Adaptations of Offshore Wind Operation and Maintenance Models for Floating Wind

Saeed, Kaiser; McMorland, Jade; Collu, Maurizio; Coraddu, Andrea; Carroll, James; McMillan, David

DOI
10.1088/1742-6596/2362/1/012036

Publication date
2022

Document Version
Final published version

Published in
Journal of Physics: Conference Series

Citation (APA)
Saeed, K., McMorland, J., Collu, M., Coraddu, A., Carroll, J., & McMillan, D. (2022). Adaptations of Offshore Wind Operation and Maintenance Models for Floating Wind. *Journal of Physics: Conference Series*, *2362*(1), Article 012036. https://doi.org/10.1088/1742-6596/2362/1/012036

Journal of Physics: Conference Series

Adaptations of Offshore Wind Operation and Maintenance Models for Floating Wind

To cite this article: Kaiser Saeed *et al* 2022 *J. Phys.: Conf. Ser.* **2362** 012036

EERA DeepWind Offshore Wind R&D Conference IOP Publishing
Journal of Physics: Conference Series **2362** (2022) 012036 doi:10.1088/1742-6596/2362/1/012036

Adaptations of Offshore Wind Operation and Maintenance Models for Floating Wind

Kaiser Saeed[1], Jade McMorland[1], Maurizio Collu[1], Andrea Coraddu[2], James Carroll[1] and David McMillan[1]

[1]University of Strathclyde, UK; [2]TU Delft, Netherlands

Email: kaiser.saeed@strath.ac.uk, jade.mcmorland@strath.ac.uk

Abstract: This paper presents the key operations & maintenance (O&M) modelling inputs for fixed-bottom wind (FBW) and highlights the adaptations required for floating offshore wind (FOW) uses. The work also highlights major repair strategies such as tow to shore (T2S) and discusses the limitations and constraints which arise in an operational context. The technical and economic feasibility of such O&M strategies requires rethinking of weather risks and constraints, new vessel technologies and operational costs. The work also collates and reviews existing FBW models which have been adapted for FOW uses and analyses O&M inputs for a tow to shore operation. Findings show that there is ambiguity in literature for tug speeds and disconnection/reconnection times of the turbine system. A performed case study investigates the sensitives of both parameters through a weather window analysis of ScotWind sites. Recommendations for future practises, including additional O&M modelling considerations and inputs for FOW uses are given.

1. Introduction

In 2020 the UK government committed to achieving Net-Zero by 2050 [1]. This has led to a surge in the development and operation of renewable energy, particularly in the offshore wind sector. FBW has seen a major cost reduction in the government's latest 2019 Contract for Difference, awarding strike prices below the wholesale value of electricity. However, the offshore wind industry now faces a new set of challenges as it moves further from shore and into deeper waters.

One solution to overcome these challenges is floating offshore wind (FOW), which minimizes the environmental impacts associated with traditional FBW. Almost all factors that deem a site suitable for FBW also apply to FOW, with the main differentiator being ocean bathymetry. In 2020, the Carbon Trust estimated that globally up to 10.7 GW of floating wind are feasible by 2030, and almost 70 GW by 2040 [2]. The 2022 ScotWind leasing round has vastly accelerated progress towards these goals by awarding 11 floating wind projects with a total capacity of 15 GW in Scottish waters.

Operations and maintenance (O&M) may account for up to 30% of the lifetime cost of a FBW farm [3]. Levelised cost of energy for FBW sites have decreased 28-49% from 2014 to 2019 due to economies of scale, maturing of the industry, and improved operational efficiency [4]. Accurate O&M projections are becoming more important throughout the project lifecycle and are vital when preparing bids for auction. Once a windfarm is commissioned, O&M remains one of few areas where significant costs and innovation can occur throughout the project lifecycle.

Creating a functional O&M model requires extensive time, investment, and expertise. The operational aspects of FBW and FOW are relatively similar, with their main differences being in maintenance strategies, specifically for major repair scenarios. The use of a floating substructure in place of a fixed-bottom foundation opens the door for a new heavy-lift maintenance strategy such as tow-to-shore (T2S), which raises questions such as “How adaptable are existing O&M models for floating wind uses?” and “Which specific adaptations need to be implemented?” Until recently, these questions have been given very little attention as the focus of literature has mainly been on the design of FOW turbine.

While this Section introduced the topic, Section 2 highlights key operational inputs (e.g., failure rates, weather parameters, and maintenance vessels) used in FBW O&M models and discusses them in a FOW context. Section 3 highlights major repair strategies such as T2S, examines the respective limitations for deployment, and presents existing T2S model inputs for tug speeds and disconnection/reconnection times. Section 4 reviews the current body of literature and presents FBW O&M models adapted for FOW uses. In Section 5, a case study investigates the sensitivities T2S inputs through a weather window analysis based on ScotWind sites. Finally, Section 6 makes recommendations for further work and highlights the importance of accurate model adaptations.

