Renewable Energy 224 (2024) 120217

Contents lists available at ScienceDirect

Renewable Energy

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

Impact of operations and maintenance on the energy production of floating offshore wind farms across the North Sea and the Iberian Peninsula

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ARTICLE INFO

Keywords:
Floating offshore wind
O&M
Energy production
Site-identification
North Sea
Iberian Peninsula

ABSTRACT

This paper evaluates how operation and maintenance (O&M) factors affect energy production and optimal deployment sites for floating offshore wind farms (FOWs) in the North Sea and the Iberian Peninsula. The geospatial analysis incorporates reliability, maintainability, accessibility, and availability aspects, and evaluates their impact on energy production. The results demonstrate that O&M factors have a significant impact on the final energy production and therefore on the identification of optimal deployment sites, both quantitatively and qualitatively. In the North Sea, promising deployment sites are identified in regions with lower wind resources but shorter turbine downtime, such as Denmark, Germany and southern Scotland. In the Iberian Peninsula, areas with high resource potential, such as the northwest Spanish and Portuguese coasts, may be less appealing than the less powerful Mediterranean regions due to lower maintainability. In particular, the efficiency of future FOW farms in the North Sea and Atlantic Ocean regions of the Iberian Peninsula heavily relies on vessel operational limits for major repairs. Increasing the significant wave height limit for major repairs from 1.5 m to 2 m results in an average capacity factor increment of 2.54% across *ScotWind* farms and over 6% along the northwest coast of the Iberian Peninsula.

1. Introduction

The alignment of climate change concerns with economic, supply chain, and national security factors has recently accelerated the energy transition plans, driving energy supply diversification and increasing investment in renewable energy sources [1,2]. In this context, floating offshore wind (FOW) is expected to contribute substantially to moving away from a carbon-intensive energy system that relies on fossil fuels [3]. However, to achieve a significant deployment of FOW turbines, energy must be generated at a cost that is competitive compared to other more traditional energy sources [4]. Therefore, thoroughly evaluating the economic viability of FOW farms is crucial as it enables cost reduction, facilitates project finance and investment, and informs policy and regulatory frameworks to support the development of this promising offshore renewable energy technology [5].

The viability of a FOW project is predominantly determined by the deployment site [6]. Consequently, identifying suitable deployment sites for FOW farms emerges as a critical factor [7]. Considering the large available area and the fact that both costs and energy production are dependent on the site, completing geospatial evaluation is highly valuable for decision makers [8]. Geospatial analysis helps decision-makers by showing how the most relevant key performance indicators (KPIs) change across different locations, enabling informed decision-making in the selection of deployment sites [9]. In this respect, obtaining reliable estimates and making appropriate decisions heavily relies on a comprehensive assessment of these KPIs.

Accurate estimation of long-term energy production through geospatial analysis is crucial to identify deployment sites, as it represents the main source of revenue [8,10]. The energy production of a FOW farm depends not only on the wind resource [8], but also on the FOW technology [11,12], farm layout [13], and operation and maintenance (O&M) strategies [14]. Specifically, the potential for wind resources has been proven to be the main driver in determining the viability of FOW projects [9,15]. However, incorporating these additional factors into geospatial analysis, along with the wind resource, is crucial,

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https://doi.org/10.1016/j.renene.2024.120217
Received 5 December 2023; Received in revised form 19 February 2024; Accepted 23 February 2024
Available online 27 February 2024
0960-1481/

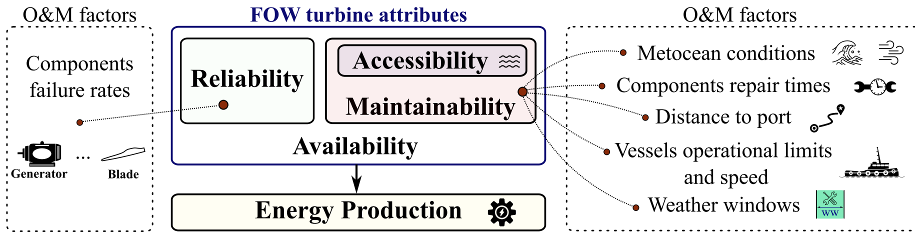


Fig. 1. The interdependencies between O&M factors, FOW turbine attributes, and energy production.

as it can significantly influence the final energy production and, thus, the assessment of the deployment sites.

In this context, the offshore wind sector is increasingly emphasising the potential benefits of incorporating O&M factors during the design phase of wind farms before entering commercial operation [16–18]. The impact of O&M factors goes beyond operational expenditures (OpEx) and can also significantly influence final energy production due to downtime periods [19]. Accordingly, O&M factors should be taken into account when estimating energy production and identifying deployment sites [20].

When evaluating the impact of O&M factors on energy production, it is essential to conduct a comprehensive assessment of system attributes that include reliability, maintainability, accessibility and availability [21]. Reliability represents the FOW turbine's ability to generate energy in the presence of failures and characterises the failure process [21]. Meanwhile, maintainability is the ability to undergo maintenance activities and characterises the repair process of the FOW turbine [21]. Accessibility is directly related to maintainability, as it represents the feasibility of accessing the turbine to carry out maintenance tasks [22,23]. Finally, availability encompasses reliability, maintainability, and accessibility, quantifying the proportion of time the FOW turbine remains operational [24]. Therefore, the availability of the FOW turbine directly affects total energy production, as no energy is generated during the downtime of the turbines [25]. Note that the availability of FOW turbines is demonstrated to vary with geographic location, as it is influenced by several O&M factors related to the specific location, such as metocean conditions, repair times, distance to ports and weather windows, which are specific to each location [25]. Fig. 1 depicts the interdependencies between O&M factors and FOW turbine attributes, illustrating the impact on energy production.

1.1. Literature review

Several studies in the literature have focused on site identification for different FOW turbines technologies and farms. These studies are usually based on techno-economic models that take into account both energy production and various cost-related factors in a predefined area, such as the European Atlantic Ocean [8], Italy [26], Ireland [27], the Mediterranean Sea [28], Portugal [29], or France and Scotland [30]. However, the impact of O&M on energy production is directly neglected [26] or oversimplified by using a fixed availability indicator derived from bottom fixed offshore wind farms, ignoring the geographical dependence [8,27–30].

Geoinformation systems (GIS)-based approaches have also been proposed for the identification of suitable FOW deployment sites in various regions, including the European Atlantic Ocean [6], Portugal [31], Spain [32] and the United Kingdom [33]. In a GIS-based approach, a sequential filtering is performed. First, locations that meet all defined constraints are identified, such as protected areas of environmental interest and military areas [6,32]. Subsequently, each feasible location is evaluated based on different criteria, such as maximising wind resource and distance from maritime routes [6,32]. However, none of the existing GIS-based approaches described in the literature considers the impact of O&M on energy production, as maximising availability or minimising downtime are not considered as evaluation criteria [6,31–33].

Both techno-economic analyses and GIS-based approaches consistently agree that optimal locations for FOW farms are characterised by areas with the highest wind resource potential [6,8,27–32]. Nonetheless, a general correlation exists between wind speed (U_w) and significant wave height (H_s), as higher U_w values correspond typically to higher H_s values, resulting in reduced accessibility [34–36]. Such a reduction in accessibility directly impacts availability, subsequently affecting energy production and the identification of deployment sites [23,30]. Nevertheless, existing techno-economic studies [8,26–30] and GIS-based approaches [6,31–33] are shown to disregard the relationship between accessibility, availability, and energy production when assessing potential deployment locations.

In this context, pure accessibility assessments are suggested in the literature in order to evaluate deployment sites [22,36–38]. These assessments evaluate the feasibility of accessing deployment sites by computing weather windows based on metocean data and vessel operational limits [22]. However, the aforementioned studies focus solely on assessing the accessibility attribute without evaluating its impact on availability and energy production [22,36–38].

The main reason why O&M aspects have been neglected in previous geospatial studies is the lack of a computationally efficient and reliable O&M model. The incorporation of the attributes of reliability, maintainability, accessibility, and availability and their impact on energy production has been mainly integrated by means of Monte Carlo-based O&M models [39–43]. Monte Carlo-based O&M models employ repeated random sampling to compute the occurrence of failures and subsequent maintenance tasks [44]. However, their major disadvantage lies in their high computational cost, since numerous simulations are required to obtain convergence in the results [43,44]. For example, a single grid point evaluation required two days of computational burden in [42]. For that reason, Monte Carlo-based O&M models are computationally prohibitive for performing broad geospatial assessments [39–43]. In this respect, an alternative analytical O&M model with similar precision, but a significantly lower computational burden is presented in [25], which has the potential to be employed in a geospatial site identification process, as demonstrated in the present study.

1.2. Motivation and contribution

To the best knowledge of the authors, no study in the existing literature accurately addresses the following research question: How do O&M factors impact energy production across a broad geographic area and, consequently, the identification of deployment sites for FOW farms? This paper aims to fill this gap by making two main contributions to the field:

1. This paper presents the first comprehensive geospatial assessment of O&M factors, including reliability, maintainability, accessibility and availability aspects into the analysis, and evaluating their impact on energy production across a broad geographical area.

