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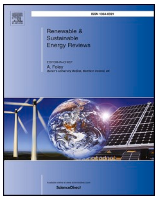

Operation and maintenance for floating wind turbines: A review

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ABSTRACT

This paper reviews the existing literature surrounding floating offshore wind (FOW) operations and maintenance (O&M) models. A review of the technology is presented with a comparison with current practise for bottom-fixed offshore wind O&M activities. This article divides existing publications into the following categories: cost modelling, O&M modelling, and safety/limiting factors. A review of the case studies used within these publications shows trends towards development in Northern Europe. Factors considered during cost modelling are discussed with a review of levelised cost of energy results for the three main types of floating support structure. The key O&M inputs for FOW applications are identified and then analysed detailing the key differences between floating and bottom-fixed applications. Finally, the publications detail the impact of the motion of the turbine on O&M activities are discussed. Key areas of FOW O&M research are identified with details of current research gaps and recommendations for future work.

1. Introduction

The past decade has seen an uptake of renewables due to the commitment of the EU to global climate action under the Paris Agreement [1]. The UK government set its own target with a commitment to Net-Zero by 2050 [2], and the Scottish Government setting an even more ambitious deadline of 2045 [3]. One of the driving forces behind these targets is the success of offshore wind within UK waters. The UK's offshore wind capacity has more than quadrupled from 2010 to 2020 (5.4 GW - 29.1) [4]. The advancement of offshore wind is much greater than previously imagined, with the UK government awarding 5.5 GW of new offshore wind in the 2019 Contract for Difference auction at a record low delivery price of £39.65/MWh (in 2012 prices) – below the current wholesale market price for electricity and thus ensuring offshore wind within the UK can be delivered unsubsidised. However, the offshore wind industry faces a new set of challenges. Water depth and increasing distances to shore add an additional complexity to current operational sites which have proven to be not only economically viable but also profitable. Therefore, extensive work is required to maintain the energy trilemma of secure, green, and affordable energy.

Several Round 4 Crown Estate and ScotWind sites for the next round of auctions (2021) are now within depths unsuitable for bottom fixed offshore wind (BFW) (>50 m), making floating offshore wind (FOW) one of the only viable options. However, the industry lacks experience with FOW technology, with only 73 MW operational installed capacity globally (2020). It is estimated that up to 70 GW of FOW could be operational by 2040 [5]. Floating foundations will not only unlock new deep-water areas for wind energy production, but also introduce potential new maintenance strategies such as tow to shore (T2S). Currently, the main components (gearbox, generator and blades) in BFW turbines are replaced using jack-up vessels (JUV) or heavy lift vessels (HLV) with cranes. These vessels are currently limited by water depth of 60 m [6]. Commercial-scale floating wind farms are expected to become competitive with BFW farms only at water depths beyond this, introducing new maintenance challenges.

Currently, floating wind is one of the leading solutions to use the available wind resource. If FOW wishes to see the same success and cost reduction as BFW, then the supply chain must be effective from the beginning in terms of both cost and quality. Currently, up to 30% of the overall cost of energy can be attributed to operations and maintenance (O&M) [7], making it a key area of cost reduction for FOW if it wishes to compete within the same market as BFW.

Several reviews have been conducted on the design challenges of FOW [8–15]. Rinaldi et al. [16] recently (2021) published a review of current status and future trends for O&M of offshore wind turbines, including FOW. At the time of writing, there has not yet been a review focused on the existing literature surrounding O&M modelling and activity for FOW. This review article aims to present current state-of-the-art O&M research with focus on FOW operational

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Abbreviations

BFW	Bottom Fixed Wind
FOW	Floating Offshore Wind
T2S	Tow to Shore
JUV	Jack Up Vessel
HLV	Heavy Lift Vessel
O&M	Operation and Maintenance
LCOE	Levelised Cost of Energy
KPI	Key Performance Indicator
OpEx	Operational Expenditure
TLP	Tension Leg Platform
Semi-sub	Semi-submersible
NPV	Net Present Value
IRR	Internal Rate of Return
CBS	Cost Breakdown Structure
LCCA	Life Cycle Cost Analysis
H_s	Significant Wave Height
CTV	Crew Transfer Vessel
SOV	Service Operation Vessel
SFV	Specialist Field Vessel
AHTSV	Anchor Handling Tug Supply Vessel

challenges. Seyr et al. [17] present a view of current decision support models for BFW. Within their review, the following influential factors in O&M modelling are identified: weather and external factors, degradation and failure modelling, vessels, personnel and spare parts, transportation and vessel routing, and economic and cost estimation. Many of these factors will be relevant for FOW O&M modelling.

The literature discussed is separated into three categories: levelized cost of energy (LCOE)/cost modelling, O&M modelling, and safety/limiting factors. Section 2 introduces the operational challenges faced by FOW operations; section 3 provides details of the existing reviews surrounding FOW. Section 4 gives details of case studies in O&M FOW simulations. Section 5 details the economic modelling work within FOW operational spending. Section 6 reviews the existing literature surrounding O&M modelling for FOW, including T2S simulations, summary of key performance indicators (KPIs), and comparison of maintenance strategies. Section 7 introduces works focused on the safety of technicians and workability of the asset. Finally, section 8 includes a summary, discusses the gaps in the literature and provides a recommendation for future work.

2. Floating wind O&M challenges

FOW has the advantage of being able to learn from the growth of BFW technology. With technology and supply chain development there is a clear and credible trajectory to delivering commercial FOW sites [18]. However, the introduction of floating systems introduces new challenges and constraints. Logistical problems, such as the increase in the distance to the shore and the harsher environment, are key areas of concern from an O&M perspective. The key challenges faced are wave sensitivity, maintainability, anchor cost/complexity, mooring cost/complexity, and turbine motion as identified by NREL [19], all of which have a direct impact on O&M. Other operational challenges include a lack of available data due to the infancy of the industry.

2.1. Environmental conditions

Like BFW, FOW concepts will still be affected by access restrictions caused by poor weather. Weather conditions such as wind speed, wind turbulence, wave height and sea condition, temperature and humidity can all have significant impact on the reliability and maintainability of the asset [20]. It is expected that the FOW will allow stronger and more constant wind to be used to its benefit, due to the anticipated increase in distance to shore. However, an increased distance from shore results in harsher weather conditions leading to a decrease in accessibility to site. This, combined with the increase in travel time, makes the use of access and weather windows vital to efficient and profitable operation. One of the main costs associated with operational expenditure (OpEx) is the opportunity cost from downtime. An opportunity cost is defined as the revenue which could have been generated, had the turbine been operational.

Exposure to harsher and more challenging environmental conditions also has the potential to result in a rapid progression of the degradation of the asset, increasing the requirement for maintenance visits to site.

2.2. Major component replacement

Due to the expected depths of FOW sites, the use of conventional major component replacement vessels will not be viable [6]. This creates an interesting challenge of how major component replacements will be conducted. New solutions have been considered including on-site solutions such as floating-to-floating transfer, floating cranes, and self-hoisting equipment, and off-site methods such as T2S [21].

Some FOW configurations offer the opportunity to be towed to shore for extensive maintenance activities. This maintenance activity is only applicable to shallow draft structure types and those FOW structures able to satisfy the intact stability requirements even when not moored, such as a tension leg platform (TLP). The viability of this strategy also depends on the port facilities. The port must have sufficient water depth, equipment (such as an onsite crane), and general scale to meet the maintenance needs of floating turbines. There is also an adapted version of this strategy known as “tow to shallow” where the turbine is towed to shallow water for maintenance at depths suitable for HLV and JUV assistance.

The overall uptake of FOW is limited by the availability of suitable port and grids infrastructure. Most European ports and harbours are not equipped to deal with the scale of operations required for installation and maintenance of such assets; this becomes an increasing issue due to the pace of installation of new BFW and FOW sites.

2.3. Turbine motions

The motion of the turbine will have a significant impact on O&M, making access and egress by personnel more challenging, as the process moves from a floating-fixed transition to a floating-floating system [22]. This could increase the difficulty of performing on-site inspections and repairs, due to the inherent dynamics of floating wind turbines, and raises concern about the safety of technicians performing maintenance on the floating structure.