2. O&M Modelling Inputs

Existing O&M models and tools specifically developed for the offshore wind industry are based on a combination of risk analysis, uncertainty analysis, and reliability engineering to model the relationship between availability, maintenance strategies, and operational costs while also accounting for weather variations. Here, the inputs for these models are grouped into five main modules: met-ocean weather, failure rates, vessel data, resources, and general operational costs [5]. For FOW uses, elements such as operational costs only require changes to the inputs, whereas others require more in-depth changes to the modelling logic. Once developed, such tools allow for accurate long-term logistical planning, forecasting asset availability, and estimating lifetime OpEx costs of projects.

2.1. Failure Module

One widely accepted classification of failure types is presented in [6], outlining how minor repairs, major repairs, major replacements, and annual service are associated to the severity of a failure. Each of them is assigned a failure rate and average repair time, which, in turn, is used to simulate a failure and associated maintenance action.

In the offshore wind industry, wind turbines are increasing in size year-over-year to maximize energy capture and lower the cost of energy. This trend is expected to continue with the deployment of FOW, deploying turbines rated as high as 15MW in coming years [7]. In parallel, the drivetrain configurations used in next generation wind turbines are moving from 3-stage gearboxes or induction generators to direct-drive or medium-speed configurations that contain permanent magnet synchronous generators. To date, failure data are very limited for offshore turbines as developers and manufacturers are hesitant to release such information into the public domain. Additionally, generalized failure data and repair times which are currently available may not be suitable for O&M modelling of next generation multi-MW turbines. Failure data for additional components such as the substructure and mooring lines are also required for FOW uses because the turbine is floating. Detailed expert elicitation and/or extrapolation from existing failure data is required to obtain suitable failure data to assess the reliability of these next generation turbines.

Depending on the chosen maintenance strategy (e.g. in-situ or portside) the time required to carry out a maintenance task is expected to vary. Due to harsh offshore conditions and the induced dynamic motions of the floater, it can be assumed that an in-situ major component replacement would take significantly longer in comparison to portside maintenance where maintenance would be performed in a more controlled environment.

2.2. Weather Parameters

Due to the far offshore nature of FOW deployment, the met-ocean conditions are expected to be more severe and to have a larger variability in comparison to an equivalent FBW site. Accessibility to the site is typically limited by significant wave height (H_s) and wind speed. These weather parameters are commonly used to represent met-ocean conditions for all offshore installation- and maintenance-related tasks. The limiting weather values are typically dependent on the respective maintenance vessel and its capabilities.

There has been relatively little use of a peak wave period (T_p) parameter, which is generally used only to evaluate motions during the installation phase of a turbine. For this reason, many O&M tools do not consider T_p in assessing weather windows and windfarm accessibility. For FOW, the use of T_p is vital due to the floating nature of the turbine. Such a parameter would allow the motions of both the FOW turbine substructure and repair vessels to be characterised to ensure safe maintenance operations and crew transfers. The flexible nature of a FOW turbine substructure incurs significantly larger dynamic responses when compared to a traditional fixed bottom wind turbine FBW turbine, as the substructure is not rigidly connected to the seabed in any of the 6 degrees of freedom.

On-site floating-to-floating repairs will require specialized heavy-lift vessels (HLVs). This is expected to incur significant multibody interactions between the floating substructure and the maintenance vessel. In these cases, the hydrodynamic interactions which arise due to the proximity of the turbine and repair vessel have a significant impact on the hydrodynamic loads, motions and response of each floating body

In [8,9] where the dynamic responses of FOW turbines are investigated, the authors suggest that weather criteria's which are normally used to assess weather windows and accessibility for maintenance operations of FBW are no longer adequate for FOW, and may require adjustments that consider the dynamic motion response of the floating structure.

2.3. Maintenance Vessels

The vessels most commonly used for maintaining FBW turbines are the crew transport vessel (CTV), service operation vessel (SOV) and the jack-up vessel (JUV). CTVs and SOVs are typically used for minor repair scenarios, whereas the JUV is used for heavy-lift maintenance of components, e.g. blade or gearbox replacements. For each of the required vessels, values for weather limits, mobilisation times, availability, and charter rate costs are required to model a repair process. Individual limits of significant wave height and wind speed for different vessel types along with the local met-ocean conditions are used to evaluate the accessibility of a site [10]. H_s limits are generally between 1.5 to 3m depending on the required vessel [11], and are used to simulate the transit between the deployment port and turbine. Wind speed limits are generally 12 m/s for the safe hoisting of turbine components between vessel and turbine.

CTV and SOV vessels are expected to be utilised for minor maintenance actions of FOW turbines. The fleet configuration will be determined by site conditions such as distance-to-shore and general met-ocean conditions. In addition to these conventional vessels, FOW sites may also require additional support from tugboats and anchor handling tug supply vessels (AHTSV) to assist with major component replacement strategies such as T2S or towing to sheltered waters. JUVs are currently unsuitable for major component replacements due to their limiting water depth; however, the tow to sheltered waters strategy may still require these vessels as part of the maintenance campaign.