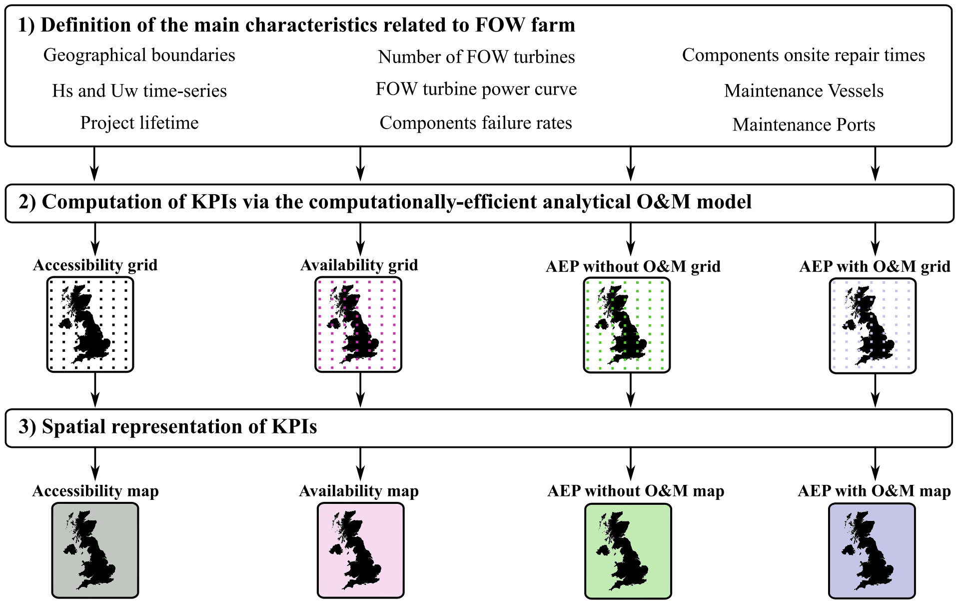


Fig. 2. Flowchart illustrating the three-step methodology for assessing KPIs of FOW farms across broad spatial areas.

2. Additionally, this paper develops the first comparative study investigating how O&M factors affect energy production in two potentially interesting regions for the deployment of FOW farms: the North Sea [45] and the Iberian Peninsula [46,47].

Note that the identification of optimal deployment sites for FOW farms is beyond the scope of this paper. Determining the optimal deployment sites requires at least considering additional factors, such as exclusion zones and costs. In contrast, the main objective of this paper is to specifically evaluate the geospatial impact of O&M factors on energy production, carrying out a more realistic assessment of the potential performance of FOW farms over the North Sea and the Iberian Peninsula. However, it should be noted that, due to the low computational cost of the analytical model used in the present study, the approach suggested here should be easily incorporated into any GIS and techno-economic frameworks for the identification of optimal deployment sites.

In this regard, considering the key role of the wind resource potential in determining optimal deployment sites [6,8,27–32], this paper performs a comparative analysis of energy production in two distinct scenarios. One scenario focuses solely on mapping the potential resources for energy generation from FOW farms, neglecting O&M factors, while the second scenario incorporates O&M factors that constrain the mapping of energy generation

The remainder of the paper is organised as follows. Section 2 presents the methodology to compute geospatial O&M assessments. The main results are presented and discussed in Section 3. Finally, conclusions are drawn in Section 4.

2. Methodology

The values of KPIs are associated with specific characteristics of FOW projects. Therefore, the methodology is illustrated through a case study conducted across the North Sea and the Iberian Peninsula. The methodology consists of three main steps: (i) definition of the specific characteristics of the FOW farm; (ii) computation of the accessibility, availability and energy production KPIs through the computationally efficient analytical O&M model presented in [25]; and (iii) generation of a spatial representation of these KPIs. The flowchart describing the three steps of the methodology is illustrated in Fig. 2.

Table 1
Main information of the selected geospatial regions.

Region	Lower left		Upper right	
	Longitude	Latitude	Longitude	Latitude
North Sea	3.5°W	51°N	9°E	59°N
Iberian Peninsula	11°W	34.75°N	6°E	45°N

2.1. Definition of the main characteristics related to FOW farm

In this paper, it is assumed that a FOW farm can be deployed at each grid point within the North Sea and the Iberian Peninsula as represented in Figs. 3(a) and 3(b), respectively. France and Belgium also have a coastline on the North Sea, although its extension is limited within the geographical boundaries established in this paper. The geographical boundaries of the North Sea and the Iberian Peninsula are provided in Table 1. The operational lifetime of FOW farms is set at 30 years, and it comprises one hundred 10 MW turbines mounted on semi-submersible platforms for an installed power of 1 GW [48]. In this sense, the selected power curve corresponds to the DTU 10-MW wind turbine, which has a cut-in speed of 4 m/s, rated power at 11.4 m/s, and cut-out speed of 25 m/s [49].

Time-series data on H_s and U_w at a 100 m height are obtained from the ERA5 reanalysis products from the European Centre for Medium-Range Weather Forecasts [50]. The data is acquired using the minimum time and spatial resolution of ERA5, with hourly measurements from 1990 to 2019, and a grid resolution of 0.25° both in longitude and in latitude [50].

Annual failure rates and onsite repair times for all the most relevant components of the semi-submersible FOW turbine are obtained from [41] and are presented in Table A.3. Failures can be classified according to various criteria, such as complete and partial failure [21]. A complete failure results in the total loss of the required function, whereas a partial failure does not. In this sense, all components' failures addressed in this paper, are considered complete failures [41].

Additionally, failures can also be classified based on their respective repair characteristics [37,51]. Accordingly, failure that requires an onsite repair time of 8 h or less is categorised as minor repair, those between 8 and 24 h are classified as medium repairs, and those above 24 h as major repairs [37]. In addition, all O&M interventions resulting from failures are considered corrective replacements and start from

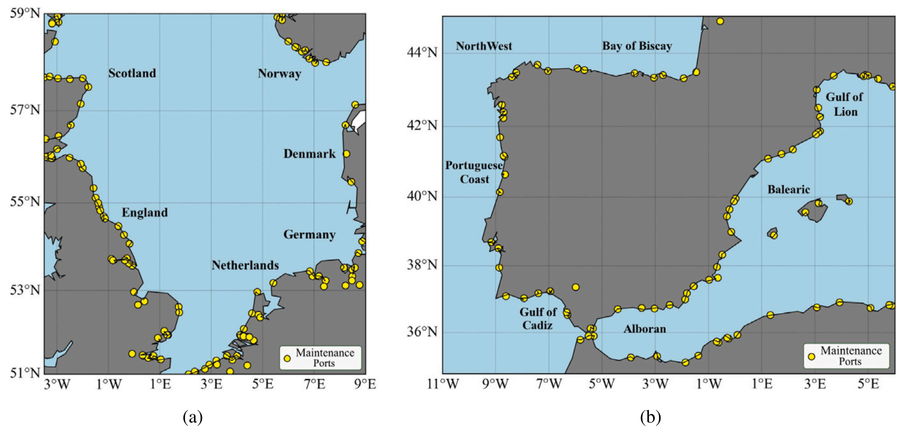


Fig. 3. Representation of maintenance ports in: (a) the North Sea, and (b) the Iberian Peninsula.

Table 2
Properties of the maintenance vessels selected for FOW case study.
Source: Extracted from [41].

Vessel Type	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

Abbreviations: CTV = Crew Transfer Vessel, FSV = Field Support Vessel, HLV = Heavy Lift Vessel.
Note: The wind speed limit is given at hub height.

the port [41]. The only exception to this classification is the floating platform, as a complete replacement of the entire floating platform would be extremely expensive [41].

To address maintenance needs, a set of generic maintenance vessels for minor, medium and major repairs has been selected, namely a Crew Transfer Vessel (CTV), a Field Support Vessel (FSV), and a Heavy Lift Vessel (HLV), respectively [41]. The speed and operational limits of the vessels are obtained from [41] and are presented in Table 2. In this context, a conservative approach is applied when defining operational limits, as same limits are established for both the transit from port to turbine and the execution of onsite repair tasks. On the other hand, it is assumed that the HLV has the capability to perform floating-to-floating lifting operations, which aligns with the planned approach for future commercial-scale FOW projects [52,53].

Furthermore, O&M ports have been identified using the World Port Index, which provides the location of major ports and terminals worldwide [54]. The designated ports for the North Sea and the Iberian Peninsula are depicted in Figs. 3(a) and 3(b) with yellow dots, respectively. To establish maintenance ports for each grid point within the defined spatial regions, assuming that each grid point represents a potential FOW farm of 1 GW, the distances to all ports have initially been calculated, followed by the selection of the closest port. Other factors, such as port depth and seabed suitability, may also play a key role in selecting maintenance ports [55]. However, due to the large number of FOW farms analysed in this study, comprehensive evaluation of all these factors is beyond the scope of this paper, and only distance is considered for port selection. The distances between FOW farms and ports are computed using the Haversine distance formula defined as [56],

$$d = 2 \cdot r \cdot \arcsin\left(\sqrt{\sin^2\left(\frac{y_{port} - y}{2}\right) + \cos(x) \cdot \cos(x_{port}) \cdot \sin^2\left(\frac{x_{port} - x}{2}\right)}\right), \quad (1)$$

where d represents the calculated distance, r is the radius of the Earth, x and y are the longitude and latitude of a particular grid point, and x_{port} and y_{port} represent the longitude and latitude of a particular port.

It is important to mention that this paper does not establish specific boundary conditions concerning the distance from shore or water depth for the deployment of FOW farms. This decision is made to facilitate a comprehensive geographical evaluation and because the techno-economic assessment falls beyond the scope of this paper.

