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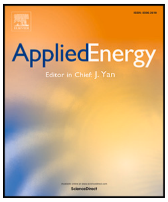

Assessing heavy maintenance alternatives for floating offshore wind farms: Towing vs. onsite replacement strategies

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ABSTRACT

This paper presents the first comparative study evaluating towing and onsite replacement strategies for heavy maintenance of floating offshore wind (FOW) turbines. The towing maintenance strategy is characterised by a Markov chain and implemented within a computationally-efficient operation and maintenance (O&M) model. This model includes all key phases of the towing strategy: transit-to-site, turbine disconnection, towing-to-port, component replacement, towing-to-site, turbine connection, and transit-to-port. Additionally, the paper provides the first spatial assessment of heavy maintenance for FOW turbines in the North Sea. Evaluation across the ScotWind area shows that onsite replacement can reduce turbine downtime, especially for quick heavy maintenance operations like blade and gearbox replacements. However, for longer operations, such as generator and pitch and hydraulic system replacements, onsite solutions are more effective than towing only when O&M vessels can operate in wave heights over 1.5 metres. Otherwise, a mixed heavy maintenance strategy is recommended, combining onsite replacements for blades and gearboxes with towing for generators and pitch and hydraulic systems. The average turbine availability reduction with the mixed strategy is 0.39%, followed by the fully towing strategy at 0.43%, and the fully onsite replacement strategy at 0.46%.

1. Introduction

To meet the world net zero targets, a rapid growth is required in installed offshore wind capacity. The most recent report of the Global Wind Energy Council shows that over 380 GW of offshore wind capacity is expected to be added in the next ten years [1]. Currently, the vast majority of the offshore wind power is generated by wind turbines that are fixed to the seabed, commonly referred to as bottom-fixed offshore wind (BFOW) turbines. However, BFOW turbines are not viable solutions for operating in deep waters (>60 m), where the most powerful and consistent wind resources can be found [2,3]. Floating offshore wind (FOW) turbines have the potential to tap into deep waters, creating opportunities in areas that BFOW turbines cannot reach.

Precommercial MW-scale FOW farms currently operating, such as Hywind Scotland and Kincardine in the UK [4,5], Windfloat Atlantic in Portugal [6], and Hywind Tampen in Norway [7], demonstrate the technical viability of FOW turbines. In the next few years, projects that sum up to 100–500 MW are expected to be deployed, leading to an estimated total of 10.9 GW by 2030 [1]. However, the commercialisation of FOW with GW farms is expected to occur in the 2030s, as evidenced by ongoing government auctions and leasing initiatives in the UK [8], South Korea [9], the US [10], Portugal [11] and Spain [12].

To scale up from demonstration projects to GW-scale farms, the cost of FOW technology must be reduced [13]. The main drivers for cost reduction are the innovations on platform designs, the integration of larger turbines and the increment in the volume of deployment [1]. Despite significant progress, FOW technology has not yet achieved convergence, as exemplified by the existence of 22 different platform designs that have reached the testing phase, along with more than 80 others still in the early stages of development [14]. In addition to the technological progress of floating turbines, improving port infrastructure [15], electrical grid capabilities [16], and operation and maintenance (O&M) procedures [17] are equally critical for achieving the commercialisation of FOW. In fact, the O&M is estimated to imply

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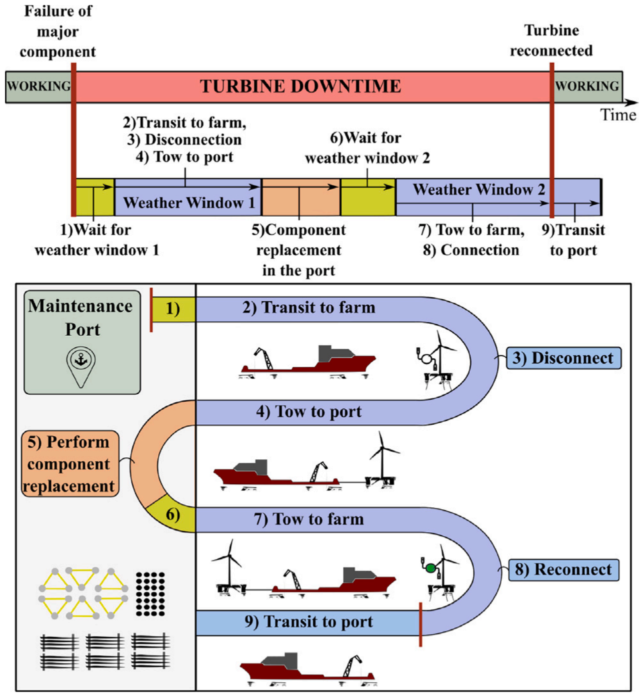


Fig. 1. The main phases of the towing maintenance strategy and the relation with turbine downtime.

between 25%–30% of the final cost [17] and poses great technological challenges to ensure FOW maintenance and reliability.

Operating at far and deep-offshore sites with stronger and more consistent winds enables the use of larger FOW turbines, potentially increasing energy production [14]. However, these attributes, which offer opportunities for FOW, also exacerbates the O&M challenges. In particular, an area of complexity in FOW turbines is the maintenance of major or heavy components, such as the blades, the generator, the gearbox and the pitch and hydraulic system [18]. The replacement of these components has historically been associated with high repair costs and lengthy repair times [19]. In addition to high cost and repair duration, the FOW present new O&M challenges in the following aspects, specifically regarding heavy maintenance:

1. The greater distances from the shore generally associates with harsher metocean conditions and longer travel times. As a result, accessing the farm becomes more challenging, leading to increased turbine downtime [20]. Particularly, increased distances notably affect the maintenance of major components due to their long replacement duration and the low operating limits of the vessels required in these operations [21].
2. The jack-up vessels employed for replacing major components in BFOW turbines are unsuitable for operations in deep waters, where FOW turbines are expected to be located [22], meaning that no technological solution exists nowadays to perform such heavy maintenance operations in deep waters.
3. The increasing dimensions of wind turbines result in heavier and higher positioned components, thereby raising the complexity of lifting operations [18].

Considering these challenges, O&M experts and specialised consultants are developing various heavy maintenance solutions for FOW turbines [23]. So far, the suggested heavy maintenance solutions can be classified into: (i) towing and (ii) onsite replacement maintenance strategies [24,25] detailed as follows.

1.1. *Towing maintenance strategy*

The towing maintenance strategy involves disconnecting the FOW turbine from the moorings and cables and towing it to a port using anchor handling tug supply (AHTS) vessels when a major component replacement is required. Hence, the major component replacement is carried out at the port, after which the turbine is towed back to the site for reconnection [24]. The main phases involved in the towing maintenance strategy and their relationship with turbine downtime are depicted in Fig. 1.

AHTS vessels are specialised vessels used for pre-laying anchors, mooring lines and towing FOW turbines. Large AHTS vessels typically measure up to 25 metres in breadth and 95 metres in length [22]. For towing operations, the primary AHTS vessel should have a bollard pull of 200 tons, supported by two smaller AHTS vessels. These vessels are typically equipped with a stern roller, small cranes and towing winches [26,27].