It is vital that future works regarding O&M modelling have an appreciation of this additional factor when considering the health and safety parameters and limitations required for safe working conditions for technicians. It is expected that additional weather and environmental factors such as peak wave period (Tp) and wave direction will be required to assess the workability of the asset [23]. The motion of the asset is also expected to have an impact on the rate of degradation of the components, particularly within the drivetrain.

3. Existing floating wind reviews

Despite the lack of commercial sites operating, several literature reviews on the technology have been carried out. At present, efforts have been focused on optimisation of the sub-structure and the advantages and disadvantages of existing technologies. Based on the literature, spar, TLP, and semisubmersible (semi-sub) support structures are the most advanced technologies. The details of existing review papers, the types of structures considered, the focus area of the review, and details of any

O&M considerations are provided in Table 1.

Most of the FOW reviews conducted thus far provide recommendations/details of O&M requirements for the technology, as shown in Table 1. It is agreed in the review literature that TLP will be the most effective for O&M, both in terms of cost and ease of maintenance, despite the fact that no TLPs have been installed at the commercial level (2021). Wang et al. [8], Henderson & Witcher [9], and Liu et al. [12] identify O&M as a key area for future research.

Rinaldi et al. [16] review current and future trends in O&M within offshore wind that covers fixed and floating turbines with a focus on reliability and maintainability through methods such as condition monitoring and the use of artificial intelligence and drones. The findings showed that condition monitoring is not currently widely used for FOW. This is due to several factors, the main being the infancy of the technology/industry. However, the floating nature of the platform will bring about a series of new requirements, such as additional environmental parameters to monitor, e.g., hydrodynamic loadings and platform motions. Although corrosion is expected to cause problems, fatigue due to wave and wind, loadings must be assessed due to platform motion. Increased use of control systems to monitor platform motions can lead to a higher number of electrical-related failures. These additional challenges reinforce the need for accurate O&M modelling of the technology and highlights the need for dedicated modelling of failure rates of such systems. The deployment of FOW is in line with the uptake of new technologies discussed in Ref. [16], therefore, it is likely that the overall maintenance strategy of the site will change due to these technological advancements. The expected challenging environmental conditions of FOW sites are likely to benefit from unmanned inspections through the use of drones due to issues with accessibility.

4. Case studies

A total of 30 studies are included within this review which have been split by topic area. This section analyses trends in the case studies used within these works. Of the 30 studies, two did not provide case studies details. Based on the literature, the key factors of a FOW case study are installed capacity (MW), distance from shore (km) and water depth (m) with the trends summarised in Fig. 1. Additional input included the number of turbines (#), wind resource (m/s), type of structure, and location.

FOW case studies used within the literature tended to also model a BFW site for direct comparison.

4.1. BFW and FOW comparisons

Comparisons between the technology are provided by Refs. [24–29]. Castella & Xavier [24] use case studies first presented in Ref. [25] with a total of five fictional scenarios with the intention of creating baseline sites near and far from shore, the fifth site being FOW. The distance from shore for BFW sites ranges from 30 to 150 km, with the FOW site being the closest to shore at 20 km. Mhyr et al. [26] uses the studies provided by Ref. [27] that compare BFW and FOW within the same site with a total of nine turbine concepts. Details regarding distance to shore, site size, installed capacity, weather conditions, and losses are identical for all sites with the only difference being water depth, at 30 m for fixed and 200 m for floating. This allows for direct comparison to be made between the concepts. The case studies first presented in Ref. [25] use different locations and strategies, making it difficult to critically compare the concepts.

Rinaldi et al. [28] and Katsouris & Andrew [29] base their comparisons on existing sites Westermost Rough and Gemini, respectively. Both works include three scenarios, one for BFW, and the remaining two for FOW, with different major component replacement strategies. Rinaldi et al. [28] compares two T2S strategies which differ based on weather windows required. The taxomony of BFW and FOW for all scenarios is identical. Katsouris & Andrew [29] model FOW with and without a T2S strategy in place, assuming that T2S would reduce costs by one third. However, the focus of this work was cost modelling, and therefore assumptions were made regarding the effectiveness of a T2S strategy.

Brons-Illings [30] and Castro-Santos et al., 2014 [31] only model FOW sites. Brons-Illings [30] compares the same site (installed capacity, turbine type, location, water depth) at varying distances to shore (37 km, 65 km and 93 km). Castro-Santos et al., 2014 [31] compares the same support structures and installed capacity at two differing locations, Agucadoura and Sao Pedro within Portugal.

From Fig. 1, it is clear that most FOW case studies lie within waters less than 100 km, with many relatively close to shore at distances less than 50 km. Although this fits the profile of existing coastal FOW sites such as Hywind and WindFloat (20–25 km), it is not representative of the far-from-shore FOW sites expected in the future.

4.2. Additional considerations

LCOE/cost modelling publications tend to include additional site

Table 1
Summary of existing literature reviews on floating offshore wind.

Paper	TLP	Semi-Sub	Spar	Barge	Other	Paper Topics	O&M Summary
Wang et al. [8]	✔	✔	✔	✔		Support structures	Recommended future work to establish cost effective infrastructures for towing, installation and maintenance
Henderson & Witcher [9]	✔	✔	✔	✔	Mini TLP	Turbine control, support structures	O&M procedures identified as a key challenge
Muskulus & Schafhirt [10]			✔		Fixed structures	Support structures	Recommendation of O&M considerations being included in the design phase.
Stewart & Muskulus [11]	✔	✔	✔			Support structures	N/A
Liu et al. [12]	✔	✔	✔			Support structures	O&M ranked best to worst (TLP, Spar, Semi-sub). Acknowledgement of O&M cost reduction as a key research area.
Leimeister et al. [13]	✔	✔	✔		10 total structures	Support structures	Spar - simple structure, easy manufacturing and maintenance Semi-sub - more challenging manufacturing and maintenance TLP - easy maintenance, complex and risky installation and disconnection for onshore maintenance
Wu et al. [14]					Fixed: monopile, gravity, tripod & jacket	Support structures	Submarine cable and other electricity *trans*-mission systems are required for erection and maintenance work, which may result in much higher costs
Chen et al. [15]	✔	✔	✔			support structures - numerical and experimental methodologies	N/A

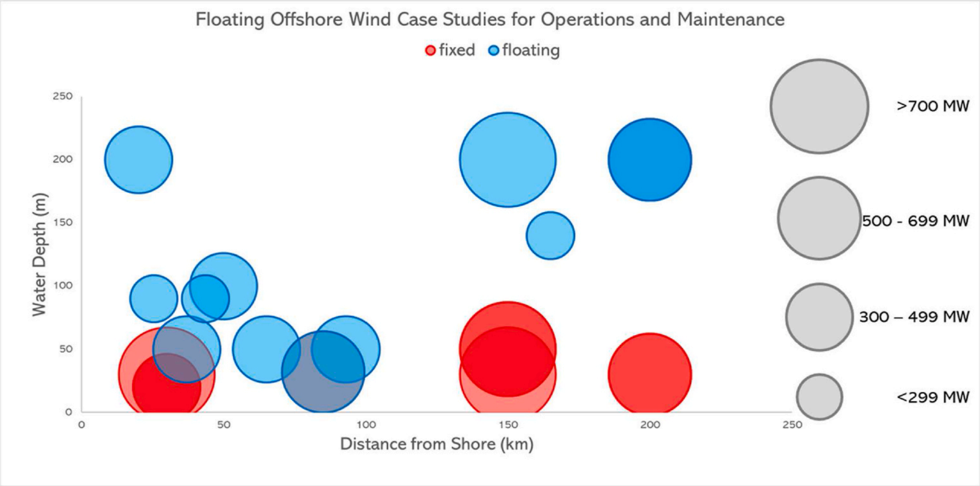


Fig. 1. Summary of case studies in the literature in terms of water depth (m), distance from shore (km), and installed.

information such as wake loss, electrical array loss, and availability as a model inputs. Bjerkster & Agnotes [27] and Heidari [32], give capacity factors of 53% and 50%, respectively, as input to their modelling. While these estimates are above that of BFW (typically less than 40% within UK waters [33]), this is a conservative estimate for FOW. Recently, Hywind Scotland announced a capacity factor of 57.1% in the 12 months to March 2021, marking a new record in the UK [34].