2.2. Computation of key performance indicators via the computationally-efficient analytical O&M model

The main KPIs for each grid point at a resolution of $0.25° x\, 0.25°$ are computed via the analytical O&M model presented in [25]. This analytical O&M model, based on Markov chains, defines the interdependencies between O&M factors, reliability, maintainability, accessibility, and availability attributes, and energy production [25]. In this respect, the farm level annual energy production ($AEP(x, y)$) is defined as [25,57],

$$AEP(x, y) = N_t \cdot \frac{E_{produced}(x, y)}{t_{lifetime}} = N_t \cdot \frac{A_t(x, y)}{t_{lifetime}} \int_0^{t_{lifetime}} P(U_w(x, y, t))\, dt\,, \quad (2)$$

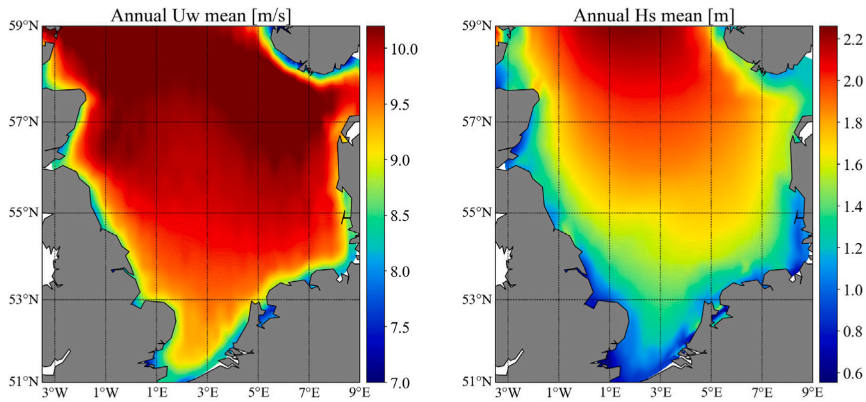
where N_t represents the total number of turbines in the farm, $t_{lifetime}$ the operational lifetime of the FOW project, $E_{produced}(x, y)$ the produced energy of a FOW turbine throughout the lifetime, $A_t(x, y)$ the average availability of a FOW turbine, $P(U_w(x, y, t))$ the power curve of a FOW turbine, $U_w(x, y, t)$ the wind speed at time instant t, and dt the continuous integration.

Turbine availability, which encompasses reliability, maintainability and accessibility, is represented using a reliability block diagram (RBD) arranged in a series configuration as in [39,41]. The operational function of each component in the RBD is modelled by a continuous-time Markov chain. For that reason, the long-term availability of turbines can be defined as [25],

$$A_t(x, y) = \prod_{i}^{N_c} \frac{\omega_{cm_i}(x, y) \cdot \mu_{cm_i}(x, y) \cdot \lambda_i}{\mu_{cm_i}(x, y) \cdot \lambda_i^2 + \omega_{cm_i}(x, y) \cdot \lambda_i^2 + \omega_{cm_i}(x, y) \cdot \mu_{cm_i}(x, y) \cdot \lambda_i}\,, \quad (3)$$

where N_c is the total number of components in the FOW turbine, λ_i the component failure rate, $\mu_{cm_i}(x, y)$ the component repair rate, and $\omega_{cm_i}(x, y)$ the component waiting rate for a weather window. Eq. (3) assumes that all turbine components are repairable, repairs bring the component to as-good-as-new state, and the distance that maintenance vessels travel from the port to the farm and from the farm to the port is the same [25]. Note that these assumptions are also assumed in all the reviewed O&M models [39–43].

The value of $\mu_{cm_i}(x, y)$ is calculated as a function of the mean duration of the trip from the port to the turbine and the onsite repair time [25]. On the other hand, $\omega_{cm_i}(x, y)$ is calculated within the accessibility submodel of the analytical O&M model as a function of the



(a) (b)

Fig. 4. Spatial distribution in the North Sea of the annual mean over a 30-year period for: (a) U_w at 100 m, and (b) H_s.

required mission window length (t_{ww_i}), operational limits of vessels, as well as $H_s(x,y)$ and $U_w(x,y)$ conditions [25]. In particular, this research work also incorporates the U_w operational limit, which is not used as an operational limit in [25]. Furthermore, an accessibility indicator is also computed as defined in [22],

$$Accessibility_i(x,y) = \frac{N_{ww_i}(x,y) \cdot t_{ww_i}}{t_{lifetime}} , \tag{4}$$

where $N_{ww_i}(x,y)$ is the total number of weather windows.

2.3. Geospatial representation of key performance indicators

The main KPIs computed using the computationally-efficient analytical O&M model with a resolution of $0.25° x\, 0.25°$ are spatially represented at a higher resolution of $0.025° x\, 0.025°$ performing a cubic interpolation [58]. This application of cubic interpolation results in a more detailed representation of the KPIs throughout the geospatial domain. Consequently, decision makers gain comprehensive insight into the variations of these KPIs across different regions.

3. Results and discussion

The results are directly dependent on the main characteristics of FOW farms, which have been consistently defined in Section 2, based on previous studies in the same areas [8,41]. Furthermore, it should be noted that the analytical O&M model employed in this paper allows sensitivity analyses of numerous parameters, such as failure rates, repair times, vessel characteristics and maintenance ports. However, due to space limitations, including all these sensitivity analyses in this paper is not feasible.

3.1. Metocean characteristics of the north sea and the Iberian Peninsula

To analyse and understand the impact of O&M factors on energy production across the North Sea and the Iberian Peninsula, it is essential to first evaluate the metocean characteristics of these regions. In this sense, the present section analyses mean U_w and H_s values in both the North Sea and the Iberian Peninsula.

The North Sea, located in northwest Europe, is geographically connected to the European Atlantic Ocean through the English Channel in the south and the Norwegian Sea in the north. The annual mean values of U_w and H_s throughout the North Sea are shown in Figs. 4(a) and 4(b), respectively. The northern part of the North Sea, particularly Scottish and Norwegian coasts, exhibits the highest U_w mean values, with mean speeds exceeding 10 m/s. However, in the majority of other areas within the North Sea, the mean speed remains above 9 m/s. Furthermore, the northern and central regions of the North Sea are characterised by considerably harsher conditions H_s compared to the southern part, with a mean H_s exceeding 1.8 m across a considerable area of the North Sea. In contrast, the southern region of the North Sea, encompassing the southern English, Belgian and Dutch coasts, is characterised by mean H_s below 1.5 m.

The Iberian Peninsula, located in southwest Europe, is bounded by the European Atlantic Ocean and the Mediterranean Sea. The annual mean values of U_w and H_s throughout the Iberian Peninsula are shown in Figs. 5(a) and 5(b), respectively. The highest mean values of U_w are observed in the northwest of the Iberian Peninsula and in the Gulf of Lion, with maximum mean speeds exceeding 9 m/s. Subsequently, considerable areas along the Portuguese coast, the Gulf of Cadiz, and the Alboran Sea exhibit mean speeds greater than 8 m/s. On the contrary, the Balearic Sea generally exhibits mean speeds below 8 m/s. Regarding wave conditions, the European Atlantic Ocean region of the Iberian Peninsula is significantly harsher than its Mediterranean Sea counterpart. In most areas within the European Atlantic Ocean region, the mean H_s exceeds 2 m, except in the Gulf of Cadiz, where they remain below 2 m. In particular, the mean H_s ranges between 1.2 and 1.5 m in the Gulf of Lion and the eastern part of the Balearic Sea, while the rest of the Mediterranean Sea exhibits mean H_s values below 1.2 m.

3.2. Accessibility analysis for minor, medium and major repairs

The accessibility indicator is associated with the characteristics of a particular maintenance task, which are defined by the repair time and maintenance vessel requirements of each task. As displayed in Table A.3, in the present study 22 possible maintenance tasks are considered per turbine. Consequently, via Eq. (4), 22 accessibility KPIs are computed for each area of study, resulting in 22 accessibility maps for the North Sea and 22 more for the Iberian Peninsula. For the sake of clarity, instead of presenting 44 maps, the mean accessibility value for each O&M category (i.e., minor, medium, and major) is calculated as follows,

$$\begin{bmatrix} Accessibility_{minor} \\ Accessibility_{medium} \\ Accessibility_{major} \end{bmatrix} = \begin{bmatrix} {N_{minor}}^{-1} \cdot \sum_{i=1}^{N_{minor}} Accessibility_i \\ {N_{medium}}^{-1} \cdot \sum_{i=1}^{N_{medium}} Accessibility_i \\ {N_{major}}^{-1} \cdot \sum_{i=1}^{N_{major}} Accessibility_i \end{bmatrix} , \tag{5}$$

where N_{minor} represents the number of different minor repair tasks per turbine (5 tasks), N_{medium} the number of different medium repair tasks per turbine (13 tasks), and N_{major} the number of different major repair tasks per turbine (4 tasks). Note that N_{minor}, N_{medium}, and N_{major} refer to the number of possible maintenance tasks for each category, not the tasks performed during the entire operational lifetime of turbines.

The spatial distributions of the mean minor, medium, and major accessibility indicators across the North Sea and the Iberian Peninsula

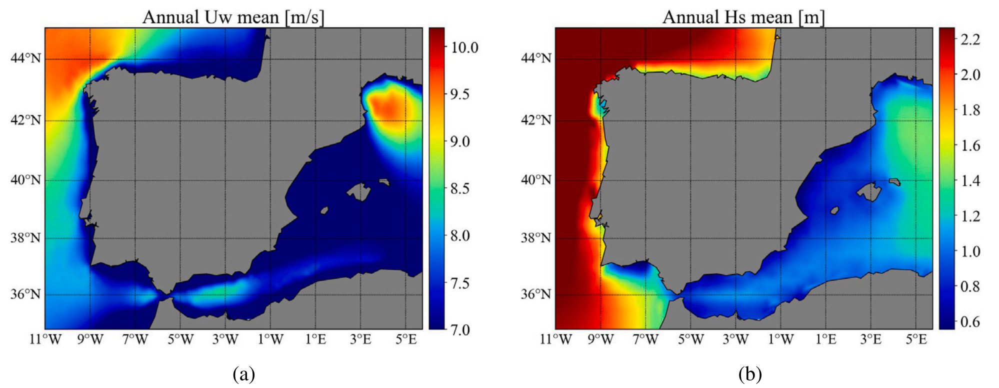


Fig. 5. Spatial distribution in the Iberian Peninsula of the annual mean over a 30-year period for: (a) U_w at 100 m, and (b) H_s.

