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A review of the technical challenges faced in floating offshore wind turbine deployment

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Abstract
The cost-effective deployment of floating offshore wind turbines is faced with a multitude of technical challenges. Several key areas of the life-cycle of floating offshore wind turbines have been discussed within this work. The key challenges and potential solutions have been presented, with state-of-the-art literature summarised to enable further work to build off. It is concluded that all areas of the use of this technology requires further maturing to de-risk this technology to entice wide-spread commercial use.

Introduction

The utilisation of offshore wind energy is one of the most important sources of renewable energy currently in development around the Globe, with Europe noted to have the largest amount of potential floating wind capacity, at 4,000 GW [1]. Studies have found floating substructures for wind turbines to provide greater advantages over the fixed-base platforms in water depths between 60m and 100m [3]. Therefore, the maturing of Floating Offshore Wind Turbines (FOWTs) may be the key to unlocking this increased availability of wind.

A limited number of Lifecycle Assessments (LCAs) have currently been conducted on FOWTs, with LCAs mainly focussed on land-based and shallow water (<30m water depths) installations [4], therefore the understanding of the risks and challenges is currently limited for this technology, resulting in an increased need for these assessments to mature this technology. This work aims to evaluate the technical challenges currently present in literature with regards to the lifecycle of FOWTs. To realise this, this paper is structured to analyse these challenges in the order seen during the lifecycle of the deployment of this technology. Namely, the economics of scaling up the technology, the design and structural challenges, followed by the manufacture, installation and operational challenges present.

Economics and importance of “scaling up”

The economies of scale mean that wind farms are ever increasing in size to reduce the Levelised Cost of Energy (LCOE) of this technology [5]. This has been predicted to plateau after the installation of 600 FOWTs by around 10- 15%, dependent on several factors such as substation configuration and vessel requirements [6]. Although increased turbine lifetime has also been noted to reduce the LCOE of the installations, this reduction has been hypothesised to not be advantageous after 25 years, due to the additional probability of exposure to severe weather conditions resulting in additional structural costs to withstand them [6]. However, cost reductions are still possible in the research and development of more cost-efficient components and maintenance procedures, such as the turbine itself and the foundation.

The increased size of turbines possible in FOWT systems has been also found to lower the LCOE of the project, due to the increased turbine blade area [7]. Studies have found that LCOE of a 500MW FOWT farm at 50m water depth to be lower than that of a fixed- bottom foundation wind farm in shallower waters [8], but without physical installations, these estimations cannot be verified. However, the scaling up of this technology should be conducted slowly, with small scale test sites used to evaluate the performance of the technology before large-scale deployment of arrays is conducted, de-risking designs, and allowing for unforeseen costs to be discovered before it is a major problem, which could be catastrophic for large-scale deployments.

Outlined by Crown Estate Scotland [9], the cost of the support infrastructure and the availability of seabed rights are just two risks to mitigate for this technology, however with suitable management this is possible. However, the proportion of the cost of the turbine is lower for offshore projects than in land-based installations, decreasing further as FOWTs are considered, due to the rising cost and complexity of the foundation technology required for these locations [4]. It has been reported that for a FOWT, only 21% of the cost is attributed to the turbine, with a further 67% for the platform, compared to 45% and 33% for the turbine and foundations in land-based applications [3]. This lower proportion of cost for the turbine in floating platforms may lead to additional development opportunities for other wind turbine designs, such as the Vertical Axis Wind Turbine (VAWT) discussed later.

Presented in Table 1 are the different locations and their respective foundations for wind turbine installation, including their respective costs and power output [10]. It can be observed that the capital expenditure and LCOE of FOWTs is predicted to be over 4 times that of a land-based installation, indicating this technology to be cost prohibitive. Yet, another source indicates that an installation of 100 Tension Leg Platform (TLP)-based FOWTs would have an LCOE of $124 (£95)/MWh, competing with the fixed-base offshore wind turbine LCOE of $179/MWh [11]. The first FOWT farm to be installed has been reported to have a net capacity factor of 65% over the first 3 months of operation [12], as well as other sources reporting predicting capacity factors of greater than 50% for FOWTs [9]. This range of results indicates the current difficulty in calculating the costs associated with this technology, requiring a considerable range of factors utilising many assumptions for the LCOE to be determined [13]. Nevertheless, the significant cost increase for FOWTs over land-based systems is still a hurdle for developers.

