Floating offshore wind turbines: Installation, operation, maintenance and decommissioning challenges and opportunities

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Abstract. The global floating offshore wind energy industry is rapidly maturing with several technologies having been installed at pilot and demonstration scales. As the industry progresses to full array-scale deployments, the optimization of marine activities related to installation, operation & maintenance and decommissioning presents a significant opportunity for cost reduction. This paper reviews the various marine operations challenges towards the commercialisation of floating wind in the

5   context of spar-type, semi-submersible and Tension Leg Platform (TLP) technologies. Knowledge gaps and research trends are identified along with a review of innovations at various stages of development which are intended to widen weather windows, reduce installation costs and improve the health and safety of floating wind related marine operations.

1 Introduction

Wind turbines are moving further offshore to deeper waters and are exploiting higher wind speeds in harsher environments

10   (McCann (2016)). This trend creates additional challenges in the design, installation, operation, maintenance and decommissioning phases of an offshore wind farm. Numerous investigations for developing efficient and optimum Floating Offshore Wind Turbine (FOWT) platforms and various innovative design concepts have been evolving in the last few years (Uzunoglu et al. (2016), EWEA (2013)). Several pilot and demonstration-scale floating wind farms are now operational in different parts of the world (eg: Wind float Atlantic – Portugal (25 MW), Hywind – Scotland(30MW)) and there is a robust pipeline of projects

15   which is expected to deliver 250 GW installed floating capacity by 2050 (DNV (2020), James and Ros (2015)).

To realize this ambition, significant reductions in LCOE (Levelized Cost of Energy) will be required across all key stages in the development of a floating wind farm (Figure 1). Marine operations represent a significant proportion of the offshore wind energy costs. Approximately 15.2% of CAPEX (Capital Expenditure), 50% of OPEX (Operational Expenditure) and 80% of DECEX (Decommissioning Expenditure) are directly related to marine operations for a bottom-fixed wind farm (Judge

20   et al. (2019)). Comparative figures for the floating wind energy industry are unavailable due to a lack of projects, however, investigations by Castro-Santos (2016) show that approximately 36% of the total floating project costs are incurred during the installation, exploitation and dismantling activities .Castro-Santos et al. (2018a) have revealed that the size of the floating wind farms has a considerable impact on installation costs and LCOE. It was found that the LCOE reduces as the farm size increases.

Figure 1. Stages in the development of a wind farm

Given the nascent nature of the floating wind energy industry and the lack of established best practices, these operations
present significant scope for optimisation and cost reduction. The FOWT industry has a significant second mover advantage
and can benefit from the technical expertise and innovations developed in the offshore oil and gas (O & G) and fixed wind
energy industries. However, the deployment of highly dynamic unmanned floating platforms is unprecedented and requires the
development of bespoke solutions to reduce the cost and increase safety of installation, operation and maintenance (O & M)
and decommissioning related marine activities.

There is overlap across the life-cycle for the various technologies and procedures for floating offshore wind turbines. For
example, assessment and prediction of metocean conditions are always required for installation, O & M and decommissioning
of floating wind farms. Towing vessels are also required in all these operational phases of a wind farm. So, it is beneficial to
combine all the studies in those areas and investigate all of them together instead of treating them separately. Since the floating
wind domain is new and maturing there is a shortage of literature that focuses on marine operations. This paper examines the
various challenges and opportunities concerning marine operations during installation, O & M and decommissioning phases of
a floating wind farm.

2   Installation, O & M and decommissioning of FOWT floater types

Floating wind platforms can be mainly classified into three broad categories according to the restoring mechanism for attain-
ing hydrostatic equilibrium. They can be ballast stabilized, buoyancy stabilized, mooring stabilized or combinations of these
(Leimeister et al. (2018), Banister (2017), Booij et al. (1999)). Figure 2 demonstrates how the different FOWTs developed
around the world fit into a stability triangle.