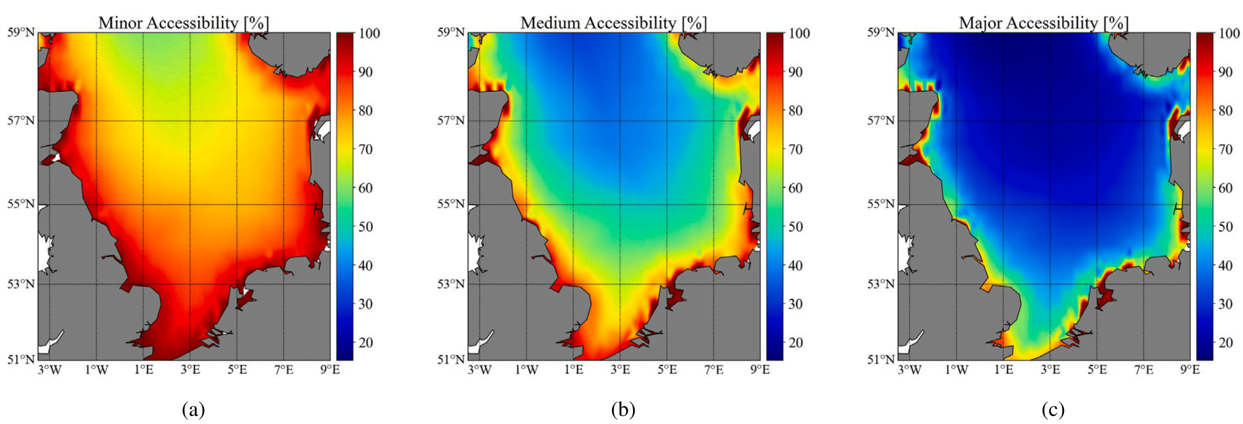


Fig. 6. Spatial distribution in the North Sea for: (a) $Accessibility_{minor}$, (b) $Accessibility_{medium}$, and (c) $Accessibility_{major}$.

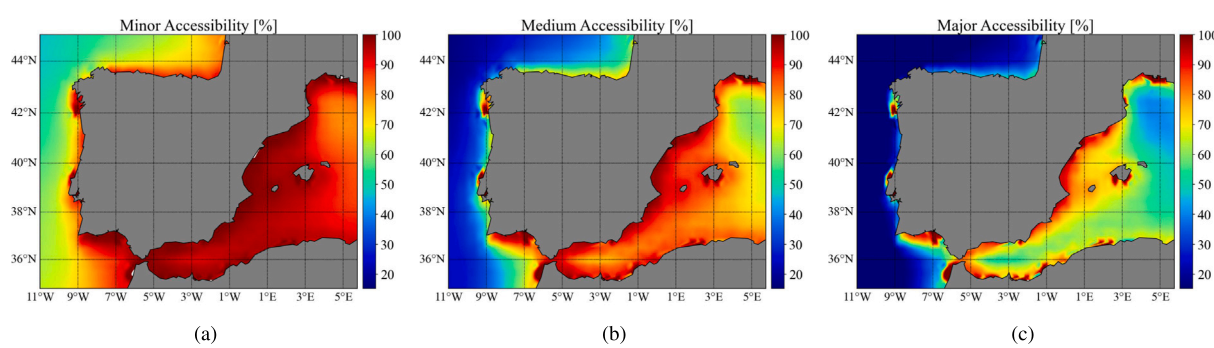


Fig. 7. Spatial distribution in the Iberian Peninsula for: (a) $Accessibility_{minor}$, (b) $Accessibility_{medium}$, and (c) $Accessibility_{major}$.

are shown in Figs. 6 and 7, respectively. From these figures, two main accessibility trends can be identified. First, the highest accessibility levels are observed for minor repairs, followed by medium repairs and finally major repairs. This trend is attributed to the fact that minor repair tasks have less restrictive operating conditions, such as required mission window length and vessels' operational limits, compared to medium and major ones. Secondly, accessibility values decrease as the distance to the ports increases. This trend is attributed to the fact that with increasing distances, the length of the required mission window also increases, leading to more restrictive operational conditions.

In addition to vessels' operational limits and the required weather window duration, local metocean conditions also influence on accessibility, resulting in reduced access opportunities during harsher U_w and H_s conditions. A comparison between the spatial distributions of mean U_w and H_s (Figs. 4 and 5, respectively) with accessibility distributions (Figs. 6 and 7, respectively) highlights that the spatial accessibility distribution is more influenced by H_s than by U_w. This effect is attributed to the operating limits of the vessels for H_s, which are more restrictive compared to those for U_w. This is consistent with other studies, such as [36], which analyses similar locations. Specifically, the

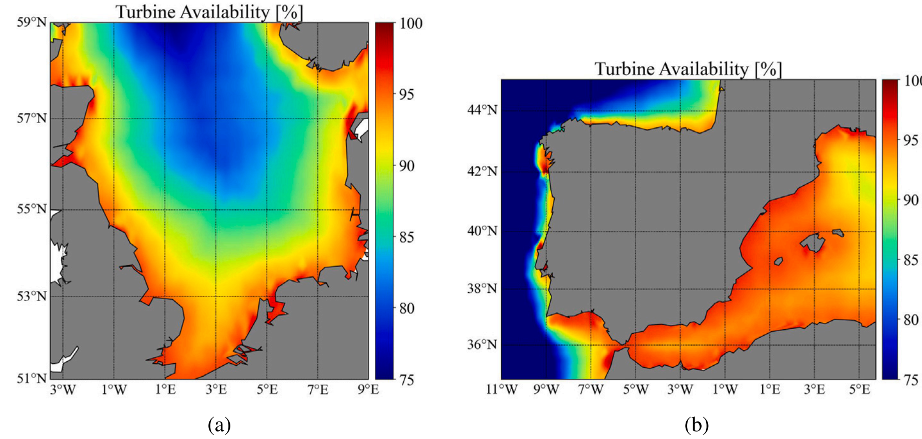


Fig. 8. Turbine availability ($A_t(x, y)$) in: (a) the North Sea, and (b) the Iberian Peninsula.

mean H_s values observed in the northern and central regions of the North Sea, as well as in the European Atlantic Ocean region of the Iberian Peninsula, exceed generally the operational limits of FSVs and HLVs. On the contrary, the mean values of U_w across the North Sea and the Iberian Peninsula remain below the operational limits of U_w. For minor and medium repairs, U_w remains, on average, more than 15 m/s below operational limits, and for major repairs, the difference exceeds 10 m/s. However, a more comprehensive analysis of the impact of H_s and U_w operational limits on main KPIs is conducted in Section 3.5.

Accessibility levels in the southern regions of the North Sea exhibit higher values compared to the central and northern parts, as observed similarly in a previous study [22]. Within the southern regions of the North Sea, accessibility levels for minor, medium, and major repairs are above 80%, 70%, and 50%, respectively. In contrast, a substantial area of the central and northern regions of the North Sea exhibits accessibility levels below 80%, 70%, and 50% for minor, medium, and major repairs, respectively.

In the Iberian Peninsula, the European Atlantic Ocean exhibits comparatively lower accessibility compared to its Mediterranean Sea counterpart due to harsher metocean conditions in the former. Within the European Atlantic region, accessibility levels for minor, medium and major repairs drop below 70%, 60%, and 30%, respectively. The exception in the European Atlantic Ocean is the Gulf of Cadiz, where considerable areas exhibit accessibility values greater than 70% for the three repair categories. On the contrary, within the Mediterranean Sea, the accessibility levels for minor, medium and major repairs are above 70%, 60%, and 30%, respectively. Even in the Alboran Sea and the Balearic Sea, accessibility levels remain consistently higher, exceeding 80%, 70%, and 50%.

3.3. Turbine availability analysis

Spatial distributions of turbine availability in the North Sea and the Iberian Peninsula are shown in Figs. 8(a) and 8(b), respectively. The availability analysis incorporates the failure rates of the components within the analysis, which are not included in the accessibility analysis presented in Section 3.2.

Turbine availability is higher in the southern regions of the North Sea compared to the central and northern regions. This can be attributed to the higher accessibility levels in the southern regions compared to the central and northern regions, as observed in Section 3.2. Within the southern region, turbine availability level is higher than 90%, with substantial areas reaching 95%. In particular, availability levels gradually decrease from 95% to 90%, and subsequently from 90% to 85%, over similar distances along the coastlines of England, Germany, the Netherlands and southern Denmark. In contrast, a similar pattern of availability decline is observed over shorter coastal distances in Scotland, Norway, and northern Denmark. In the central and northern regions of the North Sea, at maximum distances from the coasts, the availability level decreases below 85%.

In the Iberian Peninsula, turbine availability is relatively lower in the European Atlantic Ocean when compared to its Mediterranean Sea counterpart. This discrepancy can be attributed to the lower levels of accessibility experienced in the European Atlantic Ocean compared to the Mediterranean Sea, as detailed in Section 3.2. In the northwest region of the Iberian Peninsula and along the Portuguese coast, availability levels drop below 80% even at relatively short distances from the coastline. On the contrary, substantial areas in the Bay of Biscay and the Gulf of Cadiz exhibit availability values greater than 85%. Remarkably, availability values of 95% are obtained even within the Gulf of Cadiz. Meanwhile, the entire Mediterranean Sea is characterised by availability values that exceed 90%, with considerable areas in the Alboran Sea and the Balearic Sea presenting values around 95%.