As major component replacements are conducted at the port in the towing maintenance strategy, the port must meet certain requirements. Key requirements for ports include adequate space, minimum water depth, and facilities like quaysides and cranes with sufficient tip height [22]. The primary elements for lifting turbine components are the land-based cranes, which may be either ring cranes or crawler cranes [22]. Given the considerable height of FOW turbines, these cranes are frequently pushed to the limits of their lifting capacities. For instance, to install 15 MW nacelles on reference semi-submersibles FOW turbines, a crane must have a minimum capacity of 800 tons, a hook height of approximately 160 metres, and a reach of 30 metres from the quayside [22]. Furthermore, the port constraints on water depth can differ based on the FOW technology involved. Semi-submersible, barge and tension leg platforms typically require a water depth of 10–15 m, whereas spar platforms may require up to 80 m due to their deeper draught [28]. If ports lack the water depth and facilities necessary for heavy maintenance, the FOW turbines can be moored in storage areas outside the port for the components to be replaced using a vessel equipped with a large crane [22].

All marine operations require suitable weather windows (WWs) to ensure the safe execution. In this sense, the towing maintenance strategy requires at least two WWs, as illustrated in Fig. 1. The first WW is needed after the turbine fails in order to (i) transit to the farm, (ii) disconnect the turbine and (iii) tow it back to the port. The second WW is required when the replacement at the port is completed in order to (i) tow the turbine back to the farm, (ii) reconnect it, and (iii) transit again to the port. As a result, O&M personnel may have to wait in the port, at least, twice when the wind farm is inaccessible, leading to increased turbine downtime [29].

The towing maintenance strategy has proven to be a workable heavy maintenance solution at the Kincardine farm in Scotland, where two heavy maintenance operations have been already carried out on two semi-submersible FOW turbines since 2022 [30]. The technical aspects of the towing strategy, including disconnection and connection procedures, towing and port operations, were executed effectively [31]. The main difficulties emerged within the supply chain due to the limited availability of compatible marshalling ports in the North Sea. Consequently, the port of Rotterdam was selected for the heavy maintenance operation due to its supply chain facilities. However, the substantial towing distance from Scotland to the Netherlands resulted in a notable increase in turbine downtime, thus highlighting the importance of establishing ports with sufficient infrastructure near project sites [31].

1.2. *Onsite replacement maintenance strategy*

The onsite replacement maintenance strategy involves performing component replacements offshore without disconnecting the FOW turbine, as shown in Fig. 2. The onsite replacement strategy offers the potential to reduce turbine downtime as major component replacement

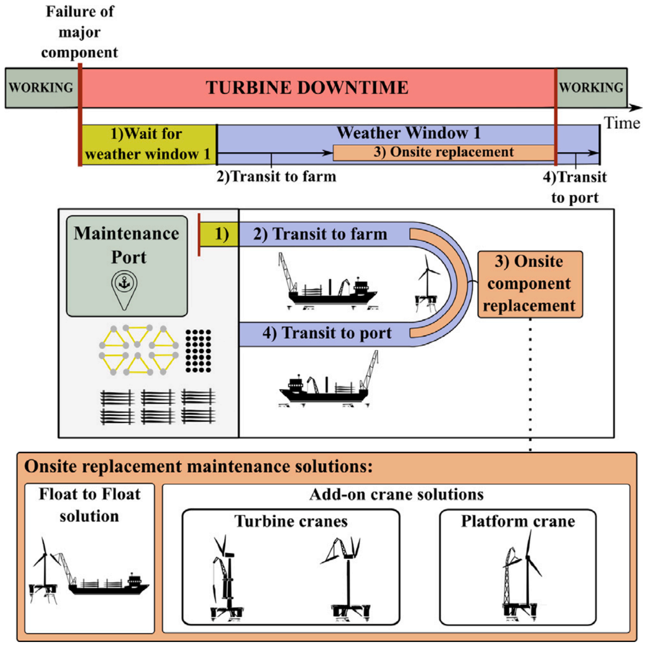


Fig. 2. The main phases of the onsite replacement maintenance strategy and the relation with turbine downtime.

Table 1
A summary of the general advantages and disadvantages of towing and onsite replacement strategy [25,32].

	Towing strategy	Onsite replacement strategy	
		Float-to-Float	Add-on cranes
TRL:	High (Proven solution)	Low	Low
Component replacement: Required port facilities: Lifting difficulty:	Port High Medium	Offshore Low Complex given vessel/turbine motions	Offshore Low Complex given swinging motions
Factors influencing WW[a]: -Transit to/from farm -Turbine (dis)-connection -Replacement duration	 ✓ ✓ ✗	 ✓ ✗ ✓	 ✓ ✗ ✓
Vessel type: Expected vessel rate:	AHTS Low	Future HLV[b] High	Standard HLV Medium
Adaptability to different FOW turbines[c]:	High	Medium	Low

[a] WW: Weather Window.

[b] Suitable HLVs for float-to-float are currently unavailable or are in development with expected high costs [25].

[c] Most add-on crane solutions are designed for specific platform concepts [25].

is performed offshore in a single visit [25]. Specifically, the onsite strategy requires at least one WW after the turbine fails in order to transit to the farm, execute the replacement of the component, and then return to the port.

Onsite replacement solutions can be classified into two categories: (i) float-to-float and (ii) add-on crane solutions [25]. The float-to-float solution involves lifting major components from a heavy lift vessel (HLV) to a FOW turbine for replacement. The float-to-float strategy requires a vessel with high lifting capacities and, at least, a heave compensation mechanism, although three-dimensional motion compensation is ideal [22]. The need for motion compensation arises from the relative movements between the vessel and the FOW turbine, which increases the complexity of the maintenance operation. However, at present, there is a shortage of suitable HLVs for such operations, with existing options being either costly or still in the design phase [25,33].

Add-on crane solutions involve integrating cranes into FOW turbines for performing component replacement. These solutions can be classified into tower- and platform-based crane options depending on whether the crane is installed on the turbine tower or on the platform [25]. The average technology readiness level (TRL) of tower and platform-based solutions is relatively low and only a few companies have performed prototype tests [31,34,35]. Unlike float-to-float solutions, standard HLVs are anticipated to be employed for add-on crane solutions. Standard HLVs are commonly utilised during the installation phases of offshore wind farms, and oil and gas platforms. These vessels typically measure up to 40 metres in breadth and up to 200 metres in length [36]. With lifting capacities reaching up to 3000 tons, standard HLVs are well-equipped to handle the demanding requirements of replacements with add-on cranes [25,37]. One of the main challenges associated with add-on solutions is the need to enhance their adaptability across different platforms and turbine configurations, as many solutions are designed to specific FOW turbines [38]. Additionally, managing the swinging movements of the crane hook can be challenging due to platform movements [32]. The main characteristics, relative advantages, and disadvantages among the towing and onsite replacement solutions are summarised in Table 1.

To effectively evaluate heavy maintenance alternatives, computationally efficient O&M models are needed. This necessity arises for two main reasons. First, the pre-commercial stage of the FOW sector and the potential for operations in unexplored deep waters require a thorough evaluation of potential deployment sites. Second, the uncertainty inherent in the FOW sector, due to the novelty of the technology and limited operational experience, demands comprehensive sensitivity evaluations. These evaluations are crucial for understanding the impact of various factors on key performance indicators, particularly in the context of heavy maintenance strategies for FOW farms. Evaluating the effects of replacement durations and the operational limits of vessels on both towing and onsite replacement strategies is essential to gain a comprehensive understanding of heavy maintenance strategies.