The installation procedures differ according to the type of the floater used. Generally, floating wind installation requires
a greater number of vessels compared to fixed wind, but the vessels are cheaper to hire and easily available (Crowle and Thies
(2021)). Even though many floating wind concepts have been developed, only a few have been successfully deployed and
commissioned in a commercial level. In the following sections, a review of the projects that have reached the Technology
Readiness Level 7 (TRL7) (EC (2017)) or above is provided with a focus on the marine operation strategies which they
employed.
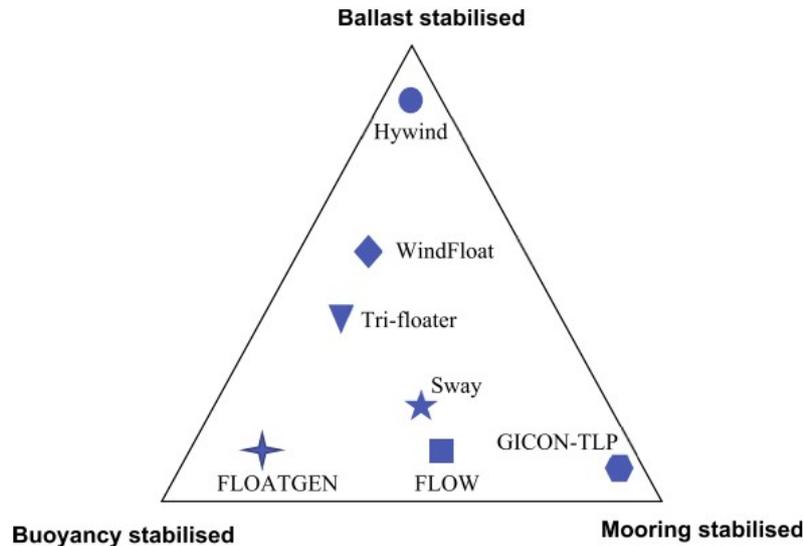
Figure 2. Stability triangle for floating structures (Jiang (2021))

2.1   Spar-type: Hywind Scotland Project

Hywind Scotland is a floating offshore wind farm, which has a rated capacity of 30MW, produced from five 6 MW turbines,
50   which has been functioning since 2017 (Equinor (b)). The spar-type floater, namely Hywind concept was developed by Equinor
ASA (Equinor (b), Skaare (2017)). A 2.3 MW demo (TRL 8) (OREC (2015)), was deployed at the west coast of Norway in
2009 for a test run of 2 years (Butterfield et al. (2007), Equinor (b)). Following the demonstration, a wind farm was installed
30 km off the coast of Aberdeenshire, Scotland. The farm has an area of approximately 4km^2 and an annual average significant
wave height of 1.8 m (Mathiesen et al. (2014)).
