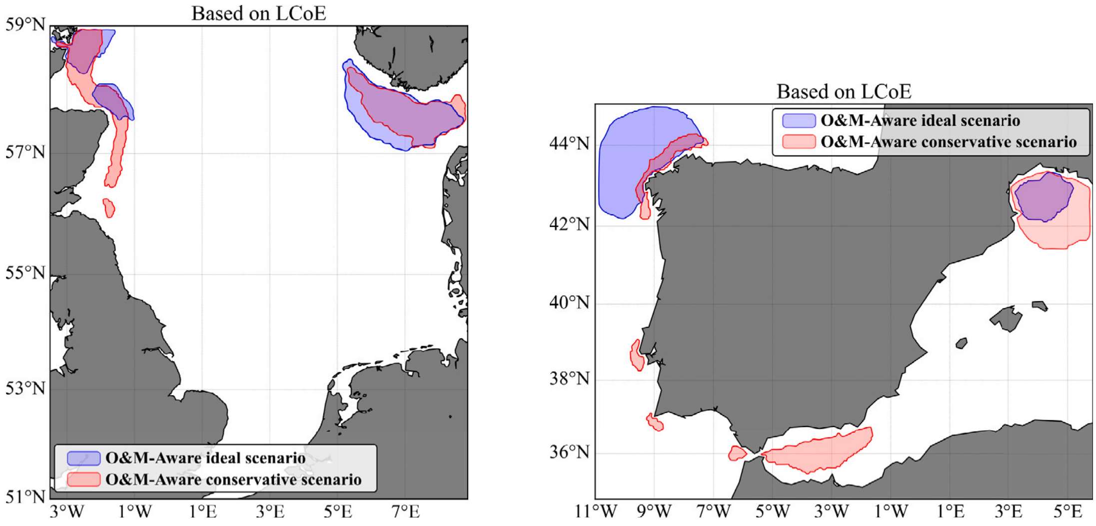


Fig. 11. The Iberian Peninsula $OpEx$ representation [%] in the $LCoE$ with: (a) Baseline scenario, (b) Conservative O&M scenario, and (c) Ideal O&M scenario.



(a) (b)

Fig. 12. The 10% of lowest $LCoE$ value locations under conservative and ideal O&M scenarios in: (a) the North Sea, and (b) the Iberian Peninsula.

Table 5
The average KPIs of the identified top 10% regions in the North Sea and the Iberian Peninsula considering both the conservative and ideal O&M Scenarios.

	North Sea		Iberian Peninsula	
	Cons.	Ideal	Cons.	Ideal
$LCoE$ [€/MWh]	142.47	94.66	187.95	114.16
$CapEx$ [€/MWh]	80.16	74.54	106.63	90.51
$CapEx/LCoE$ [%]	56.26	78.74	56.73	79.28
$OpEx$ [€/MWh]	62.31	20.12	81.32	23.65
$OpEx/LCoE$ [%]	43.77	21.26	43.27	20.72
Capacity Factor [%]	54.31	58.99	42.75	52.35
Availability [%]	90.49	96.81	90.28	96.11

In this respect, the spatial change observed between the regions identified for the conservative and the ideal O&M scenarios based on the LCoE, as depicted in Figs. 12(a) and 12(b), is significantly influenced by turbine downtime. This observation is further demonstrated in Fig. B.1, where the top 10% sites are identified only based on the AEP. The spatial change observed in Fig. B.1 between the conservative and ideal O&M scenarios is caused by the difference in turbine downtime in these two scenarios, which largely coincides with the spatial variation observed in Figs. 12(a) and 12(b). This highlights the importance of considering turbine downtime in the site-identification of FOW farms, especially given that turbine downtime is traditionally neglected in the techno-economic frameworks used for identifying FOW sites.

5. Conclusion

Accurate techno-economic models are crucial to develop and deploy floating offshore wind (FOW) farms. However, traditionally, techno-economic models oversimplify operation and maintenance (O&M) aspects, neglecting key factors such as component failure rates, accessibility due to metocean conditions, repair times, maintenance vessels and characteristics of the ports in the analysis. In this respect, this paper suggests an O&M-aware techno-economic model that considers the most relevant O&M factors.