Nevertheless, most of O&M models are not computationally-efficient, because they rely on Monte Carlo simulations [39–42]. Monte Carlo-based models use repeated random sampling methods to approximate the failure and repair processes of a FOW farm [43]. However, their main disadvantage lies in the high computational burden, as numerous iterations are required to achieve convergence in the results [43]. For example, the O&M-model assessment for a single geographical location requires at least two days of computation [42]. In this context, an alternative computationally-efficient O&M model based on Markov models with similar precision, but a significantly lower computational burden is presented in [44], which has the potential to be employed in a geospatial heavy maintenance strategies assessment, as demonstrated in the present study.

Furthermore, it should be noted that a common limitation of offshore wind O&M modelling is the limited availability of real O&M data, due to the immaturity of the technology and the sensitivity of the O&M information [23]. For FOW major replacement strategies, this is relevant due to the immaturity of the sector and the fact that, to date, only the tow-to-port strategy has been implemented in the very few real practices. The assumptions made in the following sections have been thoroughly referenced to ensure the relevance of the obtained results.

1.3. Motivation and contribution

In the coming years, the deployment of large-scale FOW farms, with large (+15MW) FOW turbines is expected. However, limited experience exists in heavy maintenance of FOW turbines, especially for such large FOW turbines, with towing maintenance serving as the only alternative nowadays [21]. Based on the high turbine downtime implications in Kincardine, it has been suggested that the “tow-to-port O&M strategy

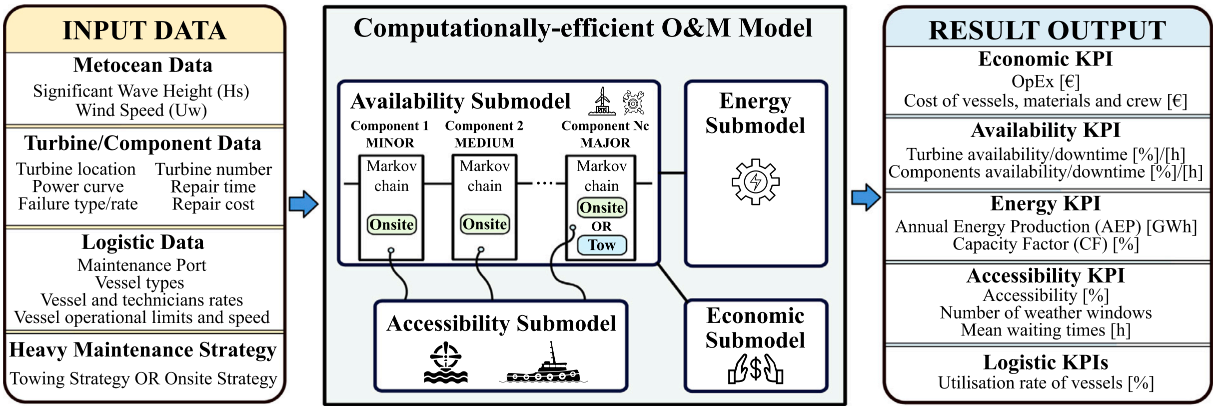


Fig. 3. Flowchart of the computationally-efficient O&M model illustrating the relationship between input data, submodels and results. Onsite replacement strategy is considered for minor and medium components. For major components, onsite replacement and towing maintenance strategies can be performed.

may hold back floating wind” [45]. In this respect, it is generally assumed that onsite replacement solutions will offer the “potential to reduce turbine downtime” [25,45]. Nonetheless, to the best of the authors’ knowledge, there is currently no study that evaluates towing and onsite replacement strategies and their downtime implications. This research covers this gap by making three main contributions:

1. The first comparative study evaluating towing and onsite replacement strategies in terms of turbine downtime, *i.e.* turbine availability.
2. A novel representation of the towing maintenance strategy based on Markov chain and integrated into an O&M model. The Markov chain model encompasses the most fundamental phases of the towing, including transit-to-site, turbine disconnection, towing-to-port, component replacement, towing-to-site, turbine connection, and transit-to-port.
3. The first spatial assessment of heavy maintenance strategies across a broad area *i.e.* in the North Sea, where future FOW farms are expected to be built under the ScotWind auction.

Therefore, the main objectives of this research are (i) to evaluate heavy maintenance strategies, (ii) to develop a comprehensive Markov chain model for towing maintenance, and (iii) to assess spatial maintenance strategies in the North Sea. To fulfil these objectives, the remainder of the paper is organised as follows: Section 2 presents the computationally-efficient O&M model with the novel representation of the towing maintenance strategy based on Markov chain, Section 3 introduces the case study of ScotWind farms, Section 4 presents the results and discussion, and Section 5 draws the main conclusions.

2. Computationally-efficient O&M model

In this section, the computationally-efficient O&M model for evaluating heavy maintenance strategies is described. As illustrated in Fig. 3, the O&M model consists of accessibility, availability, energy, and economic submodels [44]. The interdependencies between these four submodels are defined by means of a reliability block diagram (RBD) and Markov chains [44]. In this paper, the computationally-efficient O&M model presented in [44] is enhanced to articulate the towing maintenance strategy. The explanation of the O&M model in this section focuses mainly on the availability submodel, as the evaluation of heavy maintenance strategies is carried out in terms of turbine downtime. In this respect, turbine availability is modelled through a RBD arranged in a series configuration as follows [44],

$$A_{\mathrm{turb}} = \prod_{i=1}^{N_c} P_{\mathrm{w}_i} , \tag{1}$$

where A_{turb} is the turbine availability, $A_{\mathrm{turb}} \in [0,1]$, P_{w_i} is the availability of each component i modelled by a continuous-time Markov chain, $P_{\mathrm{w}_i} \in [0,1]$, and N_c the number of components of each FOW turbine.

The availability of each component, and hence, turbine availability, is directly influenced by O&M strategies. In this paper, two component-level maintenance strategies are considered: towing and onsite replacement strategies. Each maintenance strategy is represented by a continuous-time Markov chain, which is a stochastic process (*i.e*, a collection of random variables) that models the different states of the system and the transitions between these states [46,47].

2.1. Towing maintenance strategy

The Markov chain for the towing maintenance strategy is defined over a finite state-space $\Omega_{\mathrm{tow}_i} = \{\mathrm{W}_i, \mathrm{F}_i, \mathrm{TDT}, \mathrm{RP}_i, \mathrm{WP}, \mathrm{TCT}\}$ with transition rates δ_{tow_i} for each component i, as represented in Fig. 4.

A major component remains in the working state (W_i) until a failure necessitating replacement occurs. The transition from W_i to the failed state (F_i) is governed by the failure rate λ_{FOW_i}, which defines the rate a major component replacement is required. The component remains in the F_i until the metocean conditions allow for the transit, disconnection, and towing operations (TDT) to commence, which is governed by the transition rate ω_{tow_1} [operations/year] determined in the accessibility submodel. Subsequently, the TDT operations occur, governed by the transition rate α [operations/year]. Component replacement takes place in the port in the replacement state (RP_i), determined by the transition rate μ_i [replacements/year]. The turbine remains waiting in the port (WP) until metocean conditions permit the towing, connection and transit (TCT) operations to start, which is governed by the transition rate ω_{tow_2} [operations/year] determined again in the accessibility submodel. The turbine returns to operation once the towing and turbine connection operations are completed, governed by the transition rate β [operations/year].