It has been noted that a saving of 50% is possible for operation and maintenance activities, which has been noted to comprise of one third of the cost of the energy produced [14], with only 14.7% expected in construction and manufacture of load bearing components [15], displaying the gap in knowledge of operating FOWTs effectively, which is to be expected due to the lack of commercial installations currently in operation. Also noted in Table 1 are the embodied CO_2 amounts required to manufacture and install a wind turbine in each location [16]. The shallow water installations tend to have the highest CO_2 requirement, noted to be due to the machinery and materials used in the monopile installation for the foundation of the turbine. This shows an advantage of FOWTs over their shallow water counterparts, where they can be fully installed onshore and then towed into position for costs an order of magnitude less than that of fixed-bottom offshore installations [1].

Turbine and floating platform design

Several factors affect the performance of wind turbines. Namely capacity factor, operating wind speeds and turbine size. Capacity factor is a measure of the energy produced by an installation, over the maximum output possible, providing an indication on the efficiency of the installation. Relying heavily on the availability of the wind, the move of wind turbines offshore aids in the removal of land barriers that would restrict the flow of the wind, therefore increasing wind speeds and its availability. Wind turbines can operate over a range of wind speeds, with designed minimum and maximum wind speeds for operation. It is important to note that maximum power output is not reached until the rated wind speed, where power output plateaus above this speed [17]. At excessive speeds, braking systems are employed to stop the turbine, preventing destruction of components, with some turbines using a blade pitch adjusting system to feather the turbine blades to achieve this. These systems will require additional support for use in the FOWT system, due to the increased wind speeds and need for higher reliability due to the more remote nature of these installations. As the installation of wind turbines in deep water locations allows for the utilisation of larger wind turbines, blade lengths are ever increasing.

Increasing the turbine blade length has been shown require exponentially greater mass [7], therefore better materials and construction techniques are required to reduce this, possibly also aiding in the reduction of oscillatory forces, which are detrimental to the fatigue life of the turbine.

Horizontal-Axis Wind Turbines (HAWT) have noticeably been the popular choice for wind power generation over the past 20 years, resulting in a reducing LCOE as this technology is matured. However, the LCOE reduction required to incentivise the creation of FOWTs has be found to not be likely using HAWT [18].
Although most of the development in wind turbines has been used to mature the "conventional", horizontal design, research has also been conducted into the feasibility of other designs, such as VAWTs [19]. As noted previously, the lower proportional cost of the turbine within the FOWT system may lead to further development opportunities for other turbine designs such as the VAWT, which may lead to a lower LCOE for FOWTs.

The power generation capacity of VAWTs has not been increased to the same level of HAWTs, with the largest found to be only 5MW [19]. With a lower centre of gravity and simper design, the size (and therefore cost) of the platform required for stability could be decreased [20], possibly increasing its attractiveness as a technology. However, due to its lower maturity, there are more risks, with fewer case studies to use, restricting the funding sources for this design, in favour of more mature technology, HAWTs [20].

Table 1: Cost of Installations in Different Locations [9]

Turbine Type	Capital Expenditure ($/kW)	Capital Expenditure ($/MWh)	Operational Expenditure ($/MWh/year)	Levelised Cost of Energy ($/MWh)	Net Capacity Factor (%)	CO_2 Payback Period (Months) [15]
Land-Based (2.16MW)	1,590	34.9	14.4	49	41.0	6
Fixed-Bottom Offshore (4.71MW)	4,579	129.5	43.3	173	41.7	11
Floating Offshore (4.71MW)	6,383	181.2	25.6	207	41.5	8

Analysis of component reliability within a turbine has been a widely documented process, which is of importance to operators to understand the overall reliability of the systems that make up the FOWT [21]. Components such as the generator and mechanical brake systems have been found to be more prone to damage due to weather than other turbine components, only to be amplified more as further offshore installations are developed, with the proximity to water showing higher corrosion and failure rates over time. This is to be expected due to the presence of salt water, known to increase corrosion of materials such as steel, which are abundant in the design of wind turbines, showing the need for addition development to mitigate these problems in a cost effective manner [22].