The O&M-aware techno-economic model presented in this paper is applied on two O&M scenarios: a conservative scenario and an ideal scenario. These two scenarios are then compared with a baseline scenario that represents the well-known traditional techno-economic analyses. The conservative O&M scenario is focused on corrective maintenance interventions, whereas the ideal scenario considers preventive maintenance interventions. The novel results from this paper show that:

(i) The estimates for operational expenditure ($OpEx$) and $LCoE$ from the baseline techno-economic framework are more closely aligned with an ideal O&M scenario. In this ideal O&M scenario the $OpEx$ constitutes 22% to 25% of the $LCoE$ in the North Sea and 19% to 23% in the Iberian Peninsula. However, the ideal scenario assumes the continuous monitoring of the health of all critical components, a condition that may be considered optimistic given the current maturity of the FOW sector. This optimistic assumption could result in an underestimation of both $OpEx$ and $LCoE$.

(ii) In the conservative O&M scenario, the $LCoE$ increases by at least 25% and 35% compared to the baseline techno-economic framework across the North Sea and the Iberian Peninsula, respectively. In this case, the $OpEx$ constitutes between 44% to 50% of the $LCoE$ in the North Sea and 38% to 46% in the Iberian Peninsula.

The O&M-aware techno-economic model is also employed to evaluate the qualitative impact of O&M strategies on site-identification across the North Sea and the Iberian Peninsula. The results demonstrate that:

(i) As preventive O&M strategies gain presence in the FOW sector, the sites with the highest wind resource potential will be more attractive, such as areas in northern Scotland and Norway in the North Sea, and extensive areas in Galicia and the Gulf of Roses in the Iberian Peninsula. In contrast, with a mostly corrective O&M strategy, attention should be given to sites with significant wind resources but less severe metocean conditions. This includes areas in the North Sea like the south of Scotland and closer to shore in Norway. In the Iberian Peninsula, the Mediterranean Sea is prioritised over the European Atlantic Ocean, including extensive areas in the Gulf of Roses and the Alboran Sea.

(ii) Turbine downtime is a key factor that influences site-identification for FOW farms. An aspect traditionally neglected in the energy production estimation of techno-economic frameworks.

Future research will explore the influence of the tow-to-port major maintenance strategy, the addition of an offshore O&M base for O&M vessels, and the grouping of postponed maintenance tasks with other required maintenance interventions.

CRediT authorship contribution statement

Manu Centeno-Telleria: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hong Yue:** Writing – review & editing, Writing – original draft, Validation, Methodology. **James Carrol:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Jose I. Aizpurua:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Markel Penalba:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

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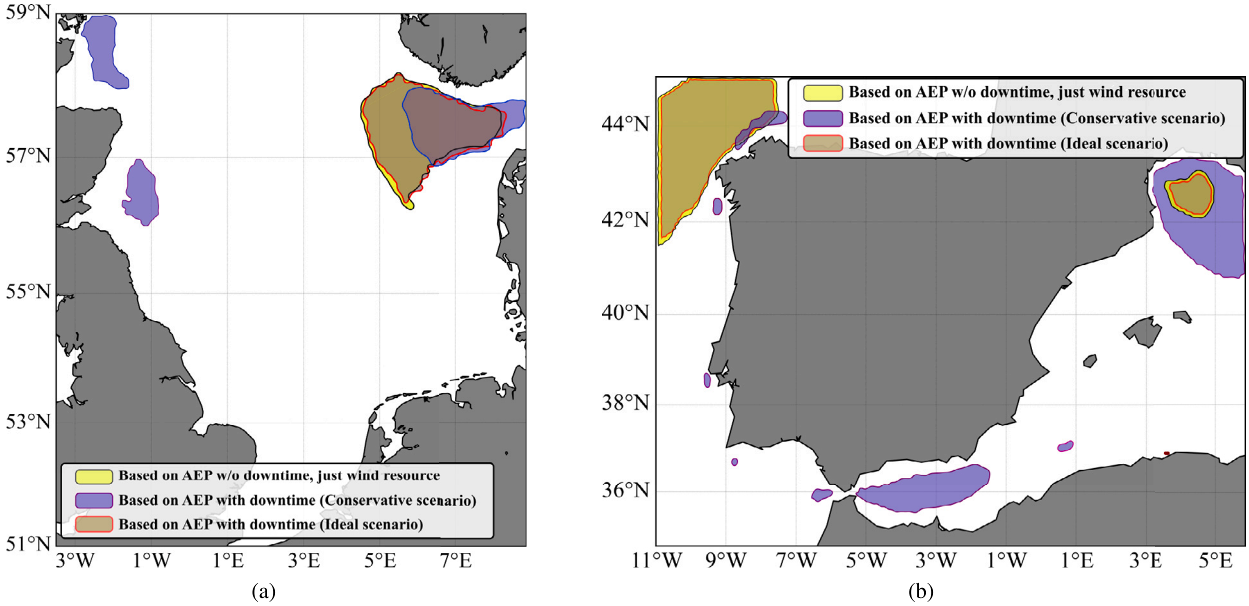
Appendix A. Characteristics for the FOW turbine