The amount of time spend in each state before making a transition, known as sojourn time, is exponentially distributed and defined by the

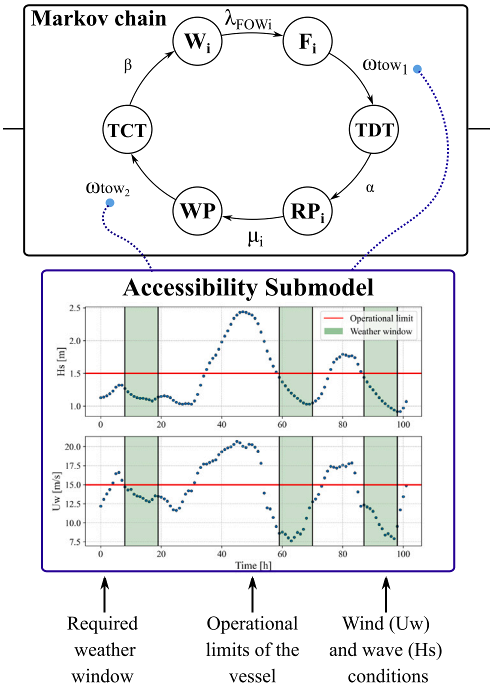


Fig. 4. The Markov chain for the towing maintenance strategy with accessibility submodel interdependency.

following transition rates,

$$\delta_{tow_i} = \begin{bmatrix} \lambda_{\mathrm{FOW}_i} \\ \omega_{\mathrm{tow}_1} \\ \alpha \\ \mu_i \\ \omega_{\mathrm{tow}_2} \\ \beta \end{bmatrix} = \begin{bmatrix} 1/MTTF_i \\ 1/MTTW_{\mathrm{WW}_1} \\ 1/MTTDT \\ 1/t_{\mathrm{replace}_i} \\ 1/MTTW_{\mathrm{WW}_2} \\ 1/MTTC \end{bmatrix}, \tag{2}$$

where $MTTF_i$ is the mean time to failure for the component i, $MTTW_{\mathrm{WW}_1}$ the mean time to wait for a WW for the TDT, $MTTDT$ the mean time to perform TDT operations, t_{replace_i} the component replacement duration, $MTTW_{\mathrm{WW}_2}$ the mean time to wait for a WW for the TCT, and $MTTC$ the mean time to transit and connect the turbine.

In this respect, $MTTF_i$ and t_{replace_i} are defined in the input data of the O&M model. On the other hand, $MTTW_{\mathrm{WW}_1}$ and $MTTW_{\mathrm{WW}_2}$ are calculated in the accessibility submodel as a function of the required WW, the operational limits of the vessels, and the metocean conditions, as represented in Fig. 3 and further detailed in [44]. Lastly, $MTTDT$ and $MTTC$ are defined as follows [48],

$$MTTDT = t_{\mathrm{transit}} + t_{\mathrm{disconnect}} + t_{\mathrm{tow}}, \tag{3}$$

$$MTTC = t_{\mathrm{tow}} + t_{\mathrm{connect}}, \tag{4}$$

where t_{transit} represents the mean duration of the trip from port to farm, calculated as a function of the distance and vessel transit speed, t_{tow} the mean duration of the trip from port to farm when towing the turbine, computed based on the distance and vessel towing speed, and $t_{\mathrm{disconnect}}$ and t_{connect} the disconnection and connection times of the turbine, which are defined in the input data of the O&M model, respectively.

The steady-state Markov chain probabilities are calculated by solving the Kolmogorov forward equation as [47],

$$\left[P_{\mathrm{TCT}_i} \;\; P_{\mathrm{WP}_i} \;\; P_{\mathrm{RP}_i} \;\; P_{\mathrm{TDT}_i} \;\; P_{\mathrm{F}_i} \;\; P_{\mathrm{W}_i}\right] \cdot \boldsymbol{Q}_{\mathrm{tow}_i} = \boldsymbol{0}, \tag{5}$$

where P_{TCT_i} is the probability for TCT, P_{WP_i} the probability for waiting at port, P_{RP_i} the probability for performing replacement at port, P_{TDT_i} the probability for TDT, P_{F_i} the probability for being in the failed state, P_{W_i} the probability for being in the working state, and Q_{tow_i} the transition rate matrix defined as,

$$\boldsymbol{Q}_{tow_i} = \begin{bmatrix} -\beta & 0 & 0 & 0 & 0 & \beta \\ \omega_{\mathrm{tow}_2} & -\omega_{\mathrm{tow}_2} & 0 & 0 & 0 & 0 \\ 0 & \mu_i & -\mu_i & 0 & 0 & 0 \\ 0 & 0 & \alpha & -\alpha & 0 & 0 \\ 0 & 0 & 0 & \omega_{\mathrm{tow}_1} & -\omega_{\mathrm{tow}_1} & 0 \\ 0 & 0 & 0 & 0 & \lambda_{FOW_i} & -\lambda_{FOW_i} \end{bmatrix}, \tag{6}$$

and assuming $P_{\mathrm{TCT}_i} + P_{\mathrm{WP}_i} + P_{\mathrm{RP}_i} + P_{\mathrm{TDT}_i} + P_{\mathrm{F}_i} + P_{\mathrm{W}_i} = 1$.

Therefore, the availability for each major component i is,

$$P_{W_i} = \frac{\beta}{\lambda_{\mathrm{FOW}_i}} \cdot \left(1 + \frac{\beta}{\omega_{\mathrm{tow}_2}} + \frac{\beta}{\mu_i} + \frac{\beta}{\alpha} + \frac{\beta}{\omega_{\mathrm{tow}_1}} + \frac{\beta}{\lambda_{\mathrm{FOW}_i}}\right)^{-1}. \tag{7}$$

2.2. Onsite replacement maintenance strategy

The Markov chain for the onsite replacement maintenance strategy is defined over a finite state-space $\Omega_{\mathrm{onsite}_i} = \{\mathrm{W}_i, \mathrm{F}_i, \mathrm{TRT}_i\}$ with transition rates $\delta_{\mathrm{onsite}_i}$ for each component i [44]. A major component remains in the W_i until a failure necessitating replacement occurs. Then, the major component remains in F_i until metocean conditions allow for the transit to the farm, the onsite replacement, and the transit-to-port (TRT). While differences may exist in how the replacement is performed between float-to-float and add-on crane solutions, all onsite solutions share the common aspect of TRT operations. The turbine returns to operation once the transit and onsite replacement are completed. In this respect, the availability of a component i is [44],

$$P_{W_i} = \frac{\omega_{\mathrm{onsite}_i} \cdot \mu_i \cdot \lambda_{\mathrm{FOW}_i}}{\mu_i \cdot \lambda^2_{\mathrm{FOW}_i} + \omega_{\mathrm{onsite}_i} \cdot \lambda^2_{FOW_i} + \omega_{\mathrm{onsite}_i} \cdot \mu_i \cdot \lambda_{\mathrm{FOW}_i}}, \tag{8}$$

where $\omega_{\mathrm{onsite}_i}$ is the waiting transition rate for onsite replacement strategy computed in the accessibility submodel as a function of the required WW, the operational limits of the vessels, and the metocean conditions.