In the past, vessel weather constraints have been the limiting factor for turbine accessibility. However, due to turbine motion, turbine workability constraints may replace vessel limits and be a key factor to influence a repair/no repair decision.

3. FOW O&M Strategies & Limitations

Major repair strategies for FOW are clustered into two groups, *in-situ* and *ex-situ*, depending on whether the operation is conducted offshore or portside. Each of the O&M strategies and their respective operational constraints are discussed, while these constraints may not appear as direct inputs into O&M models, they do indirectly impact O&M processes therefore are an important matter of discussion.

3.1. T2S Strategy

Assuming there is an appropriate weather window, the turbine is shutdown, disconnected from both the electrical mooring system, and towed back to shore for portside maintenance. Once maintenance is complete, the turbine is returned to the offshore site, reconnected and recommissioned.

As previously discussed, the T2S strategy is favoured in terms of cost effectiveness as it negates the use of an expensive JUV which also incurs significant waiting times. Instead, the strategy primarily relies on the use of readily available and inexpensive tugboats as well as AHTSVs for the initial towing and reverse procedure. For the T2S strategy to be viable, significantly longer weather windows are required for the maintenance procedure due to the disconnection, towing, reverse towing, and reconnection phases of the operation. As it stands, the associated costs, time, and manpower required for these phases are unknown or at best speculative.

In May 2022, it was reported that a turbine in the 50MW Kincardine Floating Offshore Wind Farm had suffered a failure and requires a major component replacement. The turbine is expected to be disconnected from the array and towed to an undisclosed location [12], a first for the deployment of the T2S strategy in an O&M context and a significant learning opportunity for the FOW community.

3.1.1. Distance to Shore & Towing Speed Constraints

An influential factor to define the most optimal strategy for a major component repair is the distance to shore. Too large of a distance would incur longer waiting times for an appropriate weather window for towing and result in increased wind turbine downtime. In such a case, the cost benefit of deploying a T2S strategy would be lost, and an alternate O&M strategy would become more economically viable.

As the T2S strategy has not yet been executed, there are currently no widely accepted operational values to reference. Current literature provides a wide range of tug speeds [13-18], ranging from 1.86 knots to 10 knots. The spread in reported values is shown in Figure 1. The examples in existing works only present a single speed for a tugboat, whereas accurate O&M modelling of the T2S strategy would require two speeds—the transit speed and towing speed. Depending on site conditions along the towing route and the floater type, the tugging speed may vary greatly, potentially requiring significantly longer weather windows for the tow-out and reverse phase of the T2S strategy.

In [16], a sensitivity analysis based on distance to shore concludes that for a semi-sub and tension-leg platform (TLP) floater, the T2S strategy is the most cost-effective option, whereas for a spar floater an onsite repair strategy would be more financially feasible. This is because as towing speeds for a Spar floater are 66% lower in when compared to a semi-sub or TLP counterpart.

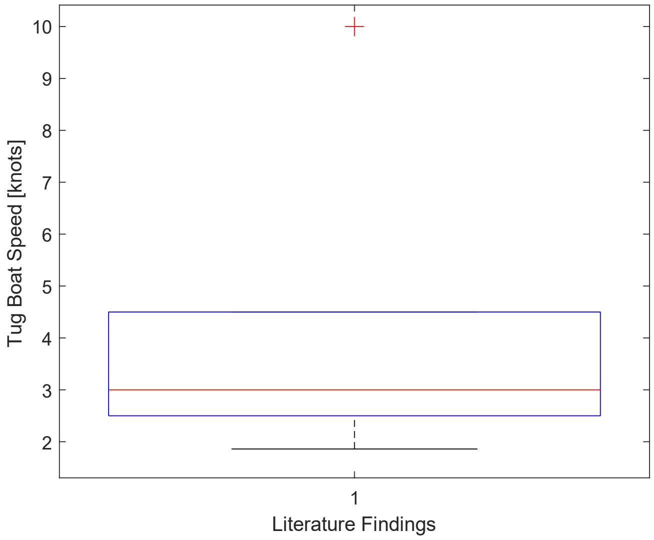

Figure 1. Range of tugboat speeds for T2S operations [13-18].

3.1.2. Port Capability & Availability

The three most widely accepted floater types for FOW deployment are the semi-sub, spar, and TLP floater. Both the semi-submersible and TLP floaters consist of a shallower draft when compared to a spar floater where the draft is elongated and deep. For this reason, and the significantly slower transit speeds previously discussed, it is expected that for a spar floater, heavy-lift maintenance will be carried out onsite rather than portside.