Currently there are three main types of floating platform used in FOWTs, focusing on their simplicity for ease of manufacture; the TLP, Spar buoy and the semi-submersible [1] [9] [23]. Table 2 shows the general capabilities of these three types. The maximum water depth for fixed offshore wind turbines to be economically viable has been noted to be 50m [2], with floating platforms found to be more desirable for operation in water depths greater than this. This depth increase allows for greater siting of installations to take advantage of the increased wind resource in previously uneconomic locations.

Designs incorporating multiple turbines within one floating platform have also been discussed, reducing the individual moorings and foundations required. However, the larger scale of structures required for this system would require much larger capital investments, resulting in a stagnation of development whilst adequate funding sources are realised. Smaller developments however have been possible, with a recent manufacture of a 1:6 scale dual-turbine model of the W2POWER, scheduled for deployment in May 2019, with the project envisioned to utilise two 10-12MW turbines at full scale [24].

Table 2: Commercial Floating Platform Types [22]

Platform Type	Operating Depth (m)	Turbine Capacity (MW)	Number Installed Offshore
TLP	50-120	5-10	1
Spar - Buoy	50-120	5-10	6
Semi-Sub	>50	5-10	1

Structural challenges and issues

The move of wind turbines to floating offshore locations introduces new engineering challenges that must be overcome for successful operation. Although increasing the size of the turbines allows for higher power generation capabilities, more advanced materials and manufacturing techniques are required to provide cost-effective reliability. Larger turbines, coupled with further offshore installations that utilise floating platforms, leads to additional problems not seen on land projects.

The increased wind loading present in FOWTs, coupled with the addition of waves, proves for additional stability problems, with some literature already evaluating this, although further methods of analysis have been noted as being required to ensure its effects on the structure is fully understood. The floating structure also provides new, un-before seen challenges in the wind turbine industry that are crucial to the success of the project. However, knowledge from the oil and gas industry, may be applied to these problems [25]. As the structure of FOWTs is not fixed to the ocean bed, systems are required to ensure station keeping, to prevent collisions or beaching, as seen by other marine devices where moorings have failed [25]. For this reason, the adequate design of mooring systems and other technologies is required to de-risk the station keeping aspect of FOWTs.

The design of moorings has been a large area of study for the station keeping of all marine-based power generation technologies. Mooring design literature has discussed the optimal designs currently theorised for FOWTs, with work by A. Campanile et al. [26] stating that 6-line mooring systems were the most suitable for the station keeping of FOWTs at water depths of 50-350m, whilst providing the greatest balance of lifetime cost, weigh and redundancy, when compared to 3 and 9-line systems [26]. The use of wire ropes was found to not be a reasonable design choice, due to the larger horizontal distances required when compared to chain cables at depths around 100-250m [26]. This spacing problem is one area where the requirements of this technology is different to that of the oil and gas industries, where the spacing of FOWTs is much closer than that seen for oil rigs. Therefore, a hybrid of cable chains and wire ropes has been identified as an area of further development to possibly rectify this. However, the use of synthetic ropes has also been identified as a low-cost alternative to wire ropes, due to their proven track record in the offshore industry.

As stated by The Carbon Trust [1], the most likely source of failure in the FOWT is expected to be from fatigue or corrosion, with the welding processes for the steel structures used in wind turbines likely to influence the crack growth behaviour significantly. Fatigue problems in turbine blades is a known problem, with ongoing research into simulation and modelling of fatigue propagation. The inclusion of additional forces present FOWTs, in the form of waves and more extreme weather conditions heightens this problem for designers [27], where even the sway of the floating platform may increase cyclic loading on the structures. For this reason, the extended use of Fluid-Structure Interactions (FSI) and other tools is required to fully evaluate systems placed into this extreme environment. Although the development of such analysis processes is required to ensure adequate evaluation is conducted [15].