3. Case study

This section defines the case study to which the computationally-efficient O&M model described in Section 2 is applied for the evaluation of heavy maintenance strategies. To that end, the geographical area, the FOW technology, and details regarding vessels and ports are defined.

Heavy maintenance strategies are evaluated in the North Sea where future FOW farms are expected to be built under the ScotWind auction, as represented in Fig. 5. In this sense, it is assumed that a FOW farm can be deployed at each grid point within this area of the North Sea. The metocean data consists of time-series on significant wave height (H_s) and wind speed (U_w) at a 100-metre height obtained from the ERA5 reanalysis for the European Centre for Medium Range Weather Forecasts [49]. The minimum time and spatial resolution of ERA5 are used, with an hourly measurement from 1990 to 2019, and a grid resolution of 0.25° in both longitude and latitude [49].

The FOW technology considered in this paper is the same as in the Kincardine FOW farm, consisting of V164-9.5 MW turbines mounted on semi-submersible platforms with four steel chains, each anchored with drag-embedment anchors [42]. Concerning the turbine specifications, the V164-9.5 MW incorporates a permanent magnet generator with a medium-speed gearbox [50]. The disconnection and reconnection operations of the semi-submersible FOW turbines under consideration are estimated to require one day each operation [31].

The rate of replacing major components of FOW turbines is currently unknown. Furthermore, reliability data from past and current

Table 2
Failure rates and replacement duration for semi-submersible FOW turbine with gearbox obtained from Carrol et al. [19], Jenkins et al. [23], and Rinaldi et al. [42].

		Blades	Gearbox	Generator	Pitch Sys.	MCR rate $\lambda_{MCR} = \sum_{i=1}^{4} \lambda_i$
BFOW	λ_i : Component replacement rate [replacements/year] [19]	0.001	0.154	0.095	0.001	0.251
	$P_i = \lambda_i/\lambda_{MCR_{BFOW}}$ [%]	0.40	61.35	37.85	0.40	100
FOW: semi-submersible and with gearbox	$\lambda_{FOW_i} = P_i \cdot \lambda_{MCR_{FOW}}$: Component replacement rate [replacements/year]	0.0007	0.1090	0.0670	0.0007	0.1770
	Replacement durations [h] [42]	31.25	44.50	67	89	–

BFOW and FOW: Bottom-Fixed Offshore Wind and Floating Offshore Wind.
MCR: Major Component Replacement.

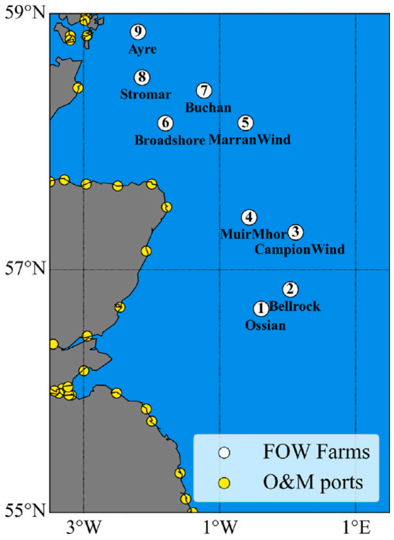


Fig. 5. Representation of the studied area in the North Sea with projected Scotwind farms and considered O&M ports.

Table 3
Characteristics of maintenance vessels [44,52].

	HLV	AHTS
Vessel speed [knots]:		
- Transit	12.5	10
- Towing with turbine	–	4
H_s limit [m]	1.5	2
U_w limit [m/s]	15	15

generations of wind turbines are scarce [23]. To the best of the authors' knowledge, the only available reliability data on replacement rates are those published by Carroll et al. [19], which are based on approximately 350 BFOW turbines with a rated capacity ranging between 2 and 4 MW, as presented in Table 2. Nevertheless, significant developments in offshore turbine technology have occurred since these first-generation turbines. In this context, Jenkins et al. [23] estimate the major replacement rates for 15 MW fixed foundation and semi-submersible FOW turbines based on [19] and a structured expert elicitation approach. The overall major replacement rate for semi-submersible FOW turbines with medium-speed gearboxes is estimated to be 0.177 replacements per year at the 95th percentile [23]. However, more details on the expected replacement rates of the individual components for FOW are not provided in [23]. In this paper, the individual component replacement rates for FOW turbines are estimated by considering the component replacement probabilities (P_i) for BFOW turbines computed according to [19] and based on the overall estimate provided by [23], as shown in Table 2. The replacement durations of these individual major components are obtained from [42].

The main characteristics of HLVs and AHTS vessels are detailed in Table 3. Operational limits for performing replacements depend on the specific capabilities of the vessels and are typically constrained by the H_s and U_w values [48]. In this context, based on existing experience in towing FOW turbines, the H_s limit of the AHTS can be defined as 2 metres [42,51]. However, determining the operational limits for onsite solutions is challenging, especially given the low TRL of these solutions. Therefore, considering that major component replacements for BFOW turbines with conventional HLVs are typically restricted to a H_s limit of 1.5 metres and a U_w limit of 15 metres per second, it seems reasonable to assume, the same operational limits for FOW turbines. In this sense, different values of the H_s limit are evaluated in Section 4 to assess their potential implications.

The O&M ports have been identified using the World Port Index [53], which are marked with yellow dots in Fig. 5. For each grid point representing a potential FOW farm, the closest port is selected based on Haversine distances [21]. Factors such as water depth, space, quaysides, and cranes may also have a significant impact on the selection of maintenance ports. However, given the large number of FOW farms analysed in this study and the lack of precise data for each port, conducting a comprehensive evaluation of all these factors is beyond the scope of this paper. Therefore, only distance is taken into account for port selection. The same ports are considered for the towing and onsite strategies, ensuring that port selection is not the differentiating factor in the comparison. In this context, full availability of vessels, technicians, and spare parts is assumed for both towing and onsite strategies.

4. Results and discussion

The evaluation of heavy maintenance strategies initially focuses on a specific FOW farm. Subsequently, the evaluation is expanded to encompass the studied area in the North Sea. Finally, the assessment focuses on determining the preferred heavy maintenance strategy in ScotWind farms.