See Table A.1.

Table A.1
Taxonomy for the semi-submersible FOW turbine and related properties adjusted from [35,67].

Component	Failure	Corrective			Preventive	
	rate $[\frac{\text{failures}}{\text{year}}]$	Dur. [h]	Cost [€]	Vess.	Dur. [h]	Cost [€]
Floater	0.98112	12	119 861	FSV	12	59 930
Mooring lines	0.14892	12	633 397	FSV	12	316 698
Anchors	0.15768	12	124 219	FSV	12	62 109
Power cable	3.23e−5	24	940 662	FSV	18	470 331
Export cable	0.167	24	5 138 105	FSV	18	2 569 052
Pitch & Hydr. sys.	1.076	89	74 873	HLV	50	37 436
Generator	0.999	67	29 505	HLV	39	14 752
Blades	0.52	31.25	20 490	HLV	21	10 245
Gearbox	0.633	44.5	23 301	HLV	28	11 650
Grease, Oil, Cooling Liq.	0.471	22	5967	FSV	17	2983
Electrical comp.	0.435	20.75	5168	FSV	16	2584
Contactor, Circuit breaker	0.43	17.5	5185	FSV	14	2592
Controls	0.428	17.5	5033	FSV	14	2516
Safety	0.392	13.25	4891	FSV	12	2445
Sensors	0.346	12.75	4538	FSV	12	2269
Pumps, Motors	0.346	11	4025	FSV	11	2012
Hub	0.235	8.3	1279	FSV	10	639
Heaters, Coolers	0.213	8	1221	CTV	10	610
Yaw system	0.189	7.3	1124	CTV	9	562
Tower, Foundation	0.05	7	1042	CTV	9	521
Power supply, Converter	0.18	8	852	CTV	10	426
Transformer	0.065	3.6	598	CTV	8	299

Note 1: Costs were given in 2019 currency values. The average conversion rate from GBP to EUR of 1.136 was used [35].
Note 2: All repair costs are associated with component replacements, with the exception of the floating platform, where a complete replacement of the entire platform would be impractical [35].



(a) (b)

Fig. B.1. The 10% of lowest AEP value locations just considering the wind resource potential, under conservative O&M scenario, and under ideal O&M scenario that minimises turbine downtime in: (a) the North Sea, and (b) the Iberian Peninsula.

Appendix B. Abbreviations and symbols

Abbrev.	**Description**
O&M	Operation and Maintenance
FOW	Floating Offshore Wind
NREL	National Renewable Energy Laboratory
ECN	Energy Research Centre of the Netherlands
CTV	Crew Transfer Vessel
FSV	Field Support Vessel
HLV	Heavy Lift Vessel
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current