When migrated from land-based installations to offshore installations, the corrosive environment of seawater necessitated the redesign of components to improve reliability. Prior research and experience gathered by the oil and gas industry will provide an insight into the needs of these structures to withstand this environment, reducing the redevelopment cost. Noted by Price and Figueira [28], corrosion reduces the thickness of components, as well as crack initiation and in turn, fatigue. For this reason, care must be taken to mitigate or reduce corrosion on FOWTs from several conditions, such as the abrasive force from waves, micro-organisms and chemicals.

This protection can take many different forms, from the passive protection given from a coating to active protection, such as an Impressed Current Cathodic Protection (ICCP), to reduce corrosion. Price and Figueira [28] also highlights how a combination of both passive and active systems should be employed to protect a structure from corrosion, for example, the ICCP system may be able to mitigate corrosion in areas where to passive coating layer has been destroyed. Where possible, these protective coatings should be applied thoroughly on land before the structure is installed, with it noted that on-site repair of coatings on marine structures is up to 50 times higher the original cost of application, €1000/m2, once logistics of labour, materials and delays due to weather conditions are considered [29].

Manufacture

Wind turbines are complex structures, comprising of several subsystems atop a steel tower, utilising composite turbine blades for weight-reduction. Ever increasing in size, offshore commercial installations currently utilise 6MW turbines, with the development of turbines of 20MW predicted [15] [30].
As mentioned previously, fatigue is a critical issue in the operations and maintenance of a wind turbine. One area of research is the effect of the manufacturing process of the composite blades in its fatigue characteristics [31]. An example of this variation includes the use of infusion resin, designed to reduce the amount of inclusions present within the component. However, during the curing process, the low viscosity resin used for this process can move around within the mould, due to small variations such as mould tension, causing areas of uneven thicknesses, which can reduce the structural performance of the overall component, as described by the National Research Council [32], highlighting the need for improvements in the manufacturing process to limit this movement.

The design of the Floating Offshore Wind Platforms (FOWPs) relies heavily on the experience gathered by the oil and gas industries for deep water operations [33]. This design reuse jump-starts the maturity in this industry, de-risking this technology and increasing the funding channels of the project, when compared to other novel designs that have not been used commercially by other industries. The use of design standards developed by the oil and gas industry for floating structures will aid significantly with the maturing of FOWP designs [34]. The performance of steel and concrete FOWPs have been evaluated, each with their own advantages. Although ultimately key design decisions should be based on project- specific factors, such as the available construction infrastructure and weather conditions. The proximity of ports to the installation location, as well as their size are key factors in determining the best platform design and manufacture techniques to use.

Noted in work by Lindenberg [35], turbine material usage is predominantly steel, with Glass-Reinforced Polymers (GRP) used for rotor blades. However, other key materials such as carbon fibre will need significantly increased production capacities to reach the future needs of turbines, with Lindenberg [35] stating that just the need for carbon fibre in turbines within the United States will reach nearly 100 million pounds per year. The only other material constraint noted by Lindenberg [35] was the number of furnaces available for the curing of the GRP turbine blades. However, it is expected that this requirement will be coupled with the need for even larger ovens to cater for the ever-increasing size of turbines, especially employed by FOWTs. Looking at the UK however, [9] reports all areas if the UK supply chain as being ready, or having a clear path to readiness for FOWT manufacture [9]. The integration of a FOWP into the FOWT system has been noted by the International Renewable Energy Agency [36] as being a technical and commercial risk, however close working with supply chains may mitigate the risk of use of this technology, where communication of key risks and design challenges is paramount to the swift discovery of solutions.

Although design simplicity is favoured for manufacture, only the spar-buoy and semi-submersible FOWPs have been noted as particularly suitable for high- volume production, necessary for the large-scale utilisation of this technology at a suitable LCOE, with the TLP failing in comparison to these types [37].

To reduce the increasing pollution of the oceans, new materials and manufacturing techniques should be developed to reduce the environmental impact, one key example being the issue of micro-plastics and the electromagnetic fields created by the power cabling, although additional habitats for marine life and birds could be created by the installations, with additional fishing exclusion zones created by the wind farm sites [30] [38].