4.1. Influence of replacement duration

To evaluate the influence of replacement durations on heavy maintenance strategies, Fig. 6 illustrates the reduction in turbine availability

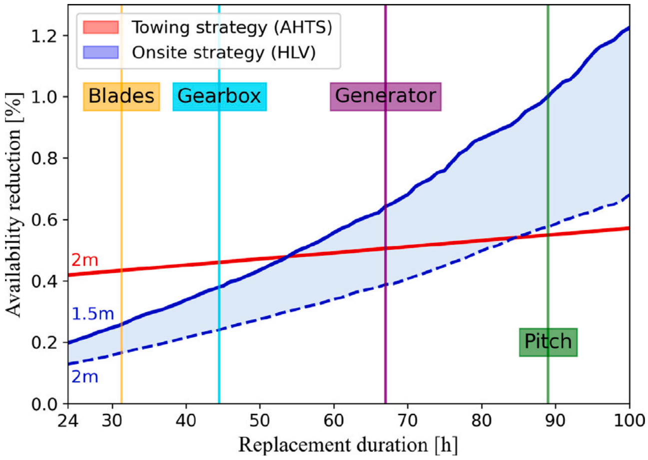


Fig. 6. Evaluation of steady-state turbine availability reduction as a function of heavy maintenance strategy, replacement duration, and operational limits of vessels at Ossian wind farm.

for both towing and on-site strategies at the Ossian wind farm. The assessment considers a replacement rate of 0.177 per year based on [23], covering replacement durations ranging from 24 h to 100 h. In this regard, the average replacement durations for blades, gearbox, generator, and pitch and hydraulic system are depicted in Fig. 6. Additionally, the impact of varying the H_s operational limit from 1.5 metres to 2 metres on turbine availability for the onsite strategy is also evaluated in Fig. 6.

Turbine availability decreases with both heavy maintenance strategies as the duration of replacement increases, reaching up to 1% reduction in the worst case scenario as shown in Fig. 6. This correlation is evident as downtime increases when it takes longer to replace a component. However, the availability reduction is more pronounced for the onsite strategy compared to the towing strategy, mainly because the required WW depends directly on the replacement duration. As the replacement duration increases, the number of available WWs decreases resulting in delayed maintenance activities, and consequently, increasing turbine downtime. The decline in turbine availability is more noticeable with a 1.5-metre operational limit compared to the 2-metre limit, because the WW requirement becomes more demanding with lower operational limits. In contrast, for the towing strategy, the number of available WWs remains unaffected by replacement duration since replacements are conducted at port. The reduction in availability with the towing strategy is only due to longer replacement times once the turbine is at the port.

The preference for the onsite strategy is evident in replacement operations that can be completed relatively quickly, such as blades and gearbox, as illustrated in Fig. 6. For longer replacement operations, such as generator and pitch and hydraulic system replacements, the preferable strategy depends on the operational limit allowed by the HLV. If the operational limit of the HLV is 1.5 metres, the towing strategy becomes preferable for replacement durations exceeding 54 h. In that case, the towing strategy is preferable for both the generator and the pitch and hydraulic system replacements. If the operational limit of the HLV is 2 metres, the towing strategy becomes preferable for replacement durations exceeding 85 h. In that scenario, the onsite strategy is preferable for the generator replacement, while towing is preferable for the pitch and hydraulic system replacement.

4.2. Evaluation expanded to the ScotWind farms

The evaluation of heavy maintenance strategies is expanded to the northern area of the North Sea in Fig. 7. For each grid point in the studied area, turbine availability is computed through the O&M model, considering both the towing strategy and the onsite strategy. Evaluations are conducted for replacement durations of 67, 80, and 89 h, thereby encompassing the replacement needs for both the generator and pitch and hydraulic system components. If the turbine availability is higher with the towing strategy, the gridpoint is marked in red; whereas, the blue colour indicates a preference for the onsite strategy. The percentage values in Fig. 7 represent the proportion of the area where each strategy is preferable relative to the total area studied.

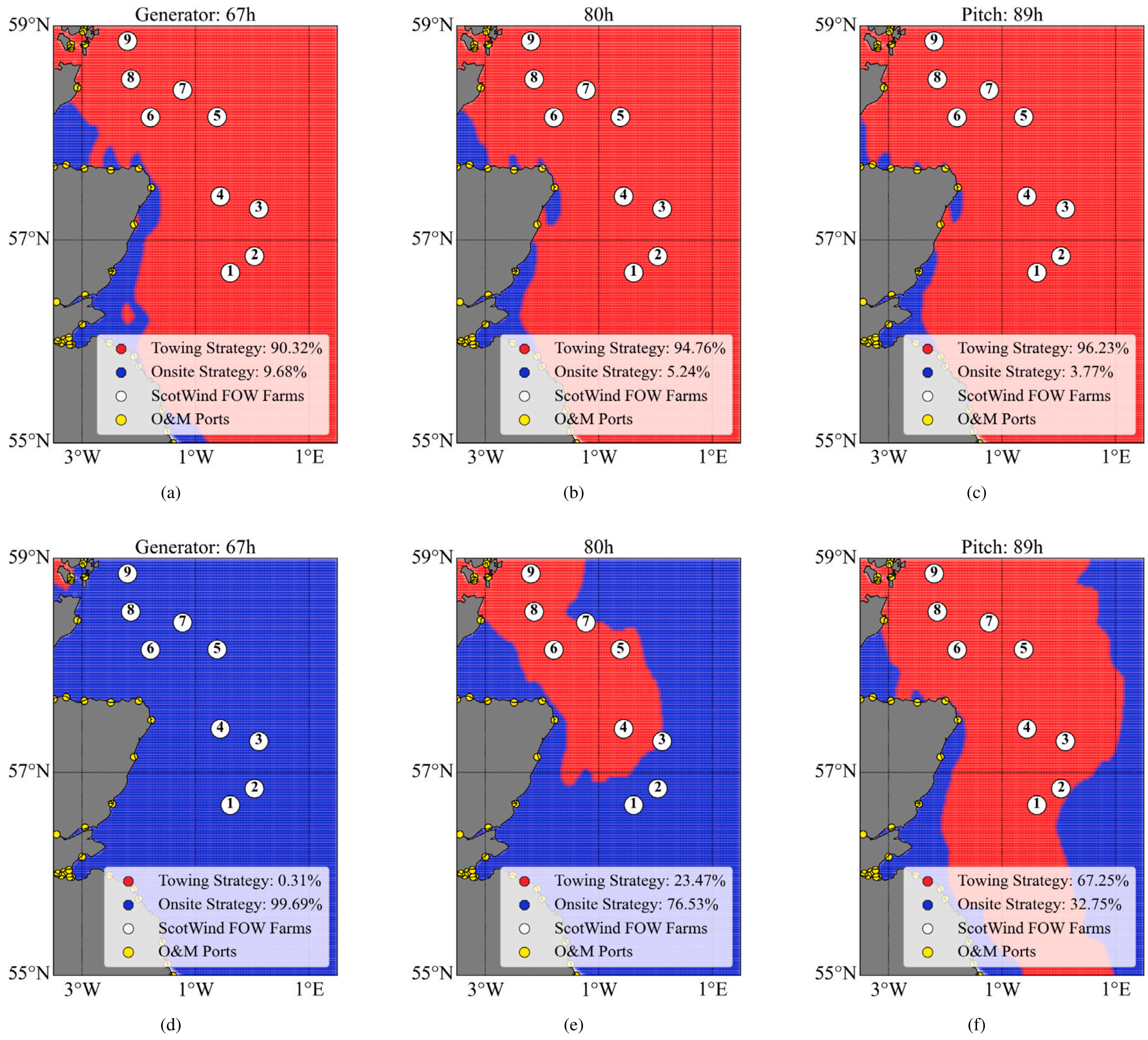
The preference observed for each heavy maintenance strategy at the Ossian wind farm ('1' in Fig. 5), regarding generator and pitch and hydraulic system replacements, remains consistent across the other farms, as illustrated in Figs. 7(a), 7(c), 7(d), and 7(f). Consequently, when considering onsite replacement for generator or pitch and hydraulic system in the ScotWind area, it is crucial to design onsite solutions that facilitate operations with operational limits greater than 1.5 metres. For shorter replacement durations, such as blades and the gearbox, the onsite strategy remains preferable across the other farms as in the Ossian wind farm, even with a 1.5 metre operational limit, as illustrated in Fig. C.9 in Appendix C. Furthermore, Fig. 7 also shows that the preference for maintenance strategies may vary across the ScotWind area. For instance, when the replacement duration is 80 h and the operational limit of HLV is considered to be 2 metres, the onsite strategy is preferred for Ossian, Bellrock, and CampionWind farms, whereas the towing strategy is favoured for the other farms, as illustrated in Fig. 7(e). These differences between farms arise because the port distance is greater for Ossian, Bellrock and CampionWind compared to the other farms, as shown in Table B.4. At longer distances, the onsite strategy gains relatively greater preference over the towing strategy, as represented in Fig. 7(f). Larger towing distances with low towing speeds significantly reduce available WWs, thus increasing turbine downtime.