4.3. Geographical areas

All locations given within these works are based in European waters. Brons-Illing [30] and Rinaldi et al. [28] model sites in the North Sea (German Bright and Westermost Rough) which has been identified as a key area of development for FOW sites in the future. The remaining literature is focused on Northern Europe with Castro-Santos et al., 2020a [35] focusing on Portugal and Castro-Santos et al., 2020b [36] looking at the Cantabric region within Spanish waters [25–27,29,31,37]. also use European based sites.

4.4. ScotWind floating considerations

In 2020, the Carbon Trust estimated that up to 10.7 GW of floating wind worldwide could be feasible by 2030, with almost 70 GW operational by 2040 [5]. The 2022 ScotWind leasing results have greatly accelerated this target by awarding 11 floating projects with a capacity of 15 GW. This highlights the pace at which the FOWT industry is growing, and in which Scotland is positioned to be an early leader.

However, this historic auction has highlighted key challenges associated with the technology. Of the 10 dedicated floating projects, the average minimum distance to shore (from the centre of the site to the closest shoreline of mainland Scotland) exceeds 100 km with an average installed capacity of 1.5 GW [38]. As shown in Fig. 1, the distance to shore for FOWT sites tends to exceed 150 km, in line with the ScotWind sites. However, case studies have been performed for sites with much lower installed capacity. However, the increase in capacity may not be a result of an increase in the number of turbines due to the rapid acceleration of turbine capacity. At present, there are little details available regarding failure rates of such machines.

Many of the case studies provided are within regions which have already benefited from BFWT. While the easterly sites within the ScotWind allocation are in close proximity to established ports and within well studied met-ocean locations, the sites located to the NE and N of the country are expected to have more challenging conditions. These new, more remote locations will have to manage existing O&M BFW challenges, in addition to specific FOWT requirements. These remote islands surrounding mainland Scotland rely heavily on ferry services for commuting and resources. There is a potential that this may limit operational limits, port availability, and vessel travel path. However, this is not a universal issue and is handled on a case-by-case basis.

Ports and additional infrastructure will significantly influence the maintenance strategy for FOWTs, particularly for major component replacement. For a T2S strategy to be viable, the port has sufficient depth, capacity, and facilities to accommodate these large assets. In addition to this, weather conditions at site must be monitored. Major competent repair/replacement at shore will require sufficient high tide and low wind speeds. As the turbine (or repair vessel) moves from deep (on site) to shallow waters (at port), there can be a significant change in wave [39], and other weather, conditions along the travel path, which could result in a failed transfer.

These selected sites have the existing challenges of bottom-fixed operation, in addition to increased distance to shore, expected challenging met-ocean conditions and limited existing infrastructure. In addition, the additional complexities of FOWT operation need to be explored. While the existing literature explores deep water sites far from shore, the scale of the modelled capacity is much smaller than the predicted future sites.

5. Levelised cost of energy/cost modelling publications

This section includes publications which produce cost estimations for FOW farms. Due to the infancy of the FOW industry, there is an additional risk for investors, making LCOE/cost reduction a key area of research. Table 2 shows the inputs and outputs within the cost models available in the literature. Key outputs include LCOE, Net Present Value (NPV), Internal Rate of Return (IRR), Cost Breakdown Structure (CBS), and Life Cycle Cost Analysis (LCCA).

In general, the LCOE studies have more detail in their site description giving factors such as availability, capacity factor and annual energy production as known site inputs.

5.1. Cost breakdown structure

Castro Santos has been identified as one of the leaders in research in this area with a number of publications focused on FOW cost modelling [31,35–37].

Works by Castro Santos et al. [35,36] act as feasibility studies for Portugal and Northern Spain respectively, using the same methodology. The study is divided into three sections: geographical, economic, and restrictions in order to determine the feasibility of the site. The geographic phase examined weather factors, such as wind and wave

Table 2
Existing cost modelling FOW studies with details of inputs and outputs/KPI.

Publication	Inputs	Outputs				
		LCOE	NPV	IRR	CBS	LCAA
Myhr et al. [26]	site details (lifetime, # turbines, installed capacity, location, losses), general resources (cost of materials) and vessel specifications (type, day rate/annual fee), investments, O&M costs, energy generation, discount rate					✓
Bjerkseter & Agotnes [27]		✓				✓
Castro-Santos et al., 2014 [31].	weather (wind speed, significant wave height, Tp), bathymetry, distance to shore/shipyard/port, platform details (length, # mooring lines, draft, # columns per platform				✓	✓
Castro-Santos et al., 2020a [35]		✓	✓	✓		
Castro-Santos et al., 2020b [36]		✓	✓	✓		
Castro-Santos et al., 2016 [37].		✓				
Heidari [32]	Cost estimations (project development, turbine, sub-structure, general function, mooring system, electric infrastructure, installation, OpEx, insurance, exchange rate)	✓				
Maienza [40]	Turbine characteristics, floating platform characteristics, vessel rates, labour costs, general parameters	✓				

conditions, using statistical methods such as the Weibull distribution. This is to determine overall available resource and site accessibility. Both studies also consider bathymetry to determine the feasibility of the location. The restrictions section analyses the three main substructure designs, spar, TLP and semi-sub, as well as distance to shore/port/shipyard. The economic phase was first developed in Refs. [31,37], where a CBS is used to define the main costs and associated sub-costs, considering the disaggregation of the process. Wind farm costs are categorised as follows: concept definition, design and development, manufacturing, installation, exploitation and dismantling. O&M costs are incorporated within the exploitation phase. The exploitation phase also includes revenue streams [35]. varies the electricity tariff from 200 to 300e/MWh to reflect the variability in the Portuguese system [36]. also varies the electricity tariff from 50 to 200 e/MWh [36]. found that to be economically feasible a FOW farm, a tariff of 200 e/MWh is required [35]. also found that FOW farms would only be feasible at the upper end of the tariff range (300 e/MWh). Both results exceed the current tariff received through the Hywind Scotland Pilot Park Renewable Obligation scheme at £160/MWh [41]. It was found that the exploitation cost consistently made up 25–30% of the total lifetime cost for all three structures considered.

Myhr et al. [26] uses the methodology described in Ref. [27] which echoes [31] by splitting the overall costs of the site into distinct phases: development and consenting, production and acquisition, installation and commissioning, operations and maintenance, and decommissioning [26,27]. included a wider range of turbine types including spar, semi-sub, tension leg spar, tension leg wind turbine, and tension leg buoy. The results indicate that LCOE values are strongly dependent on depth and distance from shore, due to mooring costs and export cable length, based on the findings, depth is the dominant parameter to determine the optimal concept for a site.

Heidari [32] is a more financially driven publication containing the most in-depth analysis of the cost structure, breaking it into 9 sections. This work also includes details regarding cost of equity and debt. The main output LCOE is given in £/MWh using the formula developed by PWC [42].

5.2. LCOE comparison for different structures

All the studies provide varying results in terms of LCOE for the spar, TLP and semi-sub platform due to variable inputs such as water depth, installed capacity, distance from shore, balance of plant, number of turbines, etc. However, the publications also disagree in terms of which support structure will result in the highest LCOE as shown in Table 3. Table 3 ranks the LCOE results within each stated publication as high, med (ium) and low. These results are ranked according to the results of each publication and have not been bench-marked against each other due to differences in methodology, case studies, and terminology used. Castro-Santos et al., 2016 [37] only considers one type of structure and Maienza [40] provides an average LCOE for all structures. Therefore, the results of these works are not included. The differences in results indicates that there is no clear choice of support structure highlighting the importance of external factors such as location, facilities and environmental elements have more of an impact on the overall LCOE than the choice of structure.

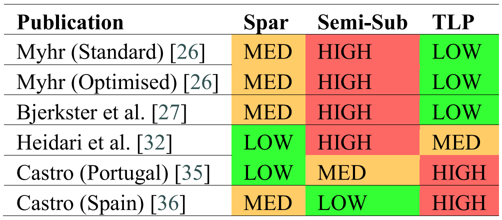
5.3. OpEx cost breakdown

Castro-Santos 2014 [31] provides detail of the OpEx methodology used within [35–37]. The O&M cost is split into preventive and corrective maintenance. Preventive maintenance includes cost of transport, direct labour, and materials for the entire system (including anchor and mooring). In addition, the number of elements needed, the type of vessel or helicopter used for maintenance, and the distance from farm to port are evaluated.