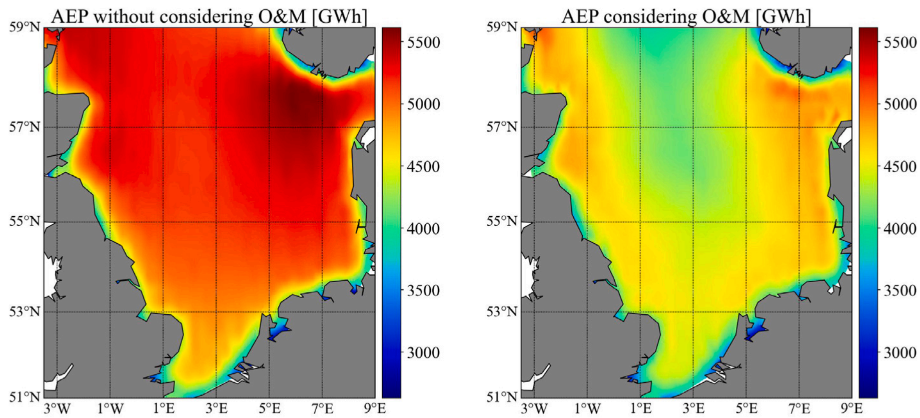
3.4. Energy production analysis

To assess the impact of O&M factors on the energy generation capabilities of FOW farms, a comparative assessment of energy production is carried out under two different scenarios.

The first scenario focuses exclusively on analysing the wind energy resource potential without considering O&M factors, assuming 100% turbine availability in Eq. (2). In this context, Figs. 9(a) and 10(a) illustrate the AEP without accounting for O&M factors in the North Sea and the Iberian Peninsula, respectively. The second scenario takes into account the downtime of the FOW farm due to O&M factors, as defined in previous sections. Figs. 9(b) and 10(b) depict the AEP including O&M factors in the North Sea and the Iberian Peninsula, respectively.

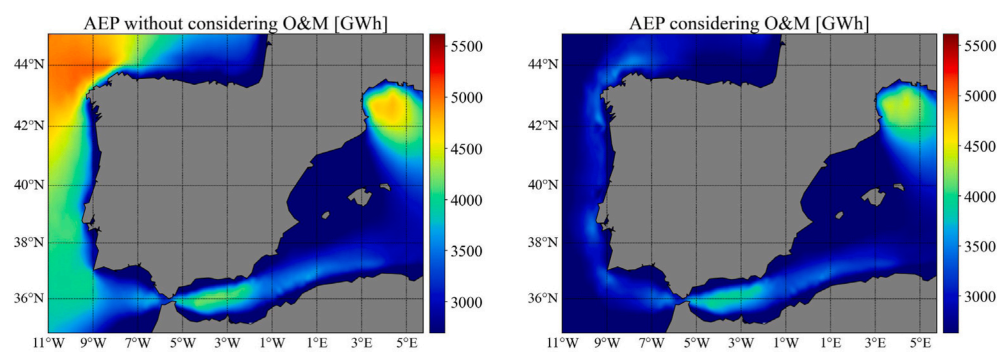
The results demonstrate that O&M factors significantly influence energy production and the identification of optimal deployment sites for FOW farms in the North Sea and the Iberian Peninsula, not only quantitatively but also qualitatively.

Incorporating O&M factors into the geospatial analysis introduces a qualitative change, as it reshapes the spatial distribution of the AEP. Figs. 9(a) and 10(a) illustrate that, in terms of wind energy resource potential, the coasts of Norway and northern Scotland in the North Sea, as well as the northwestern coast, the Portuguese coast, the Alboran Sea and the Gulf of Lion in the Iberian Peninsula, emerge as the most powerful areas. In contrast, Fig. 9(b) highlights that areas in the North Sea, which were previously perceived less favourable in terms of energy resource potential, such as the coastlines of Denmark, Germany and



(a) (b)

Fig. 9. AEP of 1 GW installed power FOW farms in the North Sea under the following scenarios: (a) Considering just wind energy resource potential, and (b) Considering both wind energy resource potential and O&M factors.



(a) (b)

Fig. 10. AEP of 1 GW installed power FOW farms in the Iberian Peninsula under the following scenarios: (a) Considering just wind energy resource potential, and (b) Considering both wind energy resource potential and O&M factors.

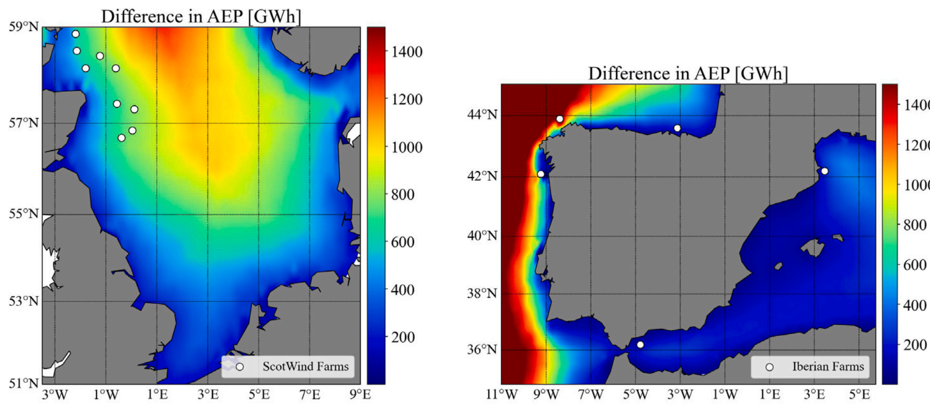
southern Scotland, may now be recognised as promising locations when considering O&M factors in the geospatial analysis. On the other hand, Fig. 10(b) illustrates that regions within the European Atlantic Ocean, such as the northwestern region and the Portuguese coast, which were previously perceived as advantageous locations in terms of energy resource potential, may now appear less powerful than the Alboran Sea and the Gulf of Lyon when considering O&M factors due to long turbine downtime in these regions.

To quantitatively assess the impact of O&M factors on energy production, the difference in AEP between the two scenarios in the North Sea and the Iberian Peninsula is shown in Figs. 11(a) and 11(b). When O&M factors are not incorporated into the AEP evaluation, the southern regions of the North Sea exhibit differences in AEP of up to 500 GWh, corresponding to an overestimation in capacity factor (CF) of up to 5.7%. The differences in AEP gradually increases from 500 GWh to 1000 GWh, ranging from 5.7% to up to 11.4% in CF, across similar distances along the coastlines of central and northern England, Germany, the Netherlands, and southern Denmark. A similar pattern of overestimation is observed on shorter coastal distances in Scotland, Norway, and northern Denmark, reaching a maximum of 1200 GWh across a considerable area, equivalent to a difference of up to 13.7% in CF.

Within the Iberian Peninsula, the difference in AEP is greater in the European Atlantic Ocean than in the Mediterranean Sea, which can be attributed to the longer turbine downtime experienced in the European Atlantic Ocean, as detailed in Section 3.3. In the northwest region and along the Portuguese coast, the AEP difference reaches values of up to 1000 GWh, equivalent to a 11.4% overestimate in CF. Even at greater distances from the coastlines, these AEP differences exceed 1500 GWh, corresponding to up to 17.12% overestimate in CF. On the contrary, significant areas within the Bay of Biscay, the Gulf of Cadiz, and throughout the Mediterranean Sea exhibit differences in AEP less than 500 GWh, which are consistent with higher levels of turbine availability in these regions.

In this context, conducting an accurate assessment of the potential impact of O&M factors on the energy production of upcoming commercial FOW projects is of great importance. Consequently, an evaluation of FOW farms that will be deployed in the North Sea is carried out under the *ScotWind* project [45], and in the Iberian Peninsula under the *MITECO* project [46], is carried out. The main characteristics of these farms are described in Table A.4. Fig. 12 shows the AEP of these farms and the associated reduction in CF resulting from the inclusion of O&M factors in energy estimation.

The comparison between FOW farms in the North Sea and the Iberian Peninsula reveals that when only the wind resource potential is considered, the North Sea farms exhibit greater power potential than those in the Iberian Peninsula. However, even with the inclusion of



(a) (b)

Fig. 11. Difference in AEP between considering O&M factors and not considering in: (a) the North Sea, and (b) the Iberian Peninsula.

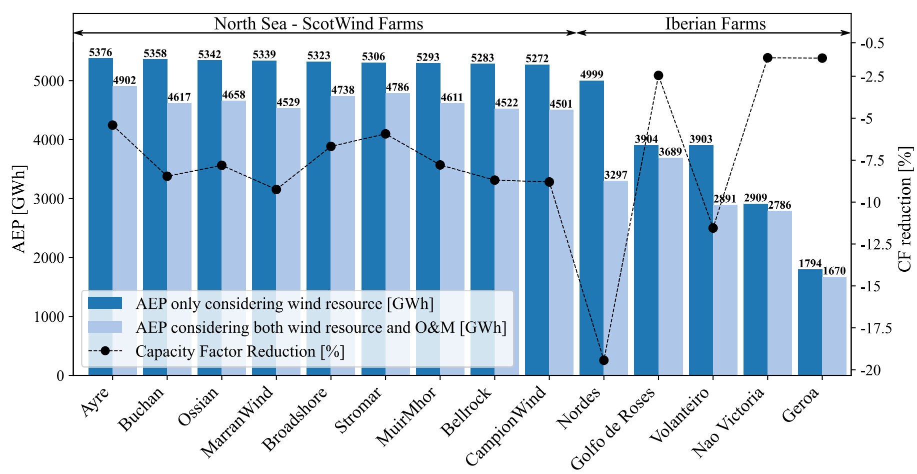


Fig. 12. Comparison of AEP between *ScotWind* and Iberian FOW farms, along with the corresponding decrease in CF due to the incorporation of O&M factors in energy estimation.

O&M factors in the analysis, North Sea farms continue to be more powerful than those of the Iberian Peninsula.