55   The spar-type substructures have high draughts which require the use of offshore assembly. The installation phase also
requires sheltered coastal waters (maximum significant wave heights are up to 0.5 m and a Beaufort wind force 4 (DNV
(2015)) for some operations. This is a challenge, as sheltered waters with high depths are required near the construction sites,
due to the high draught of the floaters. They should either be available near the ports or should be made by dredging. The
first marine operation was the installation of the suction anchors and the mooring lines. The floaters were first wet towed, out
60   into a sheltered area using tugboats. Then they were upended using water ballast. Later, the water was pumped out and solid
ballast (magnetite) was filled using a rock installation vessel. The tower and rotor assembly were mated with the floater later
(Jiang (2021)). This was done using the heavy-lift vessel, Saipem 7000 (Saipem). A notable feature of the Hywind installation
was the use of this expensive heavy-lift vessel. Significant cost cuts may be achieved by innovative installation methods in the
future, by avoiding the use of such vessels. After the mating, the wind turbines were towed to the location of the wind farm.
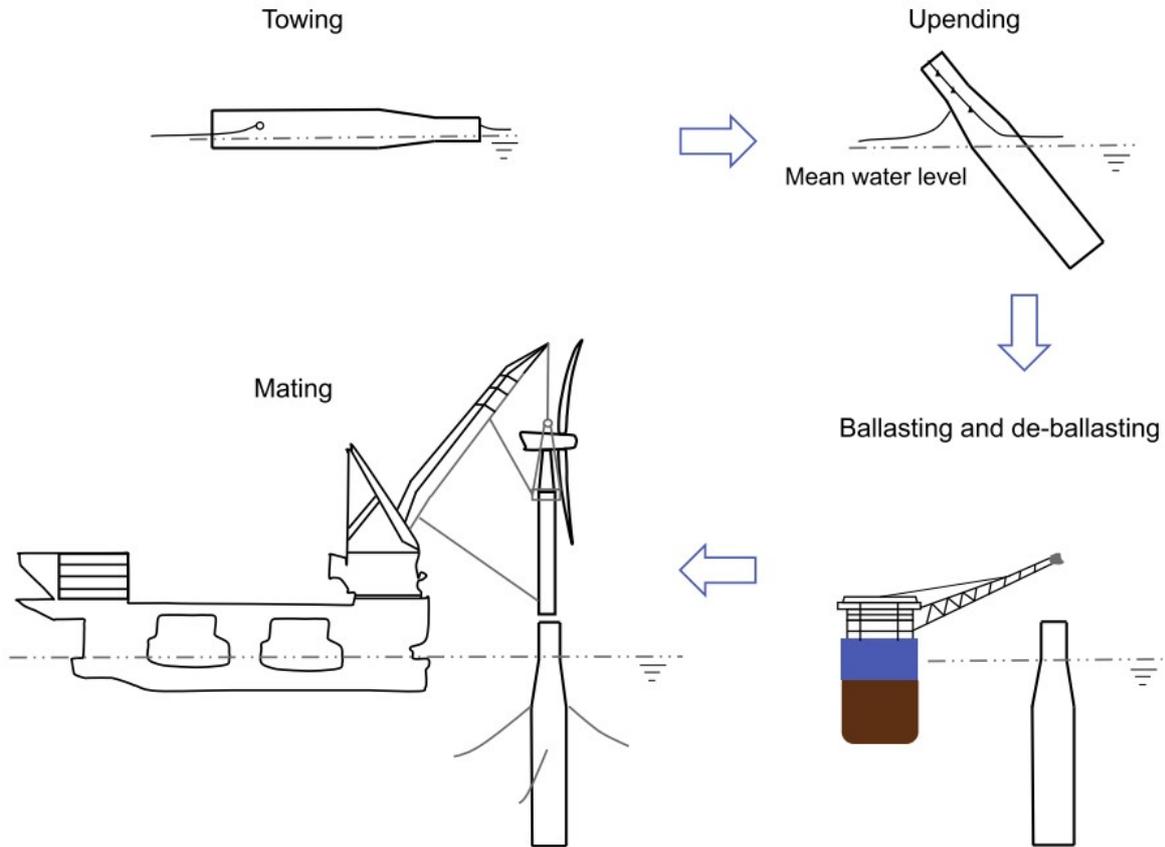
Figure 3. Stages in the installation of the Hywind Scotland Spar-type platforms (Jiang (2021))