4.3. Discussion on mixed heavy maintenance strategy

With the operational limit of the HLV set at 1.5 metres, Figs. 6 and 7 suggest that the most beneficial heavy maintenance approach involves a mixed strategy. The mixed maintenance strategy consists of onsite maintenance for the blades and gearbox, and towing for the generator, and pitch and hydraulic system. Fig. 8 compares the mixed strategy with fully onsite and fully towing strategies in terms of turbine availability. The fully onsite strategy denotes the use of the onsite solution exclusively for all major components, while the fully towing strategy involves employing the towing strategy only. The results shown in Fig. 8 demonstrate that the mixed strategy achieves the lowest turbine availability reduction, followed by fully towing and fully onsite, with average availability reduction values of 0.39%, 0.43%, and 0.46%, respectively across ScotWind farms.

The results shown in this section demonstrate that the assumption regarding onsite replacement solutions, which offer the "potential to reduce turbine downtime", is accurate. However, this assumption is true only under certain conditions. The onsite strategy has the potential to reduce turbine downtime in shorter replacement durations, such as blades and gearbox replacements. In longer replacement durations, the results demonstrate that the towing strategy may be preferable to the onsite strategy. In this context, the results in Fig. 8 demonstrate that it is even better in terms of turbine downtime to carry out all major component replacements in ScotWind farms by towing than by onsite solutions.

Nevertheless, it should be noted that when heavy maintenance is required on a specific FOW farm within the ScotWind area, the decision on the heavy maintenance strategy will not be based solely on the turbine availability indicator. Factors such as cost, precise port characteristics, vessel availability and spare parts will also be taken into account at that particular moment. In some cases, these factors may favour the towing strategy, while in others they may tend to prefer the



(a) (b) (c)

(d) (e) (f)

Fig. 7. Heavy maintenance strategy evaluation for different replacement times and operational limits of HLV: (a) $H_{s_{lim}} = 1.5$ m, (b) $H_{s_{lim}} = 1.5$ m, (c) $H_{s_{lim}} = 1.5$ m, (d) $H_{s_{lim}} = 2$ m, (e) $H_{s_{lim}} = 2$ m, (f) $H_{s_{lim}} = 2$ m.

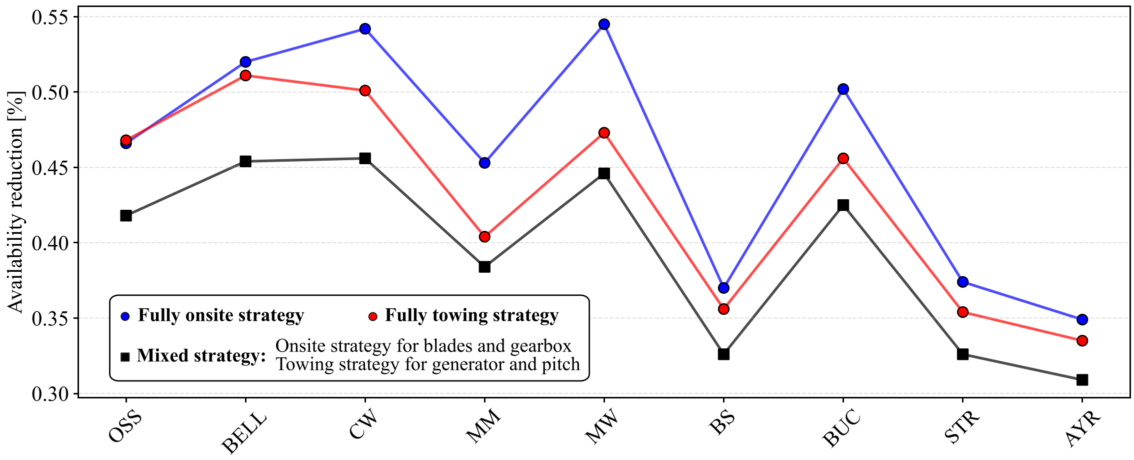


Fig. 8. The steady-state turbine availability in ScotWind farms (detailed in Table B.4) following three heavy maintenance strategies: the blue line represents the onsite strategy for all major components, the red line indicates the adoption of a towing strategy for all major components, the black line represents the mixed heavy maintenance strategy. Note that the onsite operations refer to the blades and gearbox, while the towing strategy considers the generator, and pitch and hydraulic system.

onsite strategy. Future research will further explore the influence of these factors on the decisions about the heavy maintenance strategy.

Therefore, beyond the quantitative assessment and the suggestion to perform a mixed heavy maintenance strategy, the qualitative results are more important. In this context, the authors observe that onsite replacement solutions can be more appropriate for shorter replacement durations in terms of turbine downtime, while the towing strategy may be more suitable for lengthier replacement durations.

5. Conclusion

This paper presents the first comparative study of heavy maintenance towing and onsite replacement strategies for floating offshore wind turbines. To that end, the towing maintenance strategy is characterised by a Markov chain and implemented within a computationally-efficient operation and maintenance (O&M) model. This Markov chain articulates all the key phases of the towing strategy, including transit-to-site, turbine disconnection, towing-to-port, component replacement, towing-to-site, turbine connection, and transit-to-port.

The evaluation of towing and onsite replacement maintenance strategies is conducted through an O&M model in terms of turbine availability across the ScotWind area in the North Sea. Novel results from this paper demonstrate that onsite replacement solutions have the potential to reduce turbine downtime, but this relies on (i) the replacement duration of the component and (ii) the operational limits for performing onsite solutions.

The preference for the heavy maintenance strategy varies depending on whether it involves blades, gearbox, generator, or pitch and hydraulic system, with replacement durations of 31.25, 44.5, 67, and 89 h, respectively. Additionally, it also depends on whether the onsite solutions currently under development have the capacity to operate within traditionally established operational limits for bottom-fixed offshore wind replacements, set at 1.5 metres of significant wave height (H_s) or higher limits. The results of this paper show that in ScotWind farms:

- The onsite strategy is preferable in replacement operations that can be completed relatively quickly, such as blades and gearbox replacements. This preference for the onsite strategy remains consistent across ScotWind farms even for the most demanding operational limit for H_s of 1.5 metres.
- For the onsite replacement strategy to be preferable for longer replacement durations, such as generator and pitch and hydraulic system, it is crucial to design onsite solutions that facilitate H_s operational limits greater than 1.5 metres. Specifically, for generator replacements, the onsite solution proves more advantageous than the towing strategy only if vessels with a H_s operational limit of 2 metres are available.
- A mixed heavy maintenance strategy, involving onsite replacements for the blades and gearbox, and towing for the generator and pitch and hydraulic system, emerges as the most beneficial heavy maintenance approach with vessels with operational limit of 1.5 metres for onsite solutions. The mixed strategy achieves the lowest turbine availability reduction, followed by fully towing and fully onsite, with average availability reduction values across ScotWind farms of 0.39%, 0.43%, and 0.46%, respectively.