If portside maintenance is performed, the port must have the same facilities and capabilities as a JUV which would perform the same operations, such as a heavy lift crane. In addition to facilities, port-side maintenance operations will be highly dependent on other port users. It is expected that FOW sites within close proximity to each other will utilise the same ports; therefore, this could create bottlenecks in the maintenance process if all sites experience major component replacements within a small timeframe of each other.

Finally, for some ports, the inclusion of additional weather parameters may apply. It is expected that wind speed will continue to limit lifting operations, such as blade replacement. Tidal considerations may also impact the T2S strategy, as if a site is particularly tidal, then this requirement will need to be included within the weather window calculations.

3.1.3. Disconnection & Reconnection

An important aspect of the T2S strategy is the disconnection and reconnection of the turbine from the mooring and electrical system. The current body of literature exhibits a distinct gap and lack of agreement regarding this process due to the infancy of this technology. Nonetheless, values from literature concerning the time required for the disconnection process are collected from [19-21], varying from 1 to 64 hours for the process. These findings are presented in Figure 2.

In an operational scenario, differing combinations of floater type, mooring and electrical system design, as well as local site conditions would result in a variation of disconnection/reconnection times. However, the variation is not expected to range as drastically as the findings from literature show, the authors believe that the reason is due to the industry wide uncertainty of the disconnection process and infancy of the technology.

Like towing speed, disconnection and reconnection times have the potential to significantly affect the duration of required weather windows. In any case, the duration of a weather window would span from the start of the disconnection phase to the end of the towing phase when the FOW turbine would safely dock portside for maintenance.

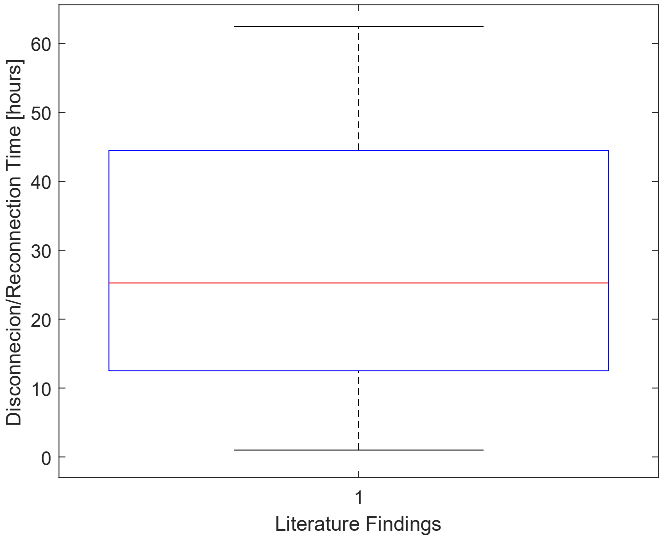

Figure 2. Disconnection/reconnection times of a turbine [19-21].

3.2. Tow to Sheltered Waters Strategy

This strategy involves towing the FOW turbine to a shallow and sheltered water offshore location for maintenance with a floating quay which allows temporary docking. In such a scenario, a JUV is used for heavy-lift maintenance as the water depth limit of 50m for the is not exceeded. Like the T2S strategy, this strategy ensures maintenance is carried out in a calmer and safer offshore environment with reduced turbine motions.

For sites where there is no suitable port infrastructure within viable proximity, this may be the only viable option. This may also be a credible solution for sites where the suitable port for T2S is oversubscribed due to a large number of offshore projects. This decision would require a cost benefit analysis of the cost of extended downtime waiting for a maintenance slot at port vs the additional cost of combined expense of building a temporary floating quay, chartering a JUV and the costs incurred in the towing process

3.3 In-situ Repair Strategies

This strategy requires a floating HLV to maintain the FOW turbine at the deployment site. Such floating-to-floating repairs in the offshore industry have only been performed extensively within the oil and gas sector. Like the JUV for FBW uses, it is expected that floating HLVs will incur high daily charter costs and incur long waiting times. As previously mentioned, a JUV is not a viable option for a heavy-lift repair of a FOW turbine as it is only capable of working in water depths up to 50m. One study in [22] shows that existing HLVs in the offshore industry do not have adequate lifting capabilities at nacelle heights (assuming a 10MW turbine). This will impact major component replacement operations for both FOW and FBW. Developers are currently working on the next generation of HLVs which are expected to be available in coming years to coincide with the first heavy-lift operations which will take place for FOW turbines.

A recently emerging alternative to floating HLVs is the use of temporary lifting crane systems which are attached to the turbine or substructure for maintenance. Such a system solves three major issues with floating HLVs for in-situ repairs; floating HLVs must be built to ensure hub heights of 120 metres above sea level are reached for next generation turbines, the induced relative motions between the turbine and maintenance vessel, and finally to manage swinging motions due to floater displacements.