65 They were then connected to the pre-installed mooring lines and final ballast corrections were performed. Figure 3 explains the steps involved in the installation of the Hywind floaters.

Metocean assessments were performed before the commencement of the project to check for suitable weather windows for marine operations. The duration characteristics of marine operations were predicted for various limiting conditions of wind and waves for a full year. Figure 4 and figure 5 show examples of the predicted characteristic durations for a limiting significant

70 wave height of 2 m for 48 hours and wind speed of 10 m/s for 48 hours respectively. Such calculations were performed for different significant wave heights and wind speeds (Mathiesen et al. (2014)). The months from April to September were found to have the widest operational time windows. The inshore assembly (upending, solid ballasting, heavy lift) and offshore installation operations (anchor & mooring, transfer & installation of wind turbine generators, cables) were scheduled and carried out in this window period.
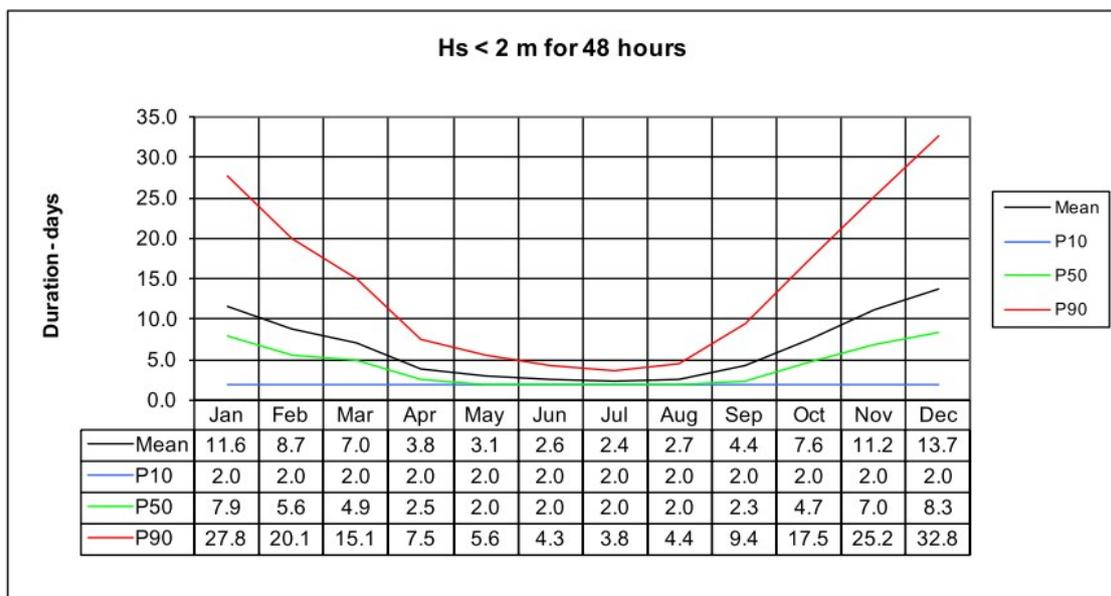
Figure 4. Characteristic durations, in-order to perform operations limited by a significant wave height of 2 m for a period of 48 hours, expected mean durations and 10, 50 and 90 percentiles (Mathiesen et al. (2014))
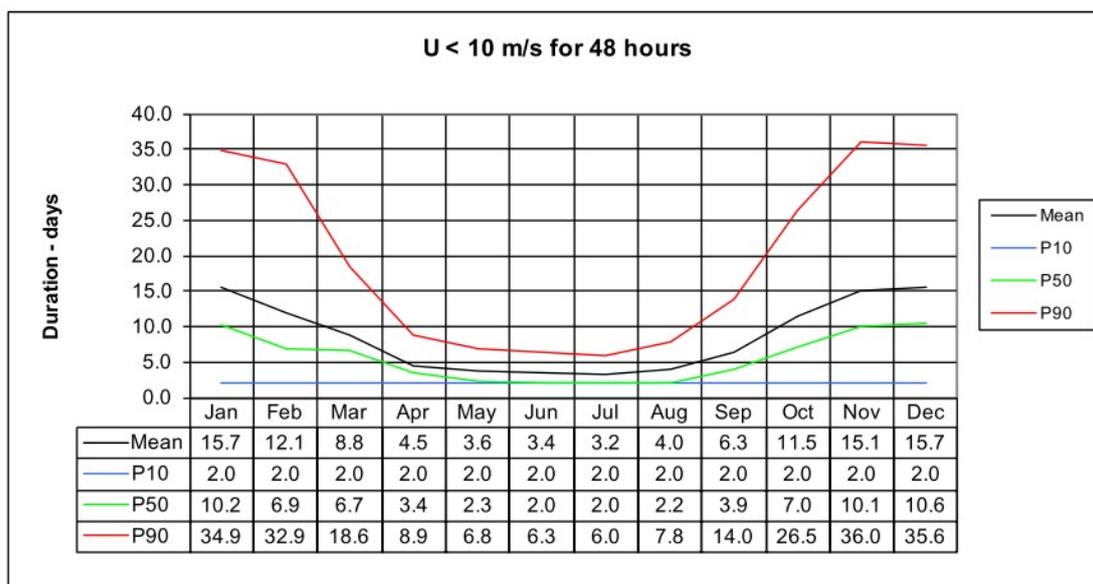
Figure 5. Characteristic durations, in-order to perform operations limited by a wind speed of 10 m/s for a period of 48 hours, expected mean durations and 10, 50 and 90 percentiles (Mathiesen et al. (2014))

75   The operation and maintenance of the wind turbine mounted on the spar-type substructure is similar to that of a bottom-fixed offshore wind turbine. A campaign-based inspection and monitoring scheme is planned for the FOWTs. Maintenance and repairs of the sub-sea systems (foundation, mooring system, cables) will follow a different approach. Periodic sub-sea inspections and maintenance will be performed using ROVs (Remotely operated underwater vehicle). Scour might also be an issue concerning the Hywind spar-type platforms as they employ suction anchors. Heavy component exchanges up to 2

80   tonnes will be performed using the platform crane and a crew transfer vessel. Heavier components like the transformer, can be exchanged using a dynamic-positioned offshore service vessel. In case of even larger components the turbines have to be towed to a sheltered region and exchange will be carried-out using heavy lift vessels (H.H.Hersleth (2016)).