In contrast, the consideration of O&M factors can modify the preference of deployment sites within the North Sea and the Iberian Peninsula farms. For example, within the North Sea region, the *Broadshore* and *Stromar* farms exhibit lower wind resource potential compared to the *Ossian* and *MarranWind* farms. However, upon considering O&M factors, the AEP is higher for the former two farms than for the latter two, attributed to reduced turbine downtime. Furthermore, the results also indicate that neglecting O&M factors in the calculation of the AEP for the *ScotWind* farms results in an average overestimation of the CF of 7.64%.

In this respect, the consideration of O&M factors within the estimation of energy production may be more significant within the farms located on the Iberian Peninsula. Specifically, in farms located along the northwest coast of the Iberian Peninsula, such as *Nordes* and *Volanteiro*, neglecting O&M factors in the AEP computation can result in an overestimation of the CF by 19.43% in the former and 11.55% in the latter. In contrast, in the Mediterranean Sea and the Bay of Biscay, the CF overestimate is less than 2.5%, attributed to shorter turbine downtime. In this sense, upon considering O&M factors, the *Golfo de Roses* farm located in the Mediterranean Sea has a 9.11% higher CF compared to the *Volanteiro* farm, despite both farms having practically the identical wind resource potentials. Moreover, the *Golfo de Roses* farm achieves a 4.48% higher CF than the *Volanteiro* farm when considering O&M factors, despite having a 14.95% lower CF solely based on wind resource potential. In the case of the *Nao Victoria*, situated in the Alboran Sea, the CF difference with *Nordes* is decreased from 23.86% to 5.83%, and with *Volanteiro* from 13.35% to 1.18% when O&M factors are included in the analysis.

These results also demonstrate that regions with lower wind resources and shorter downtime may achieve higher overall efficiency compared to regions with higher wind resources but longer downtime. Consequently, O&M factors should be considered not only during the operational phase of FOW farms but also during the preoperational phases, such as when identifying optimal deployment sites.

However, the qualitative and quantitative influence of O&M factors, especially in the North Sea and along the northwest and Portuguese coast of the Iberian Peninsula, can be largely attributed to the limited accessibility levels for major repairs. Thus, conducting a sensitivity analysis on the operational limits of vessels for performing major repairs is of significant interest.

3.5. Sensitivity analysis of vessel operational limits for major repairs

The operational limits of vessels for major repairs can play a crucial role in the sustainable development of FOW farms. Major repairs often require crane operations, which are usually restricted to U_w of

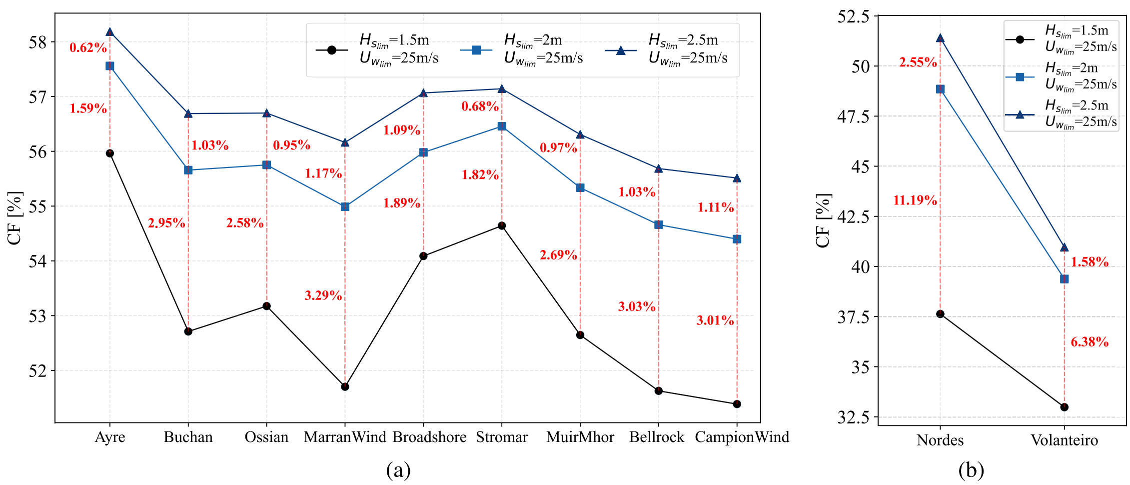


Fig. 13. Percentage change in CF in: (a) the North Sea, and (b) the Iberian Peninsula.

15 m/s [43,59]. On the other hand, the H_s limits for major repairs are typically defined within the range of 1.5 m to 2.5 m [41,43,60]. Therefore, a sensitivity analysis of vessel operational limits for major repairs is performed on *ScotWind* and *Iberian* farms in order to evaluate the impact of these operational limits on the energy production. The sensitivity analysis includes a total of six combinations of limits: 15 m/s and 25 m/s for U_w, and 1.5 m, 2 m, and 2.5 m for H_s. The results of this sensitivity analysis are provided in Table A.5.

The results show that the H_s limit has a higher influence on energy production compared to the U_w limit. Change in CF is consistently higher when the H_s limit is increased by 0.5 m than when the U_w limit is reduced by 10 m/s. Therefore, the subsequent analysis focusses on evaluating the sensitivity of the H_s operational limit while maintaining a constant U_w operational limit of 25 m/s.

Fig. 13(a) shows the CF sensitivity as a function of the H_s operational limit within *ScotWind* farms. Increasing the H_s limit from 1.5 m to 2 m leads to an average increase in CF of 2 54% in the *ScotWind* farms. In comparison, raising the H_s limit from 2 m to 2.5 m results in an average CF increase of 0.96%.

Fig. 13(b) shows the sensitivity of the CF as a function of the H_s operational limit along the northwest coast of the Iberian Peninsula. The CF is increased 11.19% and 6.38% in *Nordes* and *Volanteiro* respectively, when the H_s limit is increased from 1.5 m to 2 m. In comparison, increasing the H_s limit from 2 m to 2.5 m results in a CF increment of 2.55% and 1.58% in *Nordes* and *Volanteiro*, respectively.

The sensitivity of the CF with respect to the H_s limits is notably lower in *Geroa* in the Bay of Biscay, and in *Nao Victoria* and *Golfo de Roses* in the Mediterranean Sea, due to reduced turbine downtime in these sites. Increasing the H_s limit from 1.5 m to 2 m results in increases in CF of 0.36%, 0.14% and 0.45% in *Geroa*, *Nao Victoria*, and *Golfo de Roses*, respectively. Similarly, increasing the H_s limit from 2 m to 2.5 m results in a CF increment of 0.14%, 0.05%, and 0.2% in *Geroa*, *Nao Victoria*, and *Golfo de Roses*, respectively.

In this sense, the presence of vessels capable of performing major repairs with H_s limits of at least 2 m is crucial to minimising downtime in *ScotWind* farms and on the northwest coast of the Iberian Peninsula. If this condition is not met, Mediterranean Sea farms may be more favourable than those in the European Atlantic Ocean due to the higher maintainability of the former farms. This is supported by the fact that in *Nordes*, which has a higher potential for wind energy resources than *Rosas*, a higher AEP is achieved only if major repairs can be performed with vessels having limits of H_s of at least 2 m.

Consequently, the results demonstrate the importance of the H_s limit of vessels for major repairs in the development of upcoming FOW farms, particularly in the North Sea and on the northwest coast of the Iberian Peninsula. These findings also hold significance for vessels builders, as vessels for conducting major repairs on FOW turbines are presently in the design phase, and the H_s limit is often used in maintenance contracts [52].

Aside from the significance of maintenance, these findings also underscore the importance of FOW turbine reliability in *ScotWind* farms and on the northwest coast of the Iberian Peninsula. With the development of the FOW farms in these two regions, the focus should be on enhancing maintenance practices and reducing FOW turbine failures. That is, with fewer FOW turbine failures, the need for maintenance vessels will decrease, leading to reduced downtime and consequently, increased AEP.

4. Conclusion

This paper is unique in evaluating how operation and maintenance (O&M) factors impact energy production across a broad geographical area and, consequently, the identification of optimal deployment sites for floating offshore wind (FOW) farms. The geospatial analysis performed in this paper comprehensively incorporates O&M factors, including reliability, maintainability, accessibility and availability aspects, and evaluates their impact on energy production across the North Sea and the Iberian Peninsula. Novel results from this paper show that:

- O&M factors impact energy production and the identification of optimal deployment sites, both quantitatively and qualitatively. The O&M factors quantitatively affect energy production, because no energy is generated during turbine downtime. This downtime varies depending on the geographical location of the farm, resulting in a qualitative change in the spatial distribution of energy production. Regions with reduced wind resources and shorter downtime may exhibit higher overall efficiency than regions with higher wind resources but longer downtime.
- In the North Sea, areas identified as having not the highest wind resource potential, such as the coastlines of Denmark, Germany, and southern Scotland, may be considered promising locations when O&M factors are included in the analysis. The southern regions of the North Sea, including the coastlines of southern England, Belgium, and the Netherlands, are characterised by shorter turbine downtime due to higher maintainability. However, in these southern regions, the wind resource potential is also lower and turbine downtime is not significantly shorter than in the central and northern regions of the North Sea.