Symbols	**Description**
$LCoE$	Levelised cost of energy [€/MWh]
$OpEx$	Operational expenditures [€]
$CapEx$	Capital expenditures [€]
AEP	Annual energy production [MWh]
r	Discount rate [%]
T	Wind farm project lifetime [years]
x	Longitude [°]
y	Latitude [°]
n_{tur}	Number of turbines in the farm [·]
n_c	Number of considered components in the turbine [·]
A_{tur}	Average turbine availability [%]
A_c	Average component availability [%]
P_{farm}	Total installed capacity [MW]
d_{port}	Distance to port [km]
d_{shore}	Distance to shore [km]
h	Water depth [m]
H_s	Significant wave height [m]
U_w	Wind speed [m/s]
$C_{D\&C}$	Development and consenting services cost [€]
C_{tur}	Turbine and substructure cost [€]
C_{moor}	Mooring cost [€]
C_{inst}	Installation cost [€]
C_{dec}	Decommissioning cost [€]
n_{lines}	Number of mooring lines per turbine [·]
C_{anchor}	Anchor cost [€]
C_{line}	Mooring line cost [€/km]
C_{chain}	Chain cost [€/km]
n_{exp}	Number of export cables [·]
C_{exp}	Cost of export cables [€/km]
n_{off}	Number of offshore substations [·]
C_{off}	Cost of offshore substations [€]
n_{on}	Number of onshore substations [·]
C_{on}	Cost of onshore substations [€]
d_{inter}	Length of inter array cable [km]
C_{inter}	Cost of inter array cable [€/km]
T_{inst}	Duration of the installation [h]
$n_{tur_{trip}}$	Number of turbines carried out by the vessel [·]
V_{tug}	Towing speed [knots]
C_{tug}	Charter cost of installation vessel per day [€/h]
$C_{inst_{tur}}$	Cost of installing turbine [€]
$C_{inst_{tur}}$	Cost of installing turbine [€]
$C_{inst_{moor}}$	Cost of installing mooring system [€]
$C_{inst_{exp}}$	Cost of installing export cables [€]
$C_{inst_{inter}}$	Cost of installing inter-array cables [€]
$C_{inst_{off}}$	Cost of installing offshore substation [€]
A_{tur}	Turbine average availability [%]
$P(U_w)$	Power curve of the turbine [·]
dt	Continuous integration [·]
η_{CM}	Number of corrective maintenance tasks [·]
η_{PM}	Number of preventive maintenance tasks [·]
C_{corr}	Cost of a corrective maintenance task [€]
C_{prev}	Cost of a preventive maintenance task [€]
$C_{v_{CM}}$	Cost of a vessel for a corrective maintenance task [€]
$C_{t_{CM}}$	Cost of technicians for a corrective maintenance task [€]
$C_{m_{CM}}$	Cost of material for a corrective maintenance task [€]
$C_{v_{PM}}$	Cost of a vessel for a preventive maintenance task [€]
$C_{t_{PM}}$	Cost of technicians for a preventive maintenance task [€]
$C_{m_{PM}}$	Cost of material for a preventive maintenance task [€]

References

[1] International Energy Agency. Energy Technology Perspectives 2023. Paris: IEA; 2023.

[2] The White House. Inflation reduction act guidebook. 2022, https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf.

[3] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions: Repowereu plan. 2022, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM.

[4] Bouckaert S, Pales A, McGlade C, Remme U, Wanner B. Net Zero by 2050: A Roadmap for the Global Energy Sector. Technical Report, International Energy Agency; 2021, URL https://www.iea.org/reports/net-zero-by-2050.

[5] DNV. Hywind Scotland Floating Offshore Wind, https://www.dnv.com/news/new-dnv-gl-class-rules-for-floating-offshore-wind-expands-industry-horizon-189033.

[6] Equinor. https://www.equinor.com/energy/hywind-tampen.

[7] Principle Power. Kincardine Offshore Wind Farm, URL https://www.principlepower.com/projects/kincardine-offshore-wind-farm.

[8] Duarte T, Price S, Peiffer A, Pinheiro JM. WindFloat atlantic project: Technology development towards commercial wind farms. In: OTC offshore technology conference, vol. Day 2 Tue, May 03, 2022, 2022, D021S016R003. http://dx.doi.org/10.4043/32058-MS.

[9] Díaz H, Soares CG. Cost and financial evaluation model for the design of floating offshore wind farms. Ocean Eng 2023;287:115841. http://dx.doi.org/10.1016/j.oceaneng.2023.115841.

[10] McMorland J, Flannigan C, Carroll J, Collu M, McMillan D, Leithead W, et al. A review of operations and maintenance modelling with considerations for novel wind turbine concepts. Renew Sustain Energy Rev 2022;165:112581. http://dx.doi.org/10.1016/j.rser.2022.112581.

[11] Tavner P. Offshore Wind Power Reliability, availability and maintenance. second ed.. Institution of Engineering & Technology; 2021, http://dx.doi.org/10.1049/PBPO194E.