Two concepts are being developed by Mammoet [23]. Firstly, a modular lifting system which is installed at the top of the FOW turbine generator where lifting is performed by winches at the base of the turbine. Secondly, a dedicated crane system which connects to the turbine tower as well as the nacelle and performs all lifting tasks within the turbine crane. Both lifting systems are temporary and can be disconnected and returned to shore after maintenance. Similarly, Dolfines is developing a temporary maintenance system that attaches to the FOW turbine substructure and perform heavy lifts. The main challenge with such novel technologies is to integrate the systems to ensure resulting loads do not harm the FOW turbine. In a joint study by Carbon Trust and Conbit [24], the estimated costs for the modular lifting solution for a heavy-lift component repair are 15-20% lower when compared to a portside maintenance strategy.

4. Review of Adapted Models for FOW

Despite the vast changes needed to effectively model the O&M for a floating structure, existing models have already been adapted, such as the ECN O&M Access Tool [13] and Rinaldi et al.'s model [19]. Both models have already seen use in commercial projects [13,21]. This Section discusses the changes made in these models in relation to the factors discussed in the prior Sections. Further details of existing literature surrounding FOW O&M modelling can be found in a review by McMorland et al. [25].

4.1. ECN Adapted Model

The ECN O&M Access Tool was originally developed for use in the offshore wind sector and has assisted operational projects over the past 15 years. The adaptation of this model was part of a case study exploring baseline scenarios for near-, mid-, and far-from shore sites. The floating site is modelled as Scenario E with a distance to shore of 20 km and a water depth of 200 m, consisting of 8 MW machines with a semi-sub substructure.

An SOV is used for all regular corrective and condition-based maintenance. This vessel strategy was selected due to its ability to provide floating-to-floating transfer. The SOV is restocked using a smaller feeder vessel for smaller components and spare parts. The modellers assumed that a T2S strategy would be used for all major repairs/replacements on parts exceeding three tons.

Limited detail is provided regarding the T2S process. It is stated that only the mooring lines are disconnected during the process. The author dos, however, provide extensive details of the towing vessel, such as towing speed (8-10 knots), H_s limit (1.5 m), mobilisation time, and cost of equipment. No further limits are imposed on transfer due to the motion of the turbine.

It was found that the site was more expensive than the two most similar fixed sites by 8-55% (sites A and B), across all chosen strategies. They cite the inclusion of human workability rates through linking of met-ocean conditions to vessel dynamics as an area of work for future projects [13].

4.2. Rinaldi et al. 2020

The tool used in the Rinaldi model was developed in 2016 for the proactive management of offshore wind farms [26]. Since then, the tool has been adapted for other offshore technologies, including wave and tidal energy converters. The aim of the adapted model is to determine the effectiveness of a T2S strategy in terms of OpEx, availability and total revenue.

This adapted model uses Westermost Rough as a case study, with a distance of 40 km from the port. The work models two T2S strategies for a FOW site and standard in-situ maintenance for a FBW site to provide a direct comparison. Weather data includes wave height, wind speed, current speed and wave period and are retrieved through the WAVEWATCH simulation tool at a three-hour resolution. Three kinds of vessels are used: CTV, FSV and HLV, which are limited by both wind and significant wave height. Met-ocean and vessel inputs are taken from Rinaldi et al.'s previous work [27].

In order to make a direct comparison between fixed and floating, it is assumed that the taxonomies used for fixed and floating structures are the same, despite the additional components of the substructure of the FOW turbine. It could also be argued that this work also directly compares a T2S and an *in-situ* maintenance strategy due to this assumption.

For the T2S strategy, the transit time during towing operation is 30% higher than normal operation. Weather limits are decreased by 70% during T2S for H_s, wind speed, and current speed. No limits are directly imposed on T_p; however, this parameter may be as important as H_s in terms of acceptable vessel motion. The T2S scenario is applied for major interventions only, for 8 of the 16 components. Disconnection and reconnection are set to one hour each, which is added to the total repair time at port. Results showed FOW was more costly than FBW; However, the discontinuous FOW T2S approach yielded the highest availability and energy delivered of the three scenarios.

4.3. Key Adaptations

A summary of the key model adaptations is given in Table 1. Rinaldi et al.'s model [19] used failure rates from Carroll et al. [6] for both fixed and floating. ECN [13] provided no detail of the rates used. Both models used the same weather inputs as their FBW dedicated models. However, Rinaldi [19] did provide details regarding the additional limitations of met-ocean conditions during towing. Further, the author used the same fleet of vessels as with previous work and ECN introduced a tug vessel and justified their decision to use an SOV due to the floating-to-floating transfer.

The most significant changes to both tools came from the addition of T2S. Both used varying methods to determine which failures resulted in port maintenance. However, T2S maintenance will be implemented for scenarios which would typically require a JUV. ECN assumed that during port maintenance, there will be no requirement for a weather window. Rinaldi provided two scenarios.