Within the works by Bjerkster & Agnotes [27] and Myhr et al. [26] the O&M modelling inputs were calculated using the Operation and Maintenance Cost Estimator “OMCE” Calculator. Details of the exact inputs of the O&M modelling were not included in either publication due to their sensitive nature. This simulation tool computes the results before performing a sensitivity analysis in high- and low-scenarios to identify the main contributions to risk and uncertainty in each of the proposed concepts.

Mineza [40] calculates OpEx analytically and/or as a function of the installed power of the site. Costs are divided into operational and maintenance categories. Operational costs include the cost of seabed rental, insurance, and grid access feed. Maintenance expenditures are split into direct and indirect costs. Direct costs are presented as a sum of

Table 3
Ranking of LCOE from high to low within the existing literature for spar, semi-submersible and TLP turbine structures.



Publication	Spar	Semi-Sub	TLP
Myhr (Standard) [26]	MED	HIGH	LOW
Myhr (Optimised) [26]	MED	HIGH	LOW
Bjerkster et al. [27]	MED	HIGH	LOW
Heidari et al. [32]	LOW	HIGH	MED
Castro (Portugal) [35]	LOW	MED	HIGH
Castro (Spain) [36]	MED	LOW	HIGH

the preventive and corrective maintenance. Indirect maintenance expenditures include fixed costs faced to guarantee repair service including port fees, vessel hiring fixed costs, and maintenance planning and managing cost.

6. FOW O&M modelling publications

A total of 12 publications are considered within this section, which specifically model O&M activities within FOW sites. The section is split to discuss the O&M models used, influential factors and inputs, the type of strategy modelled, KPIs and a discussion of additional factors considered during FOW O&M operations in comparison to a BFW site.

6.1. FOW models

There has been extensive work in developing O&M modelling tools for offshore wind. A comprehensive list of academic and industry models can be found in Ref. [43]. A great deal of time, effort, and cost goes into developing accurate offshore wind O&M models. Therefore, there is a question as to whether these existing (and sometimes validated models) should be adapted for FOW use, or if a new model should be created to deal with the additional complexities of FOW farms.

6.1.1. Adaptations of existing models

Castella [24], Dewan & Asgarpour [25], Rinaldi et al. [28], Kastorous & Marina [29], Amorim [44], and Gray [45] all use modified versions of existing models. Gray [45] uses existing O&M tools which have previously only been used for wave energy converter applications. They combine the DTOcean and WES O&M tools with modifications for use on a hybrid floating wind and wave device. Amorium [44] uses the commercial tool - Shoreline [46].

[24,25,29] all use versions of the models developed by ECN. Katsourus & Marina [29] use ECN install, ECN “OWEOP” and ECN O&M tool. ECN Install is a MATLAB based offshore wind installation simulation tool. The “OWECOP” model uses the programming language Python, and also utilises a number of Microsoft Excel worksheets to model the cost components of a site. To adjust the model for FOW applications, the Excel model utilised to calculate the dimensions of the monopile, transition piece, and tower was modified in order to calculate the main dimensions of the turbine tower used for a floating structure.

Castella et al. [24] and Dewan & Asgarpour [25] use the existing ECN O&M Access tool, originally designed for BFW. The model has been adapted to include T2S within it for a FOW application. The GL-validated ECN tool has been used for nearly fifteen years within industry as a tool for BFW applications. This work forms the basis for an updated version of the ECN O&M Access tool which will introduce features such as human fatigue and vessel hydrodynamics.

Rinaldi et al. [28] adapts the model used in Ref. [47] for offshore wind, wave and tidal energy applications. The tool has also been verified for use in Ref. [48]. This model is based on the Markov Chain Monte Carlo approach, which combines random processes representing a sequence of events with repeated sampling of the same scenario subject to random variations. Key changes were required to make it suitable for FOW applications, including the addition of a T2S option for maintenance. Two T2S options are implemented, the first requiring a continuous weather window from failure to repair and the second being split into sections where the onshore repair does not require a weather window. While details are not provided, it is likely the continuous weather window for T2S is modelled as a major component failure with a large associated time to repair.

6.1.2. New models for FOWT

Brons-Illing [30], Martini et al. a [49] and Elusakin et al. [50] use models specifically designed for FOW applications with varying levels of complexity. Brons-Illing [30] uses an Excel model for three scenarios with two sub scenarios each: near, mid, and far from shore, with and without T2S operations.

Martini et al. a [49] have one of the most complex models. They used three separate models to map out the O&M logistics of a site and the impact of downtime. The first is a discrete event model, the second a floating turbine model, and finally a wind farm model which are then integrated into a single simulator. Failure and reparation times are simulated stochastically and referred to as “events”. The operational envelope for BFW is typically defined by the mean wind speed. However, for FOW, this is much more complex. This work uses a simplified FOW model from Ref. [51] considering both the environment loads (wind, currents, waves) and the reaction of the system (displacements, accelerations). Structural, mechanical, and electrical components are designed to withstand specific loads, which are often related to the platform motions. Rigid body dynamics is solved considering first-order wave loads, quasistatic mooring loads, and quasi-static aerodynamic loads providing statistical information, such as mean and standard deviation, of displacement, velocity or acceleration of any point in the structure. When any of these parameters is above a specific operational threshold, it is assumed that the wind turbine must be shut down. The model also considers the impact of wake through the use of the Jensen model [52].

Elusakin et al. [50] uses a Petri network model. This is a graphical interface tool used to model and interpret complex systems which are described as concurrent, distributed, stochastic and/or nondeterministic. A Petri Network is like a flowchart or block diagram in function consisting of four fundamental graphical features: places, transitions, arcs, and tokens. They state that O&M modelling for FOW is different to that of onshore and BFW due to the difference in the type of substructure used. The support structures introduce additional components and their associated lifetime uncertainties. They also cite poor accessibility due to dependence on weather conditions, higher failure rates of components due to harsher environment conditions, resource constraints to execute activities and spare parts availability as factors which impact the O&M scheduling problem. One of the key reasons for choosing a Petri network model is the use of a Weibull distribution for time-to-failure, making it useful for applications with limited or unavailable data, such as FOW.

6.2. Maintenance strategies

Maintenance activity across a site is typically split for modelling. This can be preventive and corrective, planned and unplanned, major or minor, repair or replacement. Details of the maintenance strategies modelled in the existing FOW literature are given in Table 4.

Table 4
Maintenance strategies for FOW modelling.

Publication	Maintenance Activity Classification	Additional Information
Castella et al. [24]	Corrective & preventive	Harbour or shore
Dewan & Asgarpour [25]	Corrective and calendar Based	Permanent base, offshore based strategy, tow to shore
Rinaldi et al. [28]	Corrective only	Maintenance split by onshore and in situ
Brons-Illing [30]	N/A	Onsite vs onshore
Utne [53]	Preventative and corrective	N/A
Martini et al. *a* [49]	N/A	Light repair, heavy repair operations
Gray* [45]	Preventive and corrective	Major/Minor Onsite/offsite
Elusakin et al. [50]	Condition Based Monitoring	4 types of maintenance: 1) heavy with crane requirement 2)small with internal crane 3)small inside nacelle 4)small outside nacelle

This shows a clear move from corrective and preventive maintenance, which was the focus of BFW turbines, to onshore vs in-situ maintenance activities. Much like the BFW modelling, maintenance activities are typically split based on the effort of repair: minor/major, repair/replacement. Brons-Illing [30] uses an onshore vs in-situ approach but further splits the failure categories into wind turbine generator, floating substructure and tower, subsea installation. Major overhaul maintenance activity was scheduled every five years.

By separating maintenance into onshore and in situ, this simplifies the modelling process for T2S. It is likely that corrective and preventive maintenance will continue, with additional sub categories for onsite and onshore.

6.2.1. Tow to shore

Dewan & Asgarpour [25] uses a T2S maintenance method. Within this scenario, regular corrective maintenance and condition-based maintenance is performed by a small SOV (reduced crew capacity). An SOV approach is chosen due to floating-floating transfer. T2S is used for heavy replacement, specifically parts with a weight over 3t. This methodology was chosen to avoid the need to charter expensive HLVs. For spare parts less than 3t, a feeder vessel is used on a regular basis to refill small spare parts on the SOV. Castella et al. [24] make reference to this work.