Installation

The installation steps required for a FOWT can be summarised as follows [39]:

1. Float Out – Hook up to tug boats and float out from the launching site
2. Transit – Towing to the installation site
3. Installation – Mooring and ballasting operations conducted
4. Cable Installation – Laying of power cables to the new turbine and testing procedures conducted
5. Termination – Connection to the power grid and disembarking FOWTs
6. Return – Transit of installation equipment and workers back to port

Ports with adequately deep harbour basins are a necessity for efficient construction of FOWTs, for without this, transport to the sea would be time consuming and prohibitively costly. The chartership of vessels and crews have also been noted to be the main cost drivers for installation [39], depending highly on the proximity of the port to the installation location, as well as the weather conditions.
Owing to the non-permeant nature of a floating platform over the fixed-base types, the possibility of location adjustment is now possible. This moveable nature of the FOWT has led to the development of technologies such as detachable electrical connections for these devices [40], providing uninterrupted power distribution to neighbouring devices, whilst allowing individual devices to be connected or removed as required, possible for servicing or movement to more desirable areas. In doing so, technologies such as this may lead to the ability for the cabling infrastructure to be installed throughout an entire wind farm at once, without the need for individual cable laying at the time of each FOWT's installation, possibly leading to a cost decrease, whilst simultaneously increasing the adaptability of the wind farm.

The installation of FOWTs excels in deep waters, negating the need for expensive piling and construction vessels needed for fixed base installations. The installation of wind turbines in conventional fixed-base structures involves the fabrication of typically a mono-pile foundation. Yet, the viability of these structures is usually limited to operating water depths of below 30m [2]. Below this depth, it has been found to not be economically viable due to the restriction on maintenance and maximum diver depths, as well as the size of structure required [2]. The use of a floating base structure for a wind turbine has currently allowed for operating depths of 100m, providing a significant operational advantage over conventional systems for the location of new installations, with the floating nature of this technology allowing for greater depths as further analysis and development is conducted [2].

Analysis into the effect of misaligned wind and wave loads on FOWTs has been conducted by [7], finding additional considerations into the location and construction of the system is required. The more extreme conditions present in deep waters, as well as making operating conditions worse for the FOWT, operation of the cable-laying and maintenance vessels may also be impeded by these increased conditions, incurring additional costs. However, the ability for larger turbines in these environments may outweigh the additional costs incurred. FOWTs require only towing to the installation location, whereas fixed-base structures require the use of large vessels to install the structure into its final location. As noted previously, the use of larger wind farms would allow for a reduction in LCOE, with the larger space availability of deep water off-shore arrays allowing for the correct spacing of turbines, as so to reduce the effect of wakes and inter-turbine interactions, further increasing the efficiency of the wind farm. One key issue highlighted with the use of deep-water offshore turbines, is the longer distances of cabling required for connection [41]. Cabling is expensive due to the material, installation and maintenance requirements, therefore if this expense can be covered by a larger array of turbines they would be more economically viable.

Parametric design tools have been developed for the whole life cost modelling of offshore wind farms, including the installation of these devices, particularly useful in the estimation of cable lengths required for connections to the substation [42], however the results of models such as these have been noted to be particularly sensitive to several factors, such as the site's location and capacity of the installation. Therefore, further development of these tools is required to provide higher accuracy results for development. This is presumed to improve over time, as more FOWTs are installed, providing more data points for these tools to be compared to.

Operation, maintenance and other key issues

The survivability and reliability of FOWTs is widely acknowledged as one of the major challenges of this technology, with the maintenance tasks of offshore wind farms noted to comprise one third of the cost of energy produced [14]. The combined wind and wave loading mentioned previously is a key topic of research in understanding the needs of the design to withstand the repetitive and adverse forces present between these two mediums. The key operations required in the upkeep of the turbines and their platforms is also an important consideration. To reduce the need for workers to inspect the installations, structural and environmental monitoring sensors are being studied as potential replacements. Structural integrity monitoring is a key component in ensuring operational capability of wind turbines [31] [43].