Table 1. Key adaptations made to Rinaldi [19] and ECN [13] O&M tools to accommodate floating turbines

			Tow to Shore			
	Met-Ocean	**Vessel**	**Strategy**	**Component**	**Limitations**	**Disconnection /Reconnection**
Rinaldi et al. [21]	H_s, Wind Speed, Tp	CTV, FSV[1], HLV	Continuous[*] Discontinuous[**]	8/16 components	Towing speed (30% ↓) H_s transfer limit (70%↓)	1 hour
ECN [15]	H_s, Wind Speed	SOV Tug	discontinuous	Weight exceeding 3 tons	N/A	N/A

[1] Field Support Vessel
* weather window length includes towing in, repair at port and towing out
* maintenance activity is split into three activities. Repair at port is not limited by weather inputs

5. ScotWind Case Study using Literature Data

The first FOW farm, Hywind, became operational in 2017. Since then, there has yet to be a major component replacement and, as a result, there is currently no operational data for this process. However, in Section 3.2 stated, T2S is a vital part of the O&M process for FOW. Due to a lack of standardised information, there is a wide range of data surrounding specific T2S processes such as the tugboat capabilities and the disconnection/reconnection process. The distribution of values for these T2S specific elements are shown in Figures 1 and 2.

To demonstrate the impact of inaccurate model inputs, a simulation is run for a number of case studies from the ScotWind allocated zones. Details of the sites used and information regarding distance to shore and water depth are provided in Figure 3.

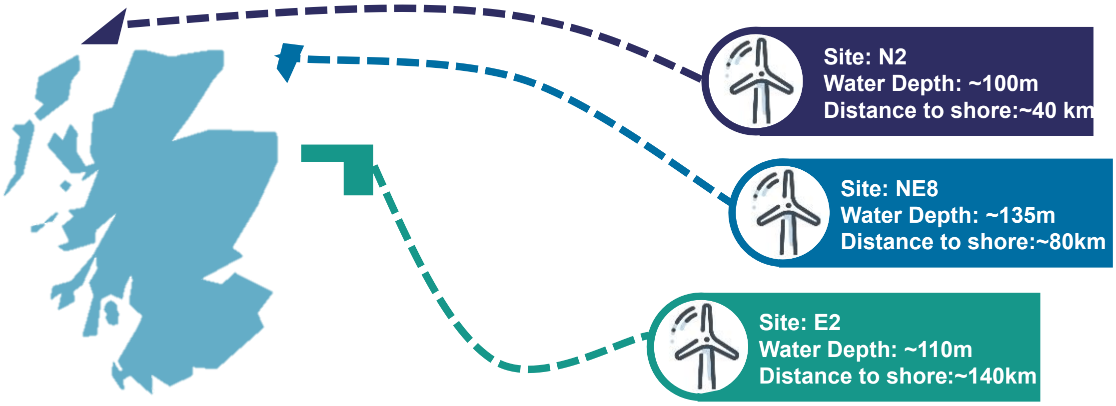

Figure 3. ScotWind zones used for the case study with details of water depth [m] and distance to shore [km].

These sites all have unique conditions and cover a wide region of Scottish waters with varying distances to shore in depths only suitable for FOW. The weather data used in this analysis is taken from ECMWF's ERA5 dataset [28]. This provides H_s and mean wind speed measurements at the central point of the site in resolution of one hour for a period of 20 years (1990-2010).

5.1 Methodology

Using the findings from the literature study, Figures 1 and 2 visualize the best and worst case scenarios to emphasise the impact of extreme value selection. This study is focused on accessibility for the required time to tow in/out the asset. This operation includes disconnection/reconnecting the asset and towing the structure from site to shore. A weather window model is used to determine the length of the weather window required and the average wait time for an appropriate window. The methodology of this process is described in Figure 4.