The case study used by Katsouris et al. [29] is similar to Ref. [25]. For the floating scenario, two cases are presented, one whereby the O&M costs are the same as that of the fixed bottom case, and the other where they are reduced by 35%. The reduction is based on the assumption that costs will be reduced if the turbines can be towed to a sheltered area near where maintenance can be carried out, also known as tow to shallow. Gray [45] models a hybrid wind and wave device. The addition of the wave energy converter created a harbour effect at the turbine, reducing the severity of the wave conditions at site. Their device has the option to be towed back to an O&M base if required, or can undergo on-site repair and inspection.

To the authors knowledge, the only two papers which explicitly model T2S operations are Rinaldi et al. [28] and Brons-Illings [30]. Rinaldi et al. [28] compare two T2S approaches with a traditional fixed turbine maintenance strategy. The T2S strategies are split into continuous and discontinuous. Continuous T2S requires a single continuous weather window for the duration of the maintenance activity (towing the structure, repair and return to sea). Discontinuous allows the weather windows to be split. Smaller weather windows are required to transport the turbine to and from shore, without weather limits restricting repair on shore. The structure is towed to shore for maintenance on 8 of the 16 components. This is one of the most in depth analysis on T2S operations with details given about towing time, towing limits and time allocated for disconnection and re-connection of the structure. However, this methodology is applied to a generic structure. It's stated that the towing transit time for a maintenance vessel towing the device is 30% higher than transit without the device. This contradicts other publications such as Bjerkster et al. [27] which provides details of vessel speed with and without towing which shows a reduction in vessel speed of 70–80%. Rinaldi et al. [28] also state that the metocean limits that constrain the vessels for tow-to-port operations (i.e., to bring the device to the onshore port for maintenance) are 70% lower than the ordinary significant wave height (H_s), wind speed, and current speed limits for the same vessels. However, these values are not provided.

Brons-Illing [30] considers one case study comparing repair-at-site and T2S strategies. There were a total of three scenarios/case studies considered with two sub scenarios each simulating near, mid and farm from shore, with and without T2S capabilities. The general focus of the paper was OpEx and the wait time for repair. The paper provided extensive detail in the activities required for a T2S maintenance approach, providing vessel details/limits and timings of each process.

The papers also produced differing results. This can be attributed to a number of factors including differences in cost models, type of modelling tool used, and case study. There are also significant differences in the publications regarding failure data. Details of the different results and the differences in input are given in Table 5.

Brons-Illing [30] models the same site at different distances to shore (37 km, 65 km and 93 km). Table 5 shows the results for the 37 km site due the site used within Rinaldi et al. [28] being 40 km from shore. Although the availability for both publications is similar, it should be noted that within Brons-Illing [30] this value was used as a model input.

Rinaldi [28] found the O&M costs for the two FOW scenarios are +17% and +21% higher than the BFW for discontinuous and continuous T2S, respectively, resulting in a decrease in total income. As Brons-Illings [30] only modelled FOW sites, there is no comparison to be made between FOW and BFW. However, they do provide a comparison between onsite maintenance only and an onsite/onshore hybrid scenario using T2S. For its closest-to-shore scenario, T2S resulted in a +17% increase in cost for a T2S scenario compared to onsite maintenance. Identical to that found in Rinaldi et al. [28] for discontinuous maintenance. For the site 65 km and 93 km from shore, Brons-Illing [30] saw an increase of +7.6% and +23% respectively when compared to a maintain on site approach.

However, T2S performed well against the BFW maintain at site approach in Ref. [28] when analysing other KPIs [28]. could be treated as a FOW site with maintenance on site only. In this case, a discontinuous T2S strategy saw an increase in energy produced, capacity factor, and revenue when compared to the BFW scenario. This highlights the importance of analysing the impact of strategies across a number of KPIs to determine the true impact of the decision.

6.3. FOW modelling influential factors

This section discusses the inputs and influential factors considered within FOW modelling. It is also important to identify the types of structures modelled as this may limit the maintenance strategy. Details of the works studied in this section are detailed in Table 6 with additional information on the type of support structure used. In the following subsections, we comment on the individual influencing factors presented in the literature.

Based on the existing FOW O&M literature, the following key inputs have been identified:

- ***Metocean conditions***: all weather data needed for analysis, typically inputted to the model as a time series. Typically includes H_s and mean wind speed.
- ***Taxonomy and Reliability***: details of the turbine structures and substructures, including associated failure rate and repair times. This section is particularly important within FOW modelling due to the increase in components, e.g. support structure, mooring system.
- ***Maintenance***: the type of maintenance (corrective/preventive, onsite/offshore) and the general maintenance schedule.
- ***Transport***: details relating to all vessels/transport needed to perform O&M activities, including cost, speed, capacity, and operational limits.
- ***Site logistics***: turbine and site modelling with details such as power curves, distance to shore, number of turbines, depth of site, etc.
- ***Cost data***: cost of repair, electricity price and other direct O&M costs such as spare parts, tax, rent & rates and balance of plant
- ***Crew***: crew availability and capacity. Some models state this as an independent input and others included within their cost data as a direct cost

The key factors identified in the table above are in line with those identified by Seyr et al. [17] for BFW O&M modelling. However, areas such as vessel routing and availability of spare parts are not included in the majority existing FOW studies. This is likely due to the infancy of the technology and lack of operational experience. It is expected that more

Table 5
Key inputs for T2S maintenance from Rinaldi et al. [28] and Brons-Illings [30].

	Tug Speed	Tug H_s	Location	Distance to shore (km)	Capacity (MW)	Availability	Lifespan (years)
Rinaldi et al. [28]	30% ↓	70% ↓	Westermost Rough	40	200	96.4, 97.1%[a]	5–15
Brons-Illings [30]	3 m/s	2 m	German Bright	37[b]	400	95	20

[a] Rinaldi models tow to shore as two separate strategies, continuous operation (96.4%) and split (97.1%).
[b] Results of the 37 km scenario used in Ref. [30] - total of 3 distances used. 37 km closest linked to Rinaldi et al. [28] case study.

Table 6
Existing O&M modelling literature with known model inputs and floating support structure.

Publication	Inputs	Support Structure
Castella et al. [24]	**failure rates, characteristic values of vessels and equipment, and weather conditions** (ECN O&M Access Tool)	Spar
Rinaldi et al. [28]	**metocean data** of the offshore location, taxonomy (sub-assemblies and components), **reliability** (failure rates, redundancies, criticalities, dependencies), power performance of the devices; specifics of the access systems (**vessels, work-boats, helicopters**); planned **maintenance schedule**	Generic/not stated
Katsouris & Marina [29]	Geographic Information System (GIS) parameters, turbine parameters, **farm parameters**, electrical infrastructure parameters, construction **costs**, project funding	Spar, semi-sub, TLP.
Brons-Illing [30]	**site logistics** (wind farm size, turbine size, distance to shore, maintenance strategy (tow to shore or maintain at site), **cost data**, feed in tariff, energy production, annual **scheduled maintenance**, time to repair, **metocean conditions**, **vessel types**	Generic
Utne [53]	**weather conditions**, wind turbine design/quality, **maintenance strategy**, **personnel**, **transport**, **spare parts**, lifting and hoisting equipment	Generic.
Martini et al. *a* [49]	**failure and repair time**, turbine model, wind farm model	Semi-sub
Amorim [44]	**weather conditions** and **vessel and technician's availability**	Semi-sub
Gray[a] [45]	platform, wave energy converter (power matrix, wave height wave period), **wind turbine** (power curve, wind speed), **failure rates**, **costs**, **vessels**	Hybrid Wind/Wave Device
Elusakin et al. [50]	**taxonomy** (subsystems and components), **type of maintenance** and **site logistics** (travel to and from WT), **failure rate** (logistic time, repair time degraded condition)	Spar
Dewan & Asgarpour [54]	**wind farm characteristics** (depth, distance, turbine size, no turbines, capacity), **vessels** (speed, charter), **maintenance strategy**, ownership of JUV, equipment	Generic
Ginatautas et al. [55]	forecast **met ocean conditions**, operation model input (cranes, vessels, lifting equipment), time series of relevant response, equipment acceptance criteria, estimates of statistical parameters of extreme equipment response distributions	Spar
Martini et al. *b* [56]	**weather inputs**, time, **reliability**	Generic

[a] Gray models a hybrid wind and wave device, however the modelling techniques and methodology are still applicable to FOW systems.

specific issues such as routing and transportation fleet optimisation will become areas of research specific to FOW in the future. Other potential inputs are specific to the modelling technique such as GIS parameters, acceptance parameters, hoisting, and lifting limits.