- In the Iberian Peninsula, areas traditionally considered to have the highest wind resource potential, such as the northwest coast and the Portuguese coast, may be considered less appealing when O&M factors are incorporated into the analysis, in contrast to areas in the Mediterranean, such as the regions in the Alboran Sea and the Gulf of Roses. In the Mediterranean, the wind resource potential is lower than in the European Atlantic Ocean, but the higher maintainability results in significantly shorter turbine downtime.
- Neglecting O&M factors in the estimation of energy production of *ScotWind* farms in the North Sea can result in an average overestimation of the capacity factor (CF) of 7.64%. In future farms located along the northwest coast of the Iberian Peninsula, such as *Nordes* and *Volanteiro*, neglecting O&M factors can result in an overestimation of CF of 19.43% and 11. 55%, respectively. In contrast, in the Mediterranean and Bay of Biscay farms, the CF overestimation is lower than 2.5%.
- The significant turbine downtime in the North Sea and along the northwest and Portuguese coast of the Iberian Peninsula are largely attributed to restricted accessibility for major repairs, including replacements of pitch and hydraulic systems, generators, blades, and gearboxes. Increasing the limit of significant wave height (H_s) limit of vessels for major repairs from 1.5 m to 2 m results in an average increase in CF of 2.54% in the *ScotWind* farms. The same increase in H_s limits results in an increase in CF of 11.19% in *Nordes* and 6.38% in *Volanteiro*. The Atlantic Ocean based *Nordes* farm only surpasses the energy production of the Mediterranean based *Roses* farm if major repairs can be conducted with a H_s limit of at least 2 m.

Consequently, the results from this paper highlight the significance of O&M during the pre-operational and operational phases of FOW farms, including the identification and operation of optimal deployment sites. Thus, O&M factors should be incorporated into the GIS and techno-economic frameworks developed to identify optimal deployment sites. Additionally, the findings of this research work can offer valuable insights to partners involved in the *ScotWind* and Iberian Peninsula FOW farms, as it evaluates the potential impact of O&M factors on the energy production of these future farms. Lastly, this paper highlights the importance of major repairs and, specifically, the operational limits of the vessels to perform these repairs, can play in the efficiency of commercial scale FOW farms. This information is also relevant to the vessels manufacturers, as vessels for performing onsite major repairs on FOW turbines are currently in the design phase, and these operational limits are considered in maintenance contracts.

Future research will explore the techno-economic aspects within geospatial analysis and will conduct a comprehensive assessment of the influence of maintenance ports and the tow-to-port major repair strategy on final key performance indicators.

CRediT authorship contribution statement

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

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.

Acknowledgements

The authors gratefully acknowledge the financial support from the Basque Government for the Predoctoral Training Research Grant Number [PRE_2022_2_0137], HAZITEK Grant Number [ZE-2021/00042], ELKARTEK Grant Number [KK-2022/00105], and Spain under Grant Number [PID2021-124245OA-I00] (MINECO/FEDER, UE). In addition, J.I. Aizpurua is funded by Juan de la Cierva Incorporacion Fellowship (Spanish State Research Agency Grant Number IJC2019-039183-I) .

Appendix. Characteristics of the components for the FOW turbine

See Tables A.3–A.5.

Table A.3
Taxonomy for the FOW turbine and related properties [41].

Components	Annual failure rate [failures/turbine/year]	Onsite repair time [h]	O&M category	Vessel
Floating platform	0.98112	12	Medium	FSV
Mooring lines	0.14892	12	Medium	FSV
Anchors	0.15768	12	Medium	FSV
Power cable	3.23e−5	24	Medium	FSV
Export cable	0.167	24	Medium	FSV
Pitch & Hydraulic sys.	1.076	89	Major	HLV
Generator	0.999	67	Major	HLV
Blades	0.52	31.25	Major	HLV
Gearbox	0.633	44.5	Major	HLV
Grease, Oil	0.471	22	Medium	FSV
Electrical comp.	0.435	20.75	Medium	FSV
Contactor	0.43	17.5	Medium	FSV
Controls	0.428	17.5	Medium	FSV
Safety	0.392	13.25	Medium	FSV
Sensors	0.346	12.75	Medium	FSV
Pumps	0.346	11	Medium	FSV
Hub	0.235	8.3	Medium	FSV
Heaters, Coolers	0.213	8	Minor	CTV
Yaw system	0.189	7.3	Minor	CTV
Tower	0.05	7	Minor	CTV
Power converter	0.18	8	Minor	CTV
Transformer	0.065	3.6	Minor	CTV

Table A.4
Main information the selected floating offshore wind farms in the North Sea and the Iberian Peninsula [45,46].

Wind farm name	Region	Latitude	Longitude	Port name	To port [mi]
Ossian	NS	56.69°N	0.392°W	Aberdeen	71.3
Bellrock	NS	56.85°N	0.036°E	Peterhead	81.79
CampionWind	NS	57.3°N	0.114°E	Peterhead	71.97
MuirMhor	NS	57.42°N	0.568°W	Peterhead	45.5126
MarranWind	NS	58.162°N	0.623°W	Fraserburgh	60.39
Broadshore	NS	58.16°N	1.8°W	Fraserburgh	33.74
Buchan	NS	58.41°N	1.232°W	Fraserburgh	57.65
Stromar	NS	58.51°N	2.145°W	Wick	34.36
Ayre	NS	58.86°N	2.2°W	St Margarets	26.88
Nao Victoria	IP	36.2°N	4.8°W	Europa Point	31
Geroa	IP	43.6°N	3.13°W	Bilbao	17.73
Golfo de Roses	IP	42.2°N	3.45°E	Rosas	14.4
Volanteiro	IP	42.1°N	9.25°W	Vigo	28.82
Nordes	IP	43.9°N	8.4°W	Ferrol	29.97

Abbreviations: NS = North Sea, IP = Iberian Peninsula.
Note 1: This paper considers that each floating offshore wind farm comprises one hundred 10 MW turbines mounted on semi-submersible platforms.
Note 2: To establish maintenance ports for each floating offshore wind farm, distances to all ports defined in the World Port Index [54] have been initially computed, followed by the selection of the closest port.

Table A.5
Annual Energy Production (AEP) of selected floating offshore wind farms in the North Sea and the Iberian Peninsula, with and without Operation and Maintenance (O&M) factors consideration.

Wind Farm Name	AEP w/o O&M [GWh]	AEP with O&M $H_{s_{lim}}$ = 1.5 m $U_{w_{lim}}$ = 25 m/s [GWh]	ΔCF [%]	$H_{s_{lim}}$ = 1.5 m $U_{w_{lim}}$ = 15 m/s [GWh]	ΔCF [%]	$H_{s_{lim}}$ = 2 m $U_{w_{lim}}$ = 25 m/s [GWh]	ΔCF [%]	$H_{s_{lim}}$ = 2 m $U_{w_{lim}}$ = 15 m/s [GWh]	ΔCF [%]	$H_{s_{lim}}$ = 2.5 m $U_{w_{lim}}$ = 25 m/s [GWh]	ΔCF [%]	$H_{s_{lim}}$ = 2.5 m $U_{w_{lim}}$ = 15 m/s [GWh]	ΔCF [%]
Ossian	5342.1	4658.08	7.81	4655.13	7.84	4883.85	5.23	4858.32	5.53	4966.79	4.28	4914.94	4.88
Bellrock	5283.86	4522.51	8.69	4522.08	8.7	4788.22	5.66	4769.06	5.88	4878.07	4.63	4834.63	5.13
CampionWind	5272.14	4501.37	8.8	4500.03	8.81	4765.24	5.79	4743.1	6.04	4862.88	4.67	4815.65	5.21
MuirMhor	5293.84	4611.78	7.79	4611	7.79	4847.34	5.1	4824.94	5.35	4932.57	4.12	4886.77	4.64
MarranWind	5339.36	4529.06	9.25	4528.63	9.25	4817.03	5.96	4798.82	6.17	4919.83	4.79	4879.03	5.25
Broadshore	5323.31	4738.14	6.68	4734.2	6.73	4930.87	4.79	4909.53	4.72	4998.95	3.7	4954.7	4.21
Buchan	5358.73	4617.5	8.46	4616.36	8.47	4875.6	5.52	4857.67	5.72	4965.96	4.48	4923.38	4.97
Stromar	5306.24	4786.68	5.93	4783.78	5.96	4945.68	4.12	4921.64	4.4	5005.65	3.43	4955.07	4.01
Ayre	5376.55	4902.42	5.41	4896	5.49	5042.14	3.82	5002.19	4.27	5096.84	3.19	5029.46	3.96
Nao Victoria	2909.28	2786.93	1.4	2786.1	1.41	2799.27	1.26	2796.2	1.29	2803.44	1.21	2799.15	1.26
Geroa	1794.07	1670.05	1.42	1670.05	1.42	1701.34	1.06	1701.15	1.06	1712.64	0.92	1712.23	0.83
Golfo de Roses	3904.47	3689.91	2.45	3681.77	2.54	3728.59	2	3707.3	2.25	3746.48	1.8	3712.55	2.19
Volanteiro	3903.48	2891.64	11.55	2891.64	11.55	3450.13	5.18	3437.39	5.32	3588.55	3.6	3566.54	3.85
Nordes	4999.92	3297.62	19.43	3297.62	19.432	4277.67	8.25	4266.51	8.37	4500.75	5.7	4469.94	6.05

Abbreviations: AEP = Farm-level annual energy production, w/o = without.
Note 1: Each floating offshore wind farm comprises one hundred 10 MW turbines mounted on semi-submersible platforms.
Note 2: $H_{s_{lim}}$ and $U_{w_{lim}}$ refer to the operational limits of heavy lift vessels used for major component replacements.
Note 3: ΔCF [%] refers to the percentage change between the CF without and with consideration of operation and maintenance factors.

References

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

[2] International Renewable Energy Agency, Geopolitics of the Energy Transition: Critical Materials, IRENA, Abu Dhabi, 2023.

[3] N. Bento, M. Fontes, Emergence of floating offshore wind energy: Technology and industry, Renew. Sustain. Energy Rev. 99 (2019) 66–82, http://dx.doi.org/10.1016/j.rser.2018.09.035.

[4] P. Tavner, Offshore Wind Power Reliability, Availability and Maintenance, second ed., Institution of Engineering & Technology, 2021, http://dx.doi.org/10.1049/PBPO194E.

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

[6] H. Díaz, S. Loughney, J. Wang, C. Guedes Soares, Comparison of multicriteria analysis techniques for decision making on floating offshore wind farms site selection, Ocean Eng. 248 (2022) 110751, http://dx.doi.org/10.1016/j.oceaneng.2022.110751.