[12] Shen W, Chen X, Qiu J, Hayward JA, Sayeef S, Osman P, et al. A comprehensive review of variable renewable energy levelized cost of electricity. Renew Sustain Energy Rev 2020;133:110301. http://dx.doi.org/10.1016/j.rser.2020.110301.

[13] Kell NP, Santibanez-Borda E, Morstyn T, Lazakis I, Pillai AC. Methodology to prepare for UK's offshore wind contract for difference auctions. Appl Energy 2023;336:120844. http://dx.doi.org/10.1016/j.apenergy.2023.120844.

[14] Martinez A. Wind energy perspectives: Climate change and economic viability of floating offshore wind (Ph.D. thesis), University College Cork; 2022.

[15] Martinez A, Iglesias G. Mapping of the levelised cost of energy for floating offshore wind in the European atlantic. Renew Sustain Energy Rev 2022;154:111889. http://dx.doi.org/10.1016/j.rser.2021.111889.

[16] Díaz H, Guedes Soares C. A novel multi-criteria decision-making model to evaluate floating wind farm locations. Renew Energy 2022;185:431–54. http://dx.doi.org/10.1016/j.renene.2021.12.014.

[17] DNV. Ocean's future to 2050. 2021, https://www.dnv.com/oceansfuture.

[18] Edwards EC, Holcombe A, Brown S, Ransley E, Hann M, Greaves D. Evolution of floating offshore wind platforms: A review of at-sea devices. Renew Sustain Energy Rev 2023;183:113416. http://dx.doi.org/10.1016/j.rser.2023.113416.

[19] Centeno-Telleria M, Aizpurua J, Penalba M. Impact of accessibility on O&M of floating offshore wind turbines: Sensitivity of the deployment site. Trends Renew Energies Offshore 2023;847–55. http://dx.doi.org/10.1201/9781003360773-94.

[20] Centeno-Telleria M, Aizpurua JI, Penalba M. Computationally efficient analytical O&M model for strategic decision-making in offshore renewable energy systems. Energy 2023;285:129374. http://dx.doi.org/10.1016/j.energy.2023.129374.

[21] World Forum Offshore Wind. Onsite major component replacement technologies for floating offshore wind: the status of the industry. 2023, https://wfo-global.org/wp-content/uploads/2023/02/WFO-FOWC-OM-White-Paper-2-Final.pdf.

[22] Rausand M, Hoyland A. System Reliability Theory: Models, Statistical Methods, and Applications, vol. 396, John Wiley & Sons; 2003.

[23] Martini M, Guanche R, Losada IJ, Vidal C. Accessibility assessment for operation and maintenance of offshore wind farms in the north sea. Wind Energy 2017;20(4):637–56. http://dx.doi.org/10.1002/we.2028.

[24] Trivedi KS, Bobbio A. Reliability and Availability Engineering: Modeling, Analysis, and Applications. Cambridge University Press; 2017, http://dx.doi.org/10.1017/9781316163047.

[25] Castro-Santos L, Filgueira-Vizoso A, Carral-Couce L, Ángel Fraguela Formoso J. Economic feasibility of floating offshore wind farms. Energy 2016;112:868–82. http://dx.doi.org/10.1016/j.energy.2016.06.135.

[26] Castro-Santos L, Silva D, Bento AR, Salvação N, Guedes Soares C. Economic feasibility of floating offshore wind farms in Portugal. Ocean Eng 2020;207:107393. http://dx.doi.org/10.1016/j.oceaneng.2020.107393.

[27] Castro-Santos L, deCastro M, Costoya X, Filgueira-Vizoso A, Lamas-Galdo I, Ribeiro A, et al. Economic feasibility of floating offshore wind farms considering near future wind resources: Case study of Iberian Coast and bay of biscay. Int J Environ Res Public Health 2021;18(5). http://dx.doi.org/10.3390/ijerph18052553.

[28] Martinez A, Iglesias G. Site selection of floating offshore wind through the levelised cost of energy: A case study in Ireland. Energy Convers Manage 2022;266:115802. http://dx.doi.org/10.1016/j.enconman.2022.115802.

[29] Martinez A, Iglesias G. Multi-parameter analysis and mapping of the levelised cost of energy from floating offshore wind in the mediterranean sea. Energy Convers Manage 2021;243:114416. http://dx.doi.org/10.1016/j.enconman.2021.114416.