6.3.1. *Weather and environmental modelling*

BFW literature has identified wind speed and H_s as the key weather considerations. Table 7 identifies the type of weather inputs included in O&M modelling of FOW sites.

Rinaldi et al. [28] uses time series weather windows which using hindcast or synthetic forecast data, refer to wind, wave and current characteristic parameters. These weather inputs are based on previous work by Rinaldi [47] which provides details of the model used for both wind and wave energy converters. These inputs are no different to that of the BFW application of the model. Wind speed, H_s and wave currents are also modelled within Katsouris & Marina [29]. Within the model after the weather restrictions are defined, the accessibility vectors are formed for each step by examining the climate data. They cite the inclusion of additional limiting factors such as swell and fog as areas of future work, however, these parameters are not specific to FOW.

Brons-Illing [30] and Dewan & Asgarpour [25] use a similar weather window approach based on H_s and wind speed. Within Brons-Illing [30] the meteorological and oceanographic data used are taken from the metocean report compiled by the Danish Hydraulic Institute that contains H_s and wind speed in 30-min time intervals based on hindcast data for a 29-year period for a site in the German Bight of the North Sea. Dewan Asgarpour [25] account for the true weather conditions at these sites using satellite weather data representative of the locations of the five case studies considered.

Martini et al. b [56] provides one of the most comprehensive list of weather conditions. They use databases developed at the Environmental Hydraulics Institute of Cantabria using long-term time series of wind and wave conditions with high spatial and temporal resolution, which have been calibrated through satellite data and validated against field data. The model simulates nonlinear wave interactions, white capping, and effects of depth-induced refraction. The time resolution is 1 h, and the data are available from 1979 to 2014. The data is provided in the form of undisturbed mean wind speed (extracted at a height of 90 m) and prevailing wind direction.

Martini et al. a [49] also utilises the Hydraulics Institute Cantabria databases. Data includes wind data (mean speed, mean direction) and

Table 7
Key weather inputs used within FOW O&M Modelling.

Publication	Weather and Environmental Condition					
	H_s	Wind Speed	Wave Current	Wind direction	Peak Wave Period	Wave Direction
Dewan & Asgarpour [25]	✓	✓				
Rinaldi et al. [28]	✓	✓	✓			
Katsouris & Marina [29]	✓	✓	✓			
Brons-Illing [30]	✓	✓				
Martini et al. *a* [49]	✓	✓		✓	✓	✓
Gintautas et al. [55]	✓	✓			✓	
Martini et al. *b* [56]	✓	✓		✓	✓	✓

wave data (H_s, wave period, mean direction) with a time resolution of 1 h are extracted for the twenty years period between 1994 and 2013.

Within industry, turbines across the site are generally fitted with metocean monitoring equipment. H_s is often viewed as the determining factor for access/no access decisions, as this is the KPI typically written into the vessel contract. However, data collected about wind speed are also vital for the overall control and monitoring of the asset.

Mean wind speed and H_s remain the key weather factors for O&M modelling offshore as these inputs are consistent across all models. However, other characteristics, specifically additional wave data, are becoming increasingly important for FOW modelling as presented within the literature. This parameter is currently lacking in existing models.

6.3.2. *Taxonomy and reliability*

Reliability data and failure rates are used within O&M modelling to determine the number of transfers per annum. Failure rates also impact the direct costs of the site as they influence maintenance activity and therefore the cost of labour, vessel charter, fuel, materials and spare parts. In some cases, failures are assumed to occur after a certain amount of time and are therefore modelled in a deterministic way. In other models, failures occur with a certain probability that is assessed based on collected data, so the failures occur randomly according to a defined probability distribution. Details of how failure rates are modelled for FOW are given in Table 8 with details of the taxonomy and components modelled.

Only one of the publications discussed [28] uses existing failure rate data. This data is from Carroll et al. [58], which is used extensively within BFW modelling. The data presented in Ref. [58] is based on 350 offshore wind turbines throughout Europe, and provides failure rates for the overall wind turbine and its sub-assemblies. Due to confidentiality, specific details cannot be given. However, the collected data is for a geared turbine with an induction machine with nominal power is between 2 and 4 MW. The data has been adapted for this work to be used by averaging the values for the maintenance categories [59]. [28] assumes that both the BFW and FOW scenarios have the same taxonomy, components, and sub-components. However, in reality, there would be an increase in the number of components for a FOW turbine. A total of 16 components are modelled, eight of which would require T2S maintenance for the FOW scenario. Due to the timeline of FOW installation, the machines are expected to exceed 10/12 MW capacity. Hence, these failure rates may be outdated.

Brons-Illing [30] did not provide details of reliability and failure data, however, they did provide details of how the failures were grouped. The failures were split into the following categories: wind turbine generator, floating substructure, and tower and subsea installation.

Elusakin et al. [50] used a system of eight FOW subsystems comprising of components: drivetrain unit, hydraulic system brake system, yaw system, pitch system, rotor system, power system, and structure. They also give details of the components which make up these systems (total of 20). The structure system accounts for elements such as the tower, the floating foundation, and mooring lines. The eight subsystems are connected in series with each other, which means that the wind turbine cannot function if any of these components fails. To model the degradation process of components, four states are defined: normal, degraded, critical, and functional failure. The component moves from normal state to degraded state after a delay represented by a Weibull distribution.

Table 8
Failure and Degradation modelling within FOW publications.

Publication	Failure Modelling	Taxonomy
Rinaldi et al. [28]	Adjusted (Carroll et al., 2016) [57]	16 components
Martini et al. *a* [49]	Exponential probability density function (pdf) with constant failure rate (γ)	12 components
Gray [45]	Monte Carlo analysis	N/A
Elusakin et al. [50]	Weibull distribution with shape parameter, β, and scale parameter, η	8 FOW subsystems comprising of components

The work by Martini et al. a [49] aimed to simulate increased failure probability for FOW sites compared to onshore, due to more severe weather conditions and platform motions [49]. uses a constant failure rate within the modelling. The methodology proposed in their work has more complex failure rates can be included such as a bathtub curve failure modelling approach. The duration of maintenance activities offshore is characterised by a relatively high degree of uncertainty, which is associated with the variability of metocean conditions and the availability of technicians and vessels. Reparation times are modelled by a lognormal pdf.

Gray [45] highlights the importance of failure rate data within O&M modelling and its associated uncertainty. The number of components modelled in unknown, however a total of 12 failure modes (ID's) were modelled. Gray [45] models failure rates using Monte-Carlo analysis.

There is a clear move from the classification of repairs being major/minor to at-shore/at-port due to the possibility of T2S. FOW turbines also introduce additional components with largely unknown failure rates. The literature also does not address how motion and a harsh environment will impact the overall degradation of assets. The scaling of turbines and its impact on failures must also be addressed, both for BFW and FOW. Despite the lack of operational failure data for FOW, other methods of failure modelling should be applied as explored in Ref. [60] by analysing future trends and using available data..

6.3.3. *Vessel*

Within BFW the typical included vessels are crew transfer vessels (CTV) and service operational vessels (SOV). During major component replacement and repairs, a JUV, HLV or specialist field vessel (SFV) may be required. Helicopters are also utilised for O&M activities but are limited due to space and weight restrictions. This section examines the fleet.

None of the examined works include heli-operations. Martini et al. a [49] do not provide details of the vessel used but include vessel expenses as a direct cost. Dewan & Asgarpour [25] provide the most comprehensive details of potential vessels including weather limitations (both H_s and wind speed), speed, technician capacity and cost. There has been no change to the H_s and wind speed transfer limit of the vessel, therefore assuming transfer from fixed to floating will be the same as floating to floating. They also provide additional details such as charter rates, number of available vessels, and mobilisation times for both the towing vessel and the jack-up barge.