It should be noted that assuming the same operational limits for onsite solutions for floating offshore wind and bottom-fixed offshore wind turbines, *i.e.* an operating limit of 1.5 metres for heavy lift vessel (HLV), may be an optimistic scenario. It is likely that the increasing size of FOW turbines will add significant complexity to lifting operations, increasing the stability requirements and, thus, reducing operational limits. Furthermore, the precise replacement rates for FOW turbines are currently unknown. Accordingly, conducting extensive sensitivity analyses on the operational limits of HLVs and major component replacement rates is crucial for evaluating their impact on maintenance strategies.

Consequently, the results of this paper highlight that turbine downtime is not always higher with the towing strategy compared to the onsite replacement strategy. In this context, as more of these towing operations are executed, there will be a clearer understanding of the infrastructure and supply chain requirements for the towing strategy to ensure minimal downtime. This is expected, as the towing strategy currently represents the only available heavy maintenance alternative. However, this does not mean that onsite replacements should disregarded in the future, as the outcomes of this paper also demonstrate their significant potential for downtime reduction. In this sense, the findings of this study hold significance for vessel manufacturers and stakeholders involved in onsite solutions, as the operational limits of the vessels play a crucial role in minimising turbine downtime and are factored into maintenance contracts.

As the evaluation of major maintenance strategies is carried out in terms of turbine downtime due to the limited availability of the cost information, future research will explore the techno-economic aspects to provide a more comprehensive assessment of these strategies. Furthermore, future work should include a comprehensive analysis on the impact of the inherent variability and uncertainty of the metocean data, as suggested in [54].

CRediT authorship contribution statement

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

Abbrev.	Description
FOW	Floating Offshore Wind
O&M	Operation and Maintenance
BFOW	Bottom-Fixed Offshore Wind
AHTS	Anchor Handling Tug Supply
HLV	Heavy Lift Vessel
TRL	Technology Readiness Level
TDT	Transit, Disconnection and Towing
TCT	Transit, Connection and Towing
MCR	Major Component Replacement
WW	Weather Window

Symbols	Description
A_{turb}	Turbine average availability [·]
P_{W_i}	Availability of each turbine component [·]
N_c	Number of components of each turbine [·]
Ω_{tow_i}	Markov state space for towing strategy [·]
W_i	Working state [·]
F_i	Failed state [·]
TDT	Transit, disconnection and towing state [·]
RP_i	Component replacing state [·]
WP	Waiting in the port state [·]
TCT	Towing, connection and transit state [·]
λ_{FOW_i}	Failure/Replacement rate [h^{-1}]
ω_{tow_1}	Waiting rate 1 [h^{-1}]
α	Transit, disconnection and towing rate [h^{-1}]
μ_i	Replacement rate [h^{-1}]
ω_{tow_2}	Waiting rate 2 [h^{-1}]
β	Towing and connection rate [h^{-1}]
$MTTF_i$	Mean time to failure of component i [h]
$MTTW_{\mathrm{WW}_1}$	Mean time to wait weather window 1 [h]
$MTTDT$	Mean time to transit, disconnect and tow [h]
t_{replace_i}	Mean time to replace component i [h]
$MTTW_{\mathrm{WW}_2}$	Mean time to wait weather window 2 [h]
$MTTC$	Mean time to transit and connect [h]
t_{transit}	Required time from port to farm [h]
$t_{\text{disconnect}}$	Required time for disconnecting turbine [h]
t_{tow}	Required time from port to farm with turbine [h]
t_{connect}	Required time for connecting turbine [h]
P_{TCT_i}	TCT steady-state probability per unit of time [·]
P_{WP_i}	WP steady-state probability per unit of time [·]
P_{RP_i}	RP steady-state probability per unit of time [·]
P_{TDT_i}	TDT steady-state probability per unit of time [·]
P_{F_i}	Failed steady-state probability per unit of time [·]
P_{W_i}	Working steady-state probability per unit of time [·]
Ω_{onsite_i}	Markov state space for onsite strategy [·]
TRT	Transit, replacement and transit state [·]
ω_{onsite_i}	Waiting rate for onsite replacement [h^{-1}]
H_s	Significant wave height [m]
U_w	Wind speed [m/s]
P_i	Replacement probability for a major component i [·]

Appendix B. Farm characteristics

See Table B.4.

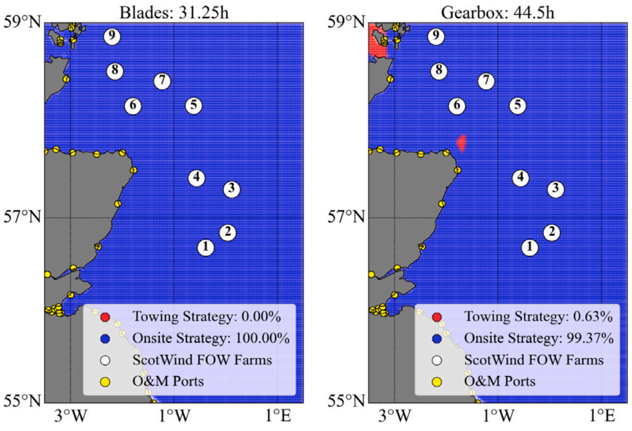
Table B.4
Main information the selected floating offshore wind farms in the North Sea and the Iberian Peninsula [12,55].

Farm name	Lat.	Long.	Port name	To port [mi]
Ossian (OSS)	56.69°N	0.39°W	Aberdeen	71.3
Bellrock (BELL)	56.85°N	0.04°E	Peterhead	81.79
CampionWind (CW)	57.30°N	0.11°E	Peterhead	71.97
MuirMhor (MM)	57.42°N	0.57°W	Peterhead	45.51
MarranWind (MW)	58.16°N	0.62°W	Fraserburgh	60.39
Broadshore (BS)	58.16°N	1.80°W	Fraserburgh	33.74
Buchan (BUC)	58.41°N	1.23°W	Fraserburgh	57.65
Stromar (STR)	58.51°N	2.15°W	Wick	34.36
Ayre (AYR)	58.86°N	2.20°W	St Margarets	26.88

Note 1: In establishing maintenance ports for each floating offshore wind farm, distances to all ports defined in the World Port Index (NGA WPI) were initially computed. Following this, the closest port was selected for each farm.

Appendix C. Heavy maintenance strategy evaluation for Blades and Gearbox

See Fig. C.9.



(a) (b)

Fig. C.9. Heavy maintenance strategy evaluation for HLV operational limit of $H_{s_{lim}} = 1.5$ m for: (a) Blades, and (b) Gearbox.

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