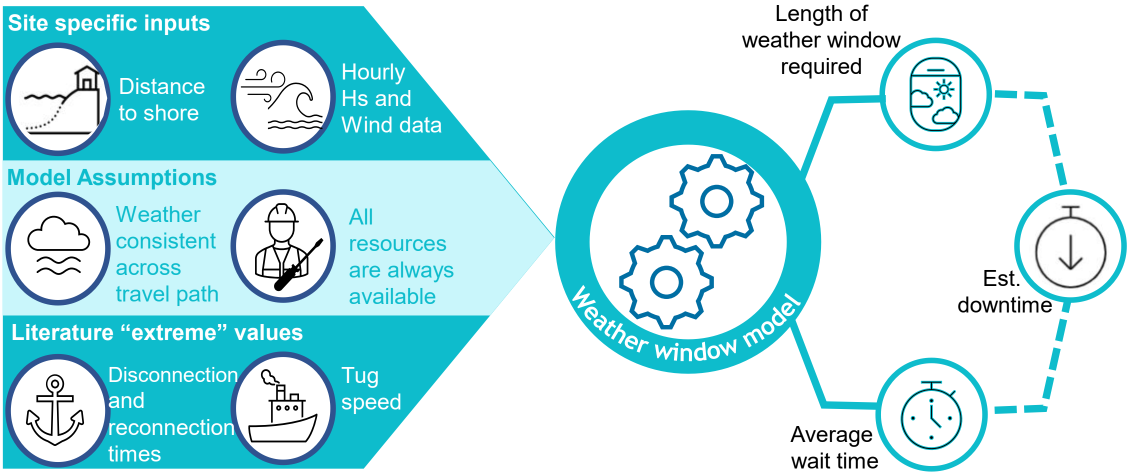

Figure 4. Overview of weather window model with details on inputs and outputs

The model defined weather windows sequentially, where one larger weather window is made up of smaller length windows, e.g., an access period of 3 hours contains 3 windows of 3 hours, 2 hours and 1 hour. It is assumed that the weather conditions taken at the centre of the site are consistent throughout the travel path of the vessel to and from site. It is also assumed that all resources, such as spare parts, vessels and crew, are always available for deployment. The length of weather window required is defined by the process from tow-in or tow-out, which includes travel time to shore, disconnection/reconnection, and transfer to port. Average waiting time is determined by averaging the number of hours between suitable weather windows. The inputs for disconnection/reconnection time and tugboat speed were taken from the most extreme values presented in the literature. However, the outlier values were removed from the above figure to provide a best and worst case scenario, as detailed in Table 2.

Table 2. Scenario inputs for disconnection/reconnection and tugboat speed

Scenario	Disconnection/reconnection time (hours)	Tugboat speed (knots)
1	24 [16]	10 [13]
2	63 [17]	1.86 [15]

5.2 Results and Discussion

Table 3 shows the results for the three sites under best and worst case conditions. The required weather window was taken as the time to reach site, disconnect the turbine and return to shore for each scenario.

Across all three scenarios, there is a significant difference in the length of the weather window. This leads to a large range in accessibility and average wait time. There is a clear link between accessibility and OpEx. Therefore, over-/under-estimating this key metric can highly skew the overall financial forecasts of the project. The cost of downtime is known as an opportunity cost. This is defined within the industry as the revenue which could have been made, had the turbine been operational during periods of failure. This can make up 28% of total OpEx [29]. The length of downtime is defined from component failure to repair, including time to repair, transfer time, and waiting time. Unrealistic projections of waiting time will have a significant impact on overall project projections.

Table 3. Weather window results for ScotWind case study

Site	Distance to Shore	Scenario	Required Weather Window (hours)	% Accessibility	% Difference	Average Wait Time (hours)	Time Difference (hours)
E2	140 km	1	32	70%	15%	133	182
		2	104	55%		315	
NE8	80 km	1	28	53%	10%	260	238
		2	86	43%		498	
N2	40 km	1	26	41%	8%	203	150
		2	75	33%		353	

The length of the weather window and the average wait time can provide an indication of expected downtime during major replacement. The importance of the wait time will be amplified for the T2S maintenance approach, for a discontinuous weather window. One of the key advantages of the T2S methodology is that when at the port, the repairs, for the most part, are independent of weather conditions, and, therefore, the time to repair process is removed from the length of the weather window. However, this process will see two sets of weather waiting periods. The first occurs when waiting for tow in, and the second when waiting for tow out. Therefore, the accurate timing of such processes is vital for an efficient operation.

The Scotwind case study presented here highlights, that a well-adapted and accurate model can only be as accurate as its inputs. While tug speed and disconnection/reconnection times comprise only a small portion of inputs, incorrect values can have significant impacts on key performance estimates. This can be the difference between a project being consented or not due to the direct link between O&M modelling and project financing.

6 Conclusion

The objective of this work is to give insight into the conceptualization and operationalization of O&M models for floating wind uses. Through an investigation of key O&M inputs used in traditional FBW, alongside FOW specific considerations, it was found that significant adaptations must be considered in order to accurately model FOW O&M strategies. The adaptations include failure rates for the newest multi-MW machines, an additional weather parameter to characterize the induced motions of the floater and maintenance vessels, as well as vessel fleets and technologies required to carry out repairs.

The T2S strategy for major component repairs holds many cost saving benefits when compared to a JUV strategy for FBW. However, T2S comes with a unique set of operational challenges and limitations which must be further explored to reap the cost benefits of using this strategy. Through the discussion in this paper, it seems ever so clear that the optimal strategy for a site would depend on a number of factors such as site characteristics, floater type, distance to shore and availability of ports, as well as availability of vessel or maintenance technologies. Therefore, it is vital to investigate the sensitivities of each of the factors by means of O&M modelling.

Reviews of models have shown that existing O&M tools can be adapted for FOW uses. However, this cannot simply be done by only editing operational inputs. Thoughtful adaptation requires an understanding of the direct, and indirect, limitations a FOW imposes on day-to-day O&M practices. Modelling of major replacement strategies such as T2S will require significant changes to existing models. This will be a challenging process as these proposed strategies are still in the concept phase and therefore limitations and operational inputs are still relatively unknown. While FOW has the benefit of the experience from FBW practices, there are still gaps in knowledge which must be addressed.