Brons-Illing [30] models three vessel types in their work, CTV, SOV, and an anchor handling tug supply vessel (AHTS). The use of an AHTS is omitted from BFW models as T2S is not considered. They include details of the number of vessels used, crew capacity, and day rates for each of the vessels used.

Gray [45] uses a tug vessel for T2S operations, but does not explicitly state details surrounding the vessel capabilities.

> [30]the H_s limit for CTV remains at 1.5 m–2 m for safe transfer. Specialist maintenance vessels such as an SOV, SFV or mothership limiting conditions ranges from 2.5 to 4 m. Rinaldi et al. [28] states that the weather limits during T2S operations decrease by 70% and the vessel speed is reduced by 30%.

However, as discussed in 6.2.1, there is a lack of standardised data surrounding T2S operations. There are discrepancies regarding the speed of a tug boat (both when towing and not towing) within the literature. Maienza et al. [40] state the lowest tug speed at 1.86 knots and Dewan & Asgarpour [25] the highest at 8–10 knots.

Table 9

Vessels considered for FOW O&M activities. Selection used for FOW maintenance. Due to the addition of a T2S strategy, specific towing vessels are expected to be included. The types of vessel used are described in Table 9.

Publication	CTV	SOV/ OSV	HLV/ JUV	SFV	Helicopter	Tug vessel	AHTS	Additional Information
Rinaldi et al. [21]	✓		✓	✓				No limit on availability
Castella et al. [26]	✓	✓	✓					Other vessels include: david crane, cable repair vessel and diving support vessel.
Brons-Illing [27]	✓	✓					✓	
Dewan & Asgarpour [41]		✓				✓		
Amorim [44]	✓							
Gray [45]	✓					✓		

Works including [25,27,30,40,61] all provide details of the cost of charter of the vessels. Harrison et al. [61] acts as a reference document providing details of the vessels and their applicability to specific support structures. A summary of the expected day rates for typical maintenance vessels is presented in Figs. 2 and 3. The figures were created by determining the interquartile range of the data set generated from the literature. Outliers were classified if they exceeded the equation (1).

$$Q_i \pm (1.5 \times \times Inter - Quartile\ Range) \tag{1}$$

where Q represents the first (Q_1 -) or third (Q_3+) quartile depending on identification of maximum or minimum outliers.

It is important to specify between a tug vessel and an AHTS as seen in Figs. 2 and 3. The price difference between the two methods is significant and therefore will have an impact on OpEx and LCOE. AHTSs are more likely to be utilised in the installation and decommissioning phase of the lifecycle, whereas the cheaper tugboat will be utilised in day-to-day operations. The JUV remains the most expensive element of the fleet; this may increase due to the expected peak in demand before 2030 [62]. The JUVs are also limited in depth to 60 m [6], making them unsuitable for FOW.

6.3.4. Economics and cost parameters

The LCOE has been covered in detail in Section 5. This section analyses the use of economic and cost parameters within articles with a focus on O&M modelling. Rinaldi et al. [63] gives details of the source of revenue for the site including a strike price of £57.50/MWh - in line with the results from the UK Round 2 offshore auction results. Nnadlil [64] uses a price of 10c€/kWh and in Dewan & Asgarpour [25] the price of energy is assumed at 13 c€/kWh. Gray [45] provides details on the split of revenue for their FOW/wave hybrid. The wave energy converter provides 28% and the FOW generator 72%. This is based on the installed capacity of each of the devices.

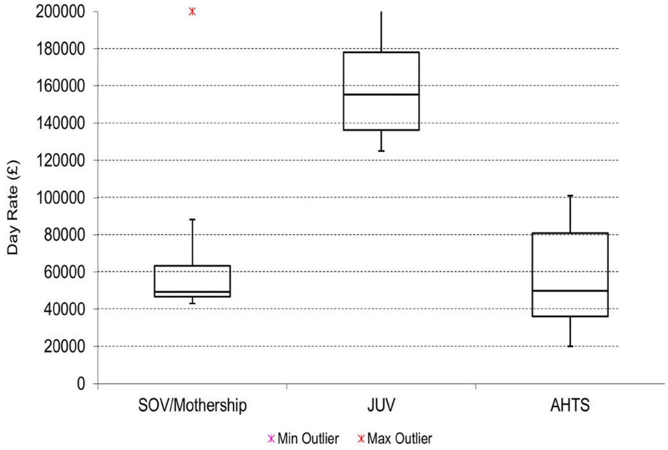


Fig. 2. Average Day Rate (£) for SOV, JUV and AHTS as found in the FOW literature.

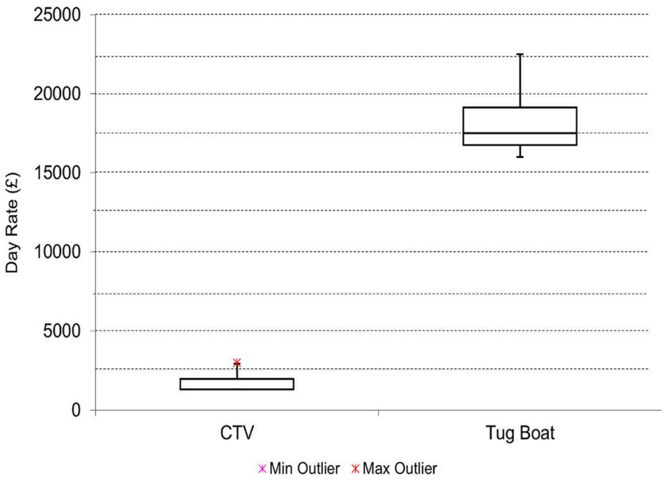


Fig. 3. Average Day Rate (£) for CTV and Tug Boats as found in the FOW literature.

One of the key outputs of many of the existing literature is LCOE, as discussed in Section 5. Brons-Illing [30] provides a comprehensive methodology to compute this, including contractual financing, contingency, insurance, soft cost, balance of station cost. However, the work does not include final LCOE outputs for the case studies presented due to the vast variability of some of the inputs such as balance of plant, cost of energy and tax.

Katsouris & Marina [29] provide cost details with respect to the cost of a turbine, the balance of the plant, the connection to the grid and the cost of financing. They also include details of the expected decommissioning costs, junior and senior debt.

Martini et al. a [49] defined the direct O&M cost as the cost of crew, vessels, resources, etc. The indirect costs are lost production.

Details of the CapEx and cost breakdown structure is beyond the scope of this review. It is important to understand the financial period in which large-scale FOW sites will become operational.

6.3.5. Additional factors

While comparisons can be made between the BFW and FOW modelling processes, there are certain additional factors that must be considered in the modelling process specific to FOW operations. Rinaldi et al. [28], Brons-Illings [30] and Dewan & Asgarpour [25] explored the possibility of T2S as part of their maintenance operations. This has been identified as the main additional factor when modelling O&M processes for FOW. This is discussed in further detail in Section 6.2.1.

Eluskin et a [50]; includes details of the mooring lines as an additional component with the potential to fail. They also acknowledge that performing FOW maintenance is more difficult, time-consuming, and risky for the personnel involved. Bjerksters [27], Martini et al. a [49] and Katsouris & Andrew [29] also provide details of the mooring system components within their analysis.

Within the LCOE papers such as [35,36] bathymetry was used as an indicator of feasibility of the site based with draft of the support structure informing a lower suitable limit. The mooring and anchoring system is included as a CAPEX cost in Ref. [40] and as a direct labour cost in Refs. [31,37].

Works including Dewan & Asgarpour [25] also identify port logistics and additional weather restrictions as areas of future research. Within the existing literature, the key addition to the work to account for the FOW structure is the inclusion of components such as the mooring lines, anchoring, etc., in addition to the T2S strategy. Other factors such as turbine motion, workability, floating-floating transfer are not considered within these works. However, this may be due to the lack of understanding of the area at this point, with a more detailed analysis of these features being integrated into the modelling process later.

6.4. *KPI*

During O&M modelling, the key outputs of the models are typically based on energy and cost, for example LCOE, OpEX, annual energy yield, and availability. Details of the outputs/KPI's modelled in the literature are provided in Table 10.

The main KPIs modelled include direct O&M costs, availability (both time and yield), and overall cost of energy (cost per kWh). Time associated with repair and maintenance is also identified as key KPIs for FOW, particularly in works with a T2S strategy.