The decommissioning of the spar-type platforms could be more expensive compared to other types of platforms. The platform has to be partially decommissioned in deep water due to the high draughts before getting towed to the quayside.

85   The blades, nacelle and tower can be dismantled using a heavy lift vessel. This incurs additional costs. The mooring lines and anchors also must be retrieved. Easily recoverable anchors can reduce decommissioning costs and time. There is scope for further investigations to develop cheaper and easy decommissioning strategies of spar-type FOWTs.

2.2   Semi-Submersible Type: WindFloat Atlantic & Kincardine Projects

In 2011, Principle Power installed a prototype semi-submersible FOWT, namely WindFloat, 5 km off the west coast of Portugal

90   (Roddier et al. (2010)). This was followed by the installation of a 25 MW floating wind farm in the west coast of Portugal. The wind farm consists of three MHI Vestas 8.4 MW turbines mounted on Principle Power's semi-submersibles (Banister (2017)). The installation operations were carried out with the help of tugs, AHTSs (Anchor Handling Tug and Supply) and ROV-Support cable-lay vessels supplied by Bourbon Offshore (Ocean-Energy-Resources). The towing operation took three days, taking the completely assembled FOWT from the port of Ferrol, Spain to the farm located 20 km off the coast of Viana

95   do Castelo, Portugal. The AHTS (Bourbon Orca (Ulstein)) used for the operations, which is an advanced vessel with a bollard pull of 180 tonnes and maximum speed of 17.1 knots. Most AHTSs were constructed to serve the O & G industry, but they make a good choice for floating wind farm installation, since there is good availability and can be used for the installation of anchors and for towing purposes. One of the floaters was loaded-out and floated-off using a semi-submersible barge, Boskalis Fjord. Compared to the Hywind project, specialized expensive heavy-lift crane vessels were not employed here. Castro-Santos

100   et al. (2013) has observed that the installation of anchoring and mooring systems is less expensive using an AHTS compared to a combination of barges and tugboats.

The Kincardine Offshore Floating Wind Farm is another project which employs semi-submersible floaters for the wind turbines (offshorewind.biz). The wind farm is located 15 km off the coast of Aberdeen, Scotland. It features a wind farm of nameplate capacity 50 MW. All of the floaters were constructed in Fene, Spain and transported to Rotterdam for mounting the

105   9.6 MW wind turbines (Umoh and Lemon (2020)).

Semi-submersibles are buoyancy-stabilized floaters. The stabilizing righting moment is contributed either by the large water-plane area of the hull or small cross-sectional areas at some distances from the central axis (Leimeister et al. (2018)). They can be fully constructed and assembled onshore. The installation of mooring system is less expensive compared to

other types of floaters, which makes semi-submersibles, one of the most cost-effective solutions from an installation point of
view (Liu et al. (2016)). The semi-submersible wind turbines are completely constructed onshore and towed to the wind farm
location and connected to the pre-installed mooring lines. Light drag-embedded anchors can be used for semi-submersibles.
The main challenge in the installation process is finding the right weather window for the marine operations as they are more
sensitive to wave heights during towing (Banister (2017)). The installation of the three FOWTs in the WindFloat project took
place in October 2019, December 2019 and May 2020 respectively (EDP (a), EDP (b)). It is very important to assess the
weather windows and downtime before commencing marine operations. Another important aspect to be considered are the
safe havens. Towing of FOWTs is a continuous operation and it is difficult to halt the operation during the process. Safe havens
should be identified along the route of the towing operation to avoid difficulties in case of harsh weather. Some of the floaters
in the WindFloat and Kincardine projects were constructed at a different location and transported to the assembly port using
specialized heavy-transport vessels. This can be avoided by carefully choosing the right port with shipyard facilities, where the
complete construction and assembly of the FOWT can be carried out.

Operation and maintenance activities can be carried-out either offshore or onshore (Banister (2017)). The periodic in-
spections, preventive maintenance and repair activities will be performed in situ (i.e., at the platform location). In case of large
corrective maintenance or repair activities the platform can be towed to a sheltered location or port. No heavy-lift vessels are
required and local vessels can be used for towing, this is beneficial in terms of promoting the use of local content and adhering
to regulations such as the Jones Act (B.Cheater (2017)) which requires usage of US built ships for marine operations in the
US waters. Due to the large size of the floater, helipads can be constructed aboard, which make access by helicopters possible.
During decommissioning the platform can be towed to shallow water or taken out of the water completely inside a dry dock
and dismantled.