[30] Nunemaker J, Buster G, Rossol M, Duffy P, Shields M, Beiter P, et al. NREL Wind Analysis Library (NRWAL). Tech. Rep., National Renewable Energy Laboratory (NREL), Golden, CO (United States); 2021.

[31] Rademakers L, Braam H, Obdam T, Van de Pieterman R. Operation and maintenance cost estimator (OMCE). Energy Res Centre Neth 2009.

[32] Li M, Jiang X, Negenborn RR. Opportunistic maintenance for offshore wind farms with multiple-component age-based preventive dispatch. Ocean Eng 2021;231:109062. http://dx.doi.org/10.1016/j.oceaneng.2021.109062.

[33] Martini M. modelization and analysis of operation and maintenance of floating offshore wind farms (Ph.D. thesis), Universidad de Cantabria; 2017.

[34] Dinwoodie I. Modelling the operation and maintenance of offshore wind farms (Ph.D. thesis), University of Strathclyde; 2014.

[35] Rinaldi G, Garcia-Teruel A, Jeffrey H, Thies P, Johanning L. Incorporating stochastic operation and maintenance models into the techno-economic analysis of floating offshore wind farms. Appl Energy 2021;301. http://dx.doi.org/10.1016/j.apenergy.2021.117420.

[36] Hammond R, Cooperman A. Windfarm operations and maintenance cost-benefit analysis tool (wombat). Tech. Rep., National Renewable Energy Lab.(NREL), Golden, CO (United States); 2022.

[37] Centeno-Telleria M, Yue H, Carrol J, Penalba M, Aizpurua JI. Impact of operations and maintenance on the energy production of floating offshore wind farms across the North Sea and the Iberian Peninsula. Renew Energy 2024;224:120217. http://dx.doi.org/10.1016/j.renene.2024.120217.

[38] Myhr A, Bjerkseter C, gotnes AA, Nygaard TA. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. Renew Energy 2014;66:714–28. http://dx.doi.org/10.1016/j.renene.2014.01.017.

[39] Bosch J, Staffell I, Hawkes AD. Global levelised cost of electricity from offshore wind. Energy 2019;189:116357. http://dx.doi.org/10.1016/j.energy.2019.116357.

[40] Rinaldi G, Portillo JCC, Khalid F, Henriques JCC, Thies PR, Gato LMC, Johanning L. Multivariate analysis of the reliability, availability, and maintainability characterizations of a spar–buoy wave energy converter farm. J Ocean Eng Mar Energy 2018;4:199–215. http://dx.doi.org/10.1007/s40722-018-0116-z.

[41] Jenkins B, Belton I, Carroll J, McMillan D. Estimating the major replacement rates in next-generation offshore wind turbines using structured expert elicitation.. In: J Phys: Conf Ser. 2362, (1):IOP Publishing; 2022, 012020.

[42] Carroll J, McDonald A, McMillan D. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy 2016;19(6):1107–19. http://dx.doi.org/10.1002/we.1887.

[43] Crown Estate Scotland. Scotwind: List of successful project partners. 2022, https://www.crownestatescotland.com/resources/documents/scotwind-list-of-successful-project-partners-170122.

[44] Spanish Ministry for Ecological Transition and the Demographic Challenge. Roadmap offshore wind and energy marine energy in Spain. 2023, https://www.miteco.gob.es/es/ministerio/planes-estrategias/desarrollo-eolica-marina-energias/enhreolicamarina-pdf_accesible_tcm30-538999.pdf.

[45] Grupo de Trabalho para o planeamento e operacionalização de centros electroprodutores baseados em fontes de energias renováveis de origem ou localização oceânica. Proposta de zonas de implantação de energias renováveis em Portugal. 2023, https://www.lneg.pt/wp-content/uploads/2023/07/20230531-GTOffshore_RelatorioFinal_vfinal.pdf.

[46] Bak C, Zahle F, Bitsche R, Kim T, Yde A, Henriksen LC, et al. The DTU 10-MW reference wind turbine. In: Danish wind power research. 2013.

[47] 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 Plan Policy 2018;13(5):281–90. http://dx.doi.org/10.1080/15567249.2018.1461150.

[48] Amante C, Eakins BW. ETOPO1 arc-minute global relief model: procedures, data sources and analysis. 2009.