The work of Martini et al. b [56] is a mix between O&M modelling and a feasibility study. The main outputs of their work is focused on accessibility at a number of or a number of locations. This is based on location, weather and transportation selection. Accessibility has a direct impact on site downtime. This will become increasingly important as sites move further from shore and weather windows become more critical.

The impact of KPIs on O&M activities has been explored by Hawker et al. [65] and Gonzalez et al. [66]. Both works found that different parties within the supply chain will have different KPIs and contractual agreements, which in some cases can be conflicting. The choice of contractual interface (turnkey operations contract, full owner-operator, multiple contractor arrangements) will impact the ranking of KPIs. The addition of FOW sites will see UK harbours/ports supporting multiple sites. In the future, the sharing of assets such as a vessel fleet and/or specialist vessels amongst a few sites may become the norm. Therefore, it is likely that faults/failures across sites will need to be prioritised. Standardised KPIs across sites are vital to effectively analyse the performance of the site and make valid comparisons to other sites/previous years of operation.

6.5. *Safety and working limit publications*

As widely cited in the literature [49], the motion of the turbine will be one of the biggest challenges for FOW O&M activities. The turbine motion is likely to have a significant impact on transfer safety and personal comfort. The work in this area is currently limited. There remain questions surrounding floating-to-floating transfers using an SOV. Within the UK it is expected that these FOW farms will be farm from shore, making an SOV the preferred choice for maintenance activities (>50 nm) [67]. Therefore, it is vital that the working limits of these vessels are explored within a FOW context. At present the SOV can safely transfer at 2.5–4 m H. Guanche et al. [68] and Li 2021 [69] both explore the suitability of a work to walk system in a FOW farm.

Guanche et al. [68] models two vessels: a catamaran equipped with fender, and a supply vessel with motion compensated gangway. The catamaran can handle wave heights up to 2 m, provided that it can work under head sea conditions and take advantage of the shielding effect of the platform. The supply vessel allows personnel transfer with wave heights up to 5 m, but it is important that roll motions are not excited.

In Li [69] special attention has been paid to the impact of second-order drift motion - which is traditionally not taken into account in operability analysis. The limiting wave heights that considering wave frequency motion concentrate about 3–5 m. At very short Tp like 4.5 s, the limiting wave height could be up to 10 m. By taking into account the nonlinear drift motions, the general limiting wave height reduces to 2–3 m.

Scheu et al. [70] examine the influence that the structural motion has on humans located on the asset in a harsh environment during maintenance activities and its implications towards personal safety, human comfort and the ability to work. The results show that the weather windows for maintenance activities are reduced by up to 5% when adhering to the guidelines that suggest limiting threshold values for acceleration exposure. The corresponding potential financial losses materializing due to longer turbine unavailability after a fault are significant. This impact is amplified by the expected increase in distance to shore for FOW sites.

The impact of safety of personnel is an area which is often neglected within O&M modelling, both for BFW and FOW. Due to the expected harsher environment and more challenging conditions of a FOW site, it is vital that these safety criteria/concerns are embedded within the O&M modelling and decision making process from the beginning. However, the overall impact of turbine motion will be largely dependent on the environmental conditions of the site. As shown in Ref. [69], the wave limits are within the existing limitations for transfer for BFW.

7. Conclusions

In this review article, an overview of current publications

Table 10
KPI/output of existing FOW O&M publications.

Publication	Availability	LCOE	Total O&M costs	Lost Energy/ Downtime	Other
Castella et al. [24]	✓	✓	✓		
Rinaldi et al. [28]	✓	✓	direct	✓	Electricity generated, capacity factor, equivalent hours, total revenue, final income
Katsouris & Marina [29]		✓			CAPEX
Brons-Illing [30]			5 years	✓	WBS (labour, vessel cost), T&I process
Utne [53]		✓	✓		
Martini et al. *a* [49]					Accessibility, waiting time
Amorim [44]			✓		Wind farm performance
Gray [45]			✓		
Elusakin et al. [50]					Expected number of repairs and associated costs
Dewan & Asgarpour [54]	✓	✓	✓		Costs per kwh, repair cost
Gintautas et al. [55]					Weather windows
Martini et al. *b* [56]				✓	

surrounding O&M modelling for FOW specific applications has been presented.

A review of the case studies used within these types of analysis has been presented for publications focused on both LCOE/cost modelling and O&M modelling. Northern Europe was determined to be the key area of development as a result of the number of case studies presented in this region. However, studies in areas such as Asia and the US have been omitted despite the potential resource and market.

There has been a significant research of cost estimation for FOWT due to the infancy of the technology and lack of commercial projects. There is a lack of agreement within the literature on which support structure will result in the lowest LCOE, revealing the importance of specific inputs, particularly environmental and geographical.

Several of the publications reviewed in this paper, which focus on LCOE and cost modelling, also act as feasibility studies for their specific location. However, one detail missing from these reports is the determination of the suitability of the existing port infrastructure. The capacity of the port will determine whether the location can support the supply chain required for FOW installation and may also limit the suitability of a T2S strategy. Ports which already support BFW sites may become oversubscribed by the addition of FOW in their seas.

The key inputs to these models have been identified as: metocean conditions, taxonomy & reliability, maintenance strategy, transport, site logistics, and cost data. Each input has been presented in further detail with details of changes needed for these inputs from a BFOWT to FOWT scenario.

The key additional considerations within the existing literature for FOWT O&M are: addition of support structure and floating components; and the T2S maintenance strategy. These factors impact the taxonomy, reliability and maintenance inputs directly. Further clarification is required for T2S operations, specifically regarding time frames and vessel abilities.

The modelling techniques, the use of weather data, and the logistics of the site are consistent with those of BFW. Weather data used within FOW applications include increased detail such as wave current and period. Within the vessel input, CTV and SOV remained the key vessel choices. However, the unsuitability of JUVs and HLVs led to the introduction of T2S through the use of tug boats.

Inclusion of the support structure and anchoring and mooring system has been the main change in FOW O&M modelling. However, because of the infancy of the industry, developer data is extremely scarce. At present, existing data bases have been used in conjunction with statistical techniques. More analysis is needed to determine the failure rates of these components in addition to understanding the impact of turbine motion and harsher environments on the degradation process of existing components.

To the authors knowledge, there are only three publications which examine the impact of the turbine motion within an O&M context. Currently, there is a disconnect between different areas of research. Factors regarding the safety of personnel and the motion of the asset are not included within the O&M modelling work. Key recommended areas of future work within O&M modelling for FOWT activities include:

- ***Wider Case Studies***: There is a need for O&M case studies for sites out with Northern Europe. In addition, there is a significant lack of case studies in sites far from shore (>50 nm) which is where the majority of sites within the North Sea are likely to be located. By adopting more relevant sites and modern technology (in terms of turbine capacity), a more realistic view of O&M and OpEx can be found
- ***Support Structure***: More data is needed regarding specific failure rates of the support structure of the FOWT. Accurate data will reduce uncertainty in the O&M model
- ***Tow To Shore***: The T2S strategy has been explored within the literature thus far. However, there are conflicting views on key aspects of the procedure such as time to disconnect, towing speed, and weather limitations. It is vital that these values become standardised
- ***Working Limits***: Research on the working limits on these floating structures is limited; however, it is widely expected and cited that the turbine motion will somewhat limit the workability. Evidence suggests that the response amplitude operator will be the most prominent indication of the safety of the working limits. Currently, typically H_s and wind speed are recorded on site. Additional measurements at site, such as Tp, may be required to ensure the safety of personnel.
- ***Multi-disciplinary Modelling***: There has been a number of reviews focused on the structural element of the different support structures used within FOWT. Within these reviews there are recommendations/key information regarding the O&M activities. The limited work done regarding working limits has some vital results which should be included within specific O&M modelling. It is recommended that a multi-disciplinary approach should take place when modelling these systems including inputs from the structural reviews and the detailed work on work-ability and safe operating limit. This, in turn, will create a more robust and reliable model.

It is expected that future work will expand upon the work cited within this review, adding FOW complexities such as detailed taxonomies, in depth detail regarding T2S operations and clarification surrounding access condition limits due to vessel movement, floating to floating transfer and technician safety.

CRediT statement

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Declaration of competing interest

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