2.3 Other upcoming projects

The Floatgen Project by Ideol (France) is another project that employs barge-type substructures (Alexandre et al. (2018),
Ideol). They can be fabricated using steel and concrete, which can help promote the use of local content and employment. The
damping pool technology developed by Ideol, is designed to stabilize the floater in harsh sea conditions. Two demonstration
projects have been in operation since 2018 and pre-commercial and commercial projects are expected to be launched in the
coming years (Ideol).

Another floater concept is the Tension Leg Platform (TLP) which is widely used in the offshore O & G industry. This
concept has also been adapted from the O & G industry for the FOWTs. Tension Leg Platform Wind Turbines (TLPWTs) are
well suited for intermediate water depths. The depth varies from 70 m, which is an approximate upper limit for fixed wind
turbines and 200 m, beyond which the spar-type platforms are considered as the most economical option (Bachynski and Moan
(2012)).

In 2008, Blue H Technologies successfully installed a pro-type TLPWT in Italy (Adam et al. (2014)). Even though many
concepts have been developed and a few prototypes have been reported, commercial scale TLPWTs are still not a reality. The
installation of a conventional TLP system is a complex process. The tendons, which hold the platform in place, are usually

installed before the platform. The TLP floater is constructed onshore and towed to the location using tugboats or transported using a bespoke barge. The platform is ballasted and connected to the pre-installed tendons. Finally, the platform is de-ballasted

145   to a draught where the tendons attain the optimum tension and the TLP is secured. Figure 6 illustrates the main components involved in the installation.

The main challenge involved in the installation of a conventional TLP is its unstable behaviour before connecting to the tendons. For the installation of an O & G TLP, bespoke barges are often used for transportation and positioning of the system, which incurs additional expenditure (James and Ros (2015)). The anchors and mooring lines system used in TLPs are designed

150   to handle high tensions and thereby more complex than the semi-submersible and spar-type platform systems. The tendons are susceptible to fatigue failure, which makes TLPs expensive in an O & M point of view also. Decommissioning of a TLP system is also expected to pose some challenges due to the complexity of the mooring system. The platform has to be carefully released from the tendons and towed back to the shore. The mooring lines and anchors are removed later.
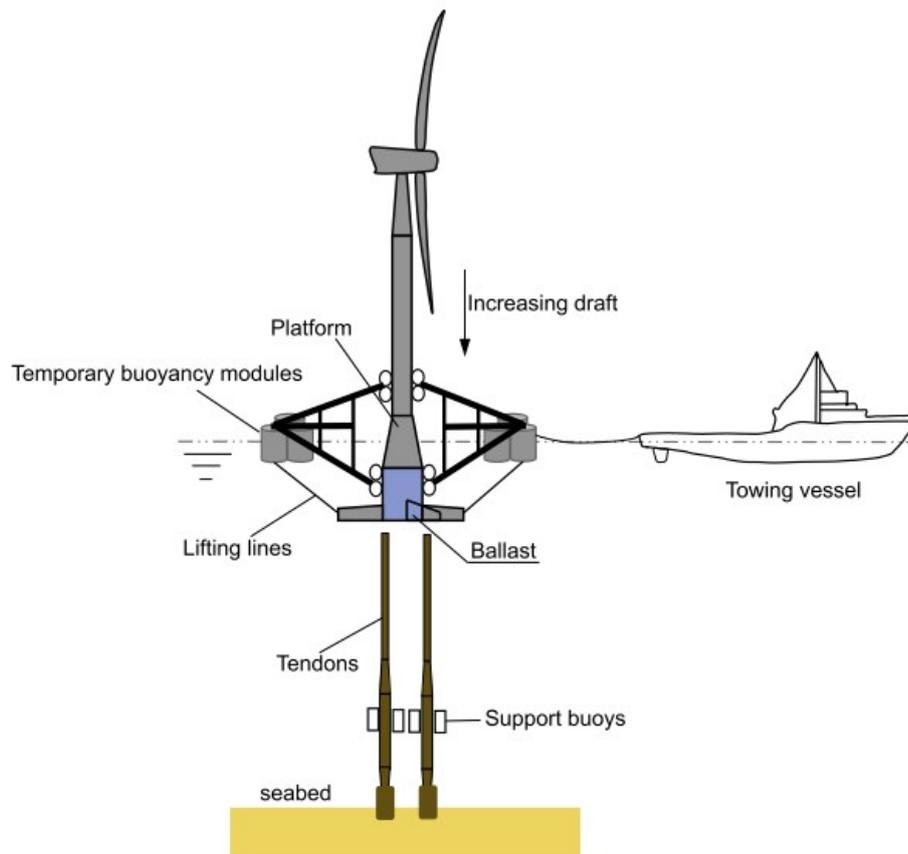
Figure 6. Installation method of a MIT/Enel TLP (Jiang (2021))