Literature reveals several projects that look to provide automated analysis of images of turbine blades for surface cracks, which could lead to structural damage if not properly maintained. Work into monitoring blade structure health, internal turbine health and position monitoring of the structure are being developed, all working to monitor the condition of separate sections of the turbine's components [31] [44]. The use of these sensors allows for the turbines health to be monitored remotely, with data sent to monitoring stations, where structural failures could be predicted, and suitable preventative measures assigned. As deep-water offshore installations are more isolated than other deployments, a higher level of automation is required to reduce the costs needed for physical assessments that may be costly to reach the remote locations FOWTs are installed in. Systems such as those proposed by Friedman et al. [45] allow for the monitoring of significant areas of the turbine system using multiple technologies to identify a fault. However, the fault will still require rectification, meaning that maintenance crews would still need to be assigned, battling the remoteness and adverse weather conditions of the installation site each time.

The adaption of monitoring and maintenance activities conducted in the deep-water oil and gas industry may reduce the difficulty for these activities for FOWTs, were it may be difficult due to the restriction on maintenance possible by humans at the remote locations, resulting in the use of Remotely Operated Vehicles (ROVs). The design of FOWT- specific ROVs coupled with the localised storage of components with the highest failure rate, may aid in the reduction of crew-visits to each installation, minimising most costs. However, development of such a system will be costly, requiring input from all areas of the systems lifecycle and extensive validation activities before this system could be relied on. The distance of offshore wind farms from the mainland is an important consideration in the operation and maintenance plans for these systems, inducing the need for remote monitoring technologies to reduce the inspection visits required by crews, whilst simultaneously providing a larger dataset for analysis and fault prediction to take place to better optimise crew visits [44]. Various Condition Monitoring Systems (CMSs) have been developed to achieve these required monitoring activities, recording parameters such as structure vibration, temperature, rotor speed and power output, as well as factors such as wind speed and direction, all at their specified sampling frequencies, tuned to capture the required amount of data needed for evaluation and fault finding, whilst simultaneously providing real-time feedback [44].

The failure rates of the different components of a fixed-base offshore wind turbine have been evaluated in literature, electrical systems to have the highest annual failure rates more than 0.5 in some cases, with an average downtime of around 2 days per failure [46]. However, due to the infancy of FOWTs, reliable data is not yet available on failure rates or their effect on downtime. It is hypothesised that the floating nature of FOWTs, coupled with their higher distances from shore will result in more difficulty in accessing the components, increasing the downtime of installations. The preventative strategy of replacing components before failure has also been theorised, where components falling into different age groups may be replaced at the same time as other repair procedures, minimising the visits required to a wind turbine for maintenance [47]. Strategies such as this will aid in the minimisation of maintenance procedures for FOWTs, where the remote nature of these installations incurs high costs from maintenance crews. However, some maintenance procedures cannot be performed on location, requiring the towing of the FOWT back to shore. Blade maintenance is an example of this, where work to ensure structural integrity of the blades is critical to the functionality of the turbine. Studies have confirmed that the blades of a turbine are the most critical components of the system, “susceptible to failure due to initiation and propagation of subsurface damage in a number of forms” [48], therefore the development of monitoring tools is paramount to ensure safety and structural integrity of FOWTs if the design and manufacture of these components cannot be improved to reduce these issues.

The use of sensors and evaluation of the ambient noise have been noted to be of use in the detection of damage in turbine blades for offshore installations [49], with other work using novel techniques such as turbine blade crack detection using drones [43]. Novel techniques such as this could be developed to allow for greater automation in the monitoring of remote FOWTs, however this technology requires maturing before acceptance in the industry, through evaluation of its robustness in poor weather conditions in the offshore environment.

Conclusion

This paper has presented a review of the technical challenges present in several key areas in the deployment of floating offshore wind turbine technology. Based on the current level of technology maturity in each of the area, the unique challenges and potential solutions have been identified where possible. These key challenges include the validation of the economies of scale predictions for large FOWT farms, the development of improved construction materials to reduce the mass of the increasing size of turbines, improved analysis techniques for the combined wind and wave loading present on FOWT installations, the adaption of current manufacturing techniques to improve the performance of large components such as turbine blades, optimisation of the power cabling connections to reduce the large costs associated with the long lengths needed for deep water offshore operations, and finally, the development of innovative solutions to reduce the operational and maintenance costs associated with the remote operation of these systems will enable cost reductions noted to be up to 50%.

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