[49] Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, et al. The ERA5 global reanalysis. Q J R Meteorol Soc 2020;146(730):1999–2049.

[50] World Forum Offshore Wind (WFO). Challenges and opportunities of major maintenance for floating offshore wind. 2021.

[51] Spinenergie. Lessons learned from heavy maintenance at the world's first commercial floating wind farm. 2023, URL https://www.spinergie.com/blog/lessons-learned-from-heavy-maintenance-at-the-worlds-first-commercial-floating-wind-farm.

[52] BVG Associates. Guide to a floating offshore wind farm. 2023, https://guidetofloatingoffshorewind.com/wp-content/uploads/2023/06/BVGA-16444-Floating-Guide-r1.pdf.

[53] National Geospatial-Intelligence Agency. World port index. 2023, https://msi.nga.mil/Publications/WPI.

[54] Akbari N, Irawan CA, Jones DF, Menachof D. A multi-criteria port suitability assessment for developments in the offshore wind industry. Renew Energy 2017;102:118–33. http://dx.doi.org/10.1016/j.renene.2016.10.035.

[55] Li M. Towards closed-loop maintenance logistics for offshore wind farms: Approaches for strategic and tactical decision-making (Ph.D. thesis), TU Delft; 2023, http://dx.doi.org/10.4233/uuid:bd895c0f-043b-43f0-a2a3-6e2d3df18121.

[56] Li M, Jiang X, Carroll J, Negenborn RR. A multi-objective maintenance strategy optimization framework for offshore wind farms considering uncertainty. Appl Energy 2022;321:119284. http://dx.doi.org/10.1016/j.apenergy.2022.119284.

[57] Johnston B, Foley A, Doran J, Littler T. Levelised cost of energy, a challenge for offshore wind. Renew Energy 2020;160:876–85. http://dx.doi.org/10.1016/j.renene.2020.06.030.

[58] Bjerkseter C, Ågotnes A. Levelised Costs of Energy for Offshore Floating Wind Turbine Concepts (Master's thesis), Norwegian University of Life Sciences, Ås; 2013.

[59] Cavazzi S, Dutton A. An offshore wind energy geographic information system (OWE-gis) for assessment of the UK's offshore wind energy potential. Renew Energy 2016;87:212–28. http://dx.doi.org/10.1016/j.renene.2015.09.021.

[60] Westwood D. Offshore Wind Assessment for Norway. Oslo: The Research Council of Norway. North Sea Energy; 2010.

[61] Topham E, McMillan D. Sustainable decommissioning of an offshore wind farm. Renew Energy 2017;102:470–80. http://dx.doi.org/10.1016/j.renene.2016.10.066.

[62] Pathways, Offshore Wind Cost Reduction. Technology Work Stream. BVG Associates: Swindon, UK; 2012.

[63] Huang L-L, Fu Y, Mi Y, Cao J-L, Wang P. A Markov-chain-based availability model of offshore wind turbine considering accessibility problems. IEEE Trans Sustain Energy 2017;8(4):1592–600. http://dx.doi.org/10.1109/TSTE.2017.2695661.

[64] Li M, Jiang X, Carroll J, Negenborn RR. A closed-loop maintenance strategy for offshore wind farms: Incorporating dynamic wind farm states and uncertainty-awareness in decision-making. Renew Sustain Energy Rev 2023;184:113535. http://dx.doi.org/10.1016/j.rser.2023.113535.

[65] Ren Z, Verma AS, Li Y, Teuwen JJ, Jiang Z. Offshore wind turbine operations and maintenance: A state-of-the-art review. Renew Sustain Energy Rev 2021;144:110886. http://dx.doi.org/10.1016/j.rser.2021.110886.

[66] Rinaldi G, Wagdy Ibrahim M, Germain N, Alexandre A, Martin B, Rezende F, et al. WindFloat performance analysis for smart operation and maintenance. In: OTC offshore technology conference, vol. Day 2 Tue, May 03, 2022, 2022, D021S016R008. http://dx.doi.org/10.4043/32043-MS.

[67] Peinado Gonzalo A, Benmessaoud T, Entezami M, García Márquez FP. Optimal maintenance management of offshore wind turbines by minimizing the costs. Sustain Energy Technol Assess 2022;52:102230. http://dx.doi.org/10.1016/j.seta.2022.102230.