6.1 Recommendations for FOW O&M Modelling

Based on the FBW O&M review and FOW requirements discussed in this work, the following changes are recommended:

- **Inclusion of T_p**: An additional parameter T_p should be considered alongside H_s and wind speed to characterise the induced wave motions and determine vessel accessibility.
- **Tugboat Speed**: In order to accurately model the towing phase of the T2S strategy, the transit speed (of initial port-to-site) and towing speed of a tugboat should be considered separately.
- **Conditions Along Towing Path**: Multiple weather points along the transit route of a T2S strategy should be considered as met-ocean conditions may vary for longer towing distances.
- **T2S as multiple phases**: Tow-in, maintenance, tow-out, and disconnection/reconnection need to be viewed as separate yet complementing phases.
- **Split Weather Windows for T2S**: Each phase of the T2S strategy requires an individual weather window instead of one single continuous window.
- **Onsite and Offsite Repair Times**: Consider different repair times for portside maintenance and offshore on-site maintenance, e.g., the same task might take longer offshore than portside due to floating-to-floating interactions incurred.

References

[1] BEIS 2020 Committee on Climate Change's 2020 progress report: government response
[2] Carbon Trust 2020 *Floating Wind Joint Industry Project: Phase II summary report*
[3] Crabtree C, et al 2015 Wind energy: UK experiences and offshore operational challenges Power and Energy IMechE. 2015;229(7)727746
[4] Wiser, R *et al* 2021. Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nature Energy* **6** 555–65
[5] Seyr, H *et al* 2019 Decision support models for operations and maintenance for offshore wind farms: a review *Applied Sciences* **9** 278
[6] Carroll J *et al* 2015 Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines *Wind Energ*y **19** 1107–19
[7] Baraniuk C 2021 Why giant turbines are pushing the limits of possibility *BBC News*
[8] Scheu M *et al* 2018 Human exposure to motion during maintenance on floating offshore wind turbines *Ocean Eng*. **165** 293-306
[9] Jenkins B *et al* 2021 Limiting wave conditions for the safe maintenance of floating wind turbines *Journal of Physics: Conference Series* **2018** 012023
[10] Dinwoodie I *et al* 2015 Reference cases for verification of operation and maintenance simulation models for offshore wind farms *Wind Engineering* **39** 1–14
[11] O'Connor M *et al* 2013 Weather window analysis of irish and portuguese wave data with relevance to operations and maintenance of marine renewables *Renewable Energy* **52** 57–66
[12] Renews Ltd 2022 Kincardine facing turbine repair job https://renews.biz/77609/kincardine-facing-turbine-repair-job/
[13] Dewan A *et al* 2016 *Reference O&M Concepts for Near and Far Offshore Wind Farms*
[14] Maienza C *et al* 2020 A life cycle cost model for floating offshore wind farms *Applied Energy* **266** 114716
[15] Cermelli C *et al* 2012 Implementation of a 2MW floating wind turbine prototype offshore portugal *Offshore Technology Conference OTC-23492-MS*
[16] Offshore Wind Innovation Hub 2020 *Floating Wind: Cost Modelling of major repair strategies*
[17] Schwarzkopf M-A *et al* 2020 Identification of floating-wind-specific O&M requirements and monitoring technologies *COREWIND H2020 project*
[18] Brons-Illing C 2016 Analysis of operation and maintenance strategies for floating offshore wind

farms

[19] Rinaldi, G *et al* 2020. Improvements in the O&M modelling of floating offshore wind farms. *Developments in Renewable Energies Offshore*. CRC Press, 481-487.

[20] Conbit 2020 Who will maintain floating offshore wind turbines?

[21] Rinaldi, G. *et al 2018* Verification and Benchmarking Methodology for O&M Planning and Optimization Tools in the Offshore Renewable Energy Sector. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*. 10.

[22] Carbon Trust 2021 *Floating Wind Joint Industry Project: Phase III summary report*

[23] Conbit 2020 Who Should Maintain Floating Offshore Wind Turbines? https://www.conbit.eu/blog/who-should-maintain-floating-offshore-wind-turbines

[24] Carbon Trust 2021 Floating Wind Technology Acceleration Competition

[25] McMorland, J et al 2022. Operation and maintenance for floating wind turbines: A review. Renewable and Sustainable Energy Reviews, 163, p.112499.

[26] Rinaldi G *et al* 2016 A Computational Tool for the Pro-Active Management of Offshore Farms

[27] Rinaldi G 2019 An integrated operation and maintenance framework for offshore renewable energy

[28] ERA5 ECMWF https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

[29] Castellà, F.X 2020 Operations and maintenance costs for offshore wind farm. Analysis and strategies to reduce O&M costs. *Master's thesis, Universitat*