The GICON-TLP (Adam et al. (2014), Kausche et al. (2018)) is another innovative concept. The TLP system is placed
155   on a floating slab and dry-towed to the location. The slab is then ballasted which submerges the TLP into the required final
draught. Figure 7 shows this installation method proposed by GICON. There are many upcoming concepts that are designed
to allow alternative installation methods. An example is the TetraSpar concept (Borg et al. (2020)) which features a tetrahedral
floating structure equipped with a keel, which can be ballasted and lowered into a certain depth on site. The keel can be air-
ballasted and towed to the offshore location. Once the mooring lines are hooked, the keel is lowered and the system starts
160   acting like a spar-type platform. The TetraSpar has been developed aiming to implement large-scale industrial production, as
they consist only of cylindrical tubes bolted together. Theses platforms do not require specialized vessels for installation since
they can be towed using low-cost and widely available tugs (Andersen et al. (2018)).
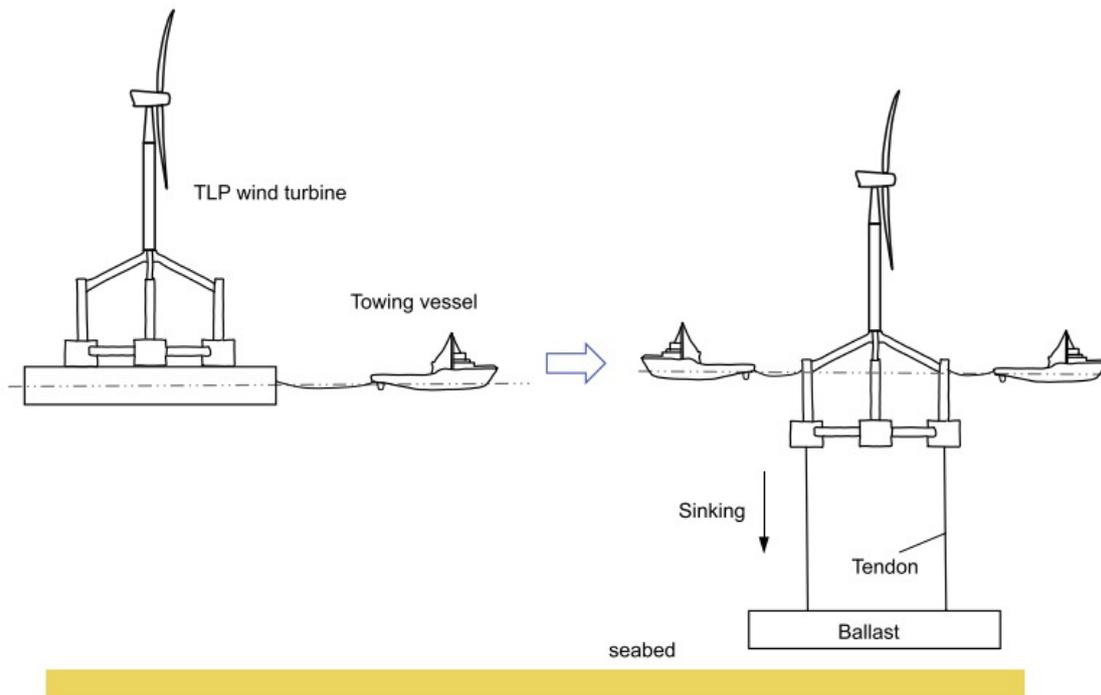
Figure 7. Installation of a GICON TLP (Jiang (2021))

As mentioned above, different types of FOWTs have advantages and disadvantages when it comes to installation, O& M