[7] H. Díaz, C. Guedes Soares, A novel multi-criteria decision-making model to evaluate floating wind farm locations, Renew. Energy 185 (2022) 431–454, http://dx.doi.org/10.1016/j.renene.2021.12.014.

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

[9] A. Martinez, Wind Energy Perspectives: Climate Change and Economic Viability of Floating Offshore Wind (Ph.D. thesis), University College Cork, 2022.

[10] A. Ulazia, J. Sáenz, G. Ibarra-Berastegi, S.J. González-Rojí, S. Carreno-Madinabeitia, Global estimations of wind energy potential considering seasonal air density changes, Energy 187 (2019) 115938, http://dx.doi.org/10.1016/j.energy.2019.115938.

[11] A. Ghigo, L. Cottura, R. Caradonna, G. Bracco, G. Mattiazzo, Platform optimization and cost analysis in a floating offshore wind farm, J. Mar. Sci. Eng. 8 (11) (2020) 835, http://dx.doi.org/10.3390/jmse8110835.

[12] M. Collu, M. Borg, Design of floating offshore wind turbines, in: C. Ng, L. Ran (Eds.), Offshore Wind Farms, Elsevier Inc., United States, 2016, pp. 359–385, http://dx.doi.org/10.1016/B978-0-08-100779-2.00011-8.

[13] G. Froese, S.Y. Ku, A.C. Kheirabadi, R. Nagamune, Optimal layout design of floating offshore wind farms, Renew. Energy 190 (2022) 94–102, http://dx.doi.org/10.1016/j.renene.2022.03.104.

[14] M. Martini, R. Guanche, I. Losada-Campa, I. Losada, The impact of downtime over the long-term energy yield of a floating wind farm, Renew. Energy 117 (2018) 1–11, http://dx.doi.org/10.1016/j.renene.2017.10.032.

[15] L. Castro-Santos, V. Diaz-Casas, Sensitivity analysis of floating offshore wind farms, Energy Convers. Manage. 101 (2015) 271–277, http://dx.doi.org/10.1016/j.enconman.2015.05.032.

[16] Sennen, Involve O&M teams during construction and reap the rewards, 2023, https://www.sennen.tech/news/involve-om-teams-during-construction-and-reap-the-rewards/.

[17] J. McMorland, M. Collu, D. McMillan, J. Carroll, Operation and maintenance for floating wind turbines: A review, Renew. Sustain. Energy Rev. 163 (2022) 112499, http://dx.doi.org/10.1016/j.rser.2022.112499.

[18] G. Rinaldi, P.R. Thies, L. Johanning, Current status and future trends in the operation and maintenance of offshore wind turbines: A review, Energies 14 (9) (2021) 2484, http://dx.doi.org/10.3390/en14092484.

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

[20] G.E. Barter, A. Robertson, W. Musial, A systems engineering vision for floating offshore wind cost optimization, Renew. Energy Focus 34 (2020) 1–16, http://dx.doi.org/10.1016/j.ref.2020.03.002.

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

[22] M. Martini, R. Guanche, I.J. Losada, C. Vidal, Accessibility assessment for operation and maintenance of offshore wind farms in the North Sea, Wind Energy 20 (4) (2017) 637–656, http://dx.doi.org/10.1002/we.2028.

[23] M. Centeno-Telleria, J. Aizpurua, M. Penalba, Impact of accessibility on O&M of floating offshore wind turbines: Sensitivity of the deployment site, Trends Renew. Energies Offshore (2023) 847–855., http://dx.doi.org/10.1201/9781003360773-94.

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

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

[26] C. Maienza, A. Avossa, F. Ricciardelli, D. Coiro, G. Troise, C.T. Georgakis, A life cycle cost model for floating offshore wind farms, Appl. Energy 266 (2020) 114716, http://dx.doi.org/10.1016/j.apenergy.2020.114716.

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

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

[29] L. Castro-Santos, A. Filgueira-Vizoso, L. Carral-Couce, J.Á.F. Formoso, Economic feasibility of floating offshore wind farms, Energy 112 (2016) 868–882, http://dx.doi.org/10.1016/j.energy.2016.06.135.

[30] M. Lerch, M. De-Prada-Gil, C. Molins, G. Benveniste, Sensitivity analysis on the levelized cost of energy for floating offshore wind farms, Sustain. Energy Technol. Assess. 30 (2018) 77–90, http://dx.doi.org/10.1016/j.seta.2018.09.005.

[31] H. Díaz, R. Fonseca, C. Guedes Soares, Site selection process for floating offshore wind farms in Madeira Islands, Adv. Renew. Energies Offshore (2019) 729–737.

[32] L. Castro-Santos, M.I. Lamas-Galdo, A. Filgueira-Vizoso, Managing the oceans: Site selection of a floating offshore wind farm based on GIS spatial analysis, Mar. Policy 113 (2020) 103803, http://dx.doi.org/10.1016/j.marpol.2019.103803.

[33] S. Loughney, J. Wang, M. Bashir, M. Armin, Y. Yang, Development and application of a multiple-attribute decision-analysis methodology for site selection of floating offshore wind farms on the UK Continental Shelf, Sustain. Energy Technol. Assess. 47 (2021) 101440, http://dx.doi.org/10.1016/j.seta.2021.101440.

[34] K. Mittendorf, Joint description methods of wind and waves for the design of offshore wind turbines, Mar. Technol. Soc. J. 43 (2009) 23–33, http://dx.doi.org/10.4031/MTSJ.43.3.2.

[35] G.J. Van Bussel, W. Bierbooms, The DOWEC Offshore Reference Windfarm: analysis of transportation for operation and maintenance, Wind Eng. 27 (5) (2003) 381–391, http://dx.doi.org/10.1260/030952403322770986.

[36] E.-B. Konuk, M. Centeno-Telleria, A. Zarketa-Astigarraga, J.-I. Aizpurua, G. Giorgi, G. Bracco, M. Penalba, On the definition of a comprehensive technology-informed accessibility metric for offshore renewable energy site selection, J. Mar. Sci. Eng. 11 (9) (2023) 1702, http://dx.doi.org/10.3390/jmse11091702.

[37] D. Rowell, B. Jenkins, J. Carroll, D. McMillan, How does the accessibility of floating wind farm sites compare to existing fixed bottom sites? Energies 15 (23) (2022) 8946, http://dx.doi.org/10.3390/en15238946.

[38] R.T. Walker, J. van Nieuwkoop-McCall, L. Johanning, R.J. Parkinson, Calculating weather windows: Application to transit, installation and the implications on deployment success, Ocean Eng. 68 (2013) 88–101, http://dx.doi.org/10.1016/j.oceaneng.2013.04.015.

[39] I. Dinwoodie, Modelling the Operation and Maintenance of Offshore Wind Farms (Ph.D. thesis), University of Strathclyde, 2014.

[40] M. Martini, Modelization and Analysis of Operation and Maintenance of Floating Offshore Wind Farms (Ph.D. thesis), Universidad de Cantabria, 2017.

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

[42] G. Rinaldi, J.C.C. Portillo, F. Khalid, J.C.C. Henriques, P.R. Thies, L.M.C. Gato, L. Johanning, Multivariate analysis of the reliability, availability, and maintainability characterizations of a Spar–Buoy wave energy converter farm, J. Ocean Eng. Mar. Energy 4 (2018) 199–215, http://dx.doi.org/10.1007/s40722-018-0116-z.

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

[44] I. Dinwoodie, D. Mcmillan, Operational strategies for offshore wind turbines to mitigate failure rate uncertainty on operational costs and revenue, Renew. Power Gener. IET 8 (2014) 359–366, http://dx.doi.org/10.1049/iet-rpg.2013.0232.

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

[46] 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.

[47] Grupo de Trabalho para o planeamento e operacionalização de centros eletroprodutores 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.

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

[49] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L.C. Henriksen, M.H. Hansen, J.P.A.A. Blasques, M. Gaunaa, A. Natarajan, The DTU 10-MW reference wind turbine, in: Danish Wind Power Research, 2013.

[50] H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, et al., The ERA5 global reanalysis, Q. J. R. Meteorol. Soc. 146 (730) (2020) 1999–2049.

[51] J. Carroll, A. McDonald, D. McMillan, Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines, Wind Energy 19 (6) (2016) 1107–1119, http://dx.doi.org/10.1002/we.1887.

[52] 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.

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

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

[55] N. Akbari, C.A. Irawan, D.F. Jones, D. Menachof, A multi-criteria port suitability assessment for developments in the offshore wind industry, Renew. Energy 102 (2017) 118–133, http://dx.doi.org/10.1016/j.renene.2016.10.035.

[56] R.A. Azdy, F. Darnis, Use of haversine formula in finding distance between temporary shelter and waste end processing sites, in: Journal of Physics: Conference Series, Vol. 1500, IOP Publishing, 2020, 012104, http://dx.doi.org/10.1088/1742-6596/1500/1/012104.

[57] L. Castro-Santos, E. Martins, C.G. Soares, Cost assessment methodology for combined wind and wave floating offshore renewable energy systems, Renew. Energy 97 (2016) 866–880, http://dx.doi.org/10.1016/j.renene.2016.06.016.

[58] P. Virtanen, R. Gommers, T.E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, et al., SciPy 1.0: fundamental algorithms for scientific computing in Python, Nature Methods 17 (3) (2020) 261–272.

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

[60] M. Li, M. Wang, J. Kang, L. Sun, P. Jin, An opportunistic maintenance strategy for offshore wind turbine system considering optimal maintenance intervals of subsystems, Ocean Eng. 216 (2020) 108067, http://dx.doi.org/10.1016/j.oceaneng.2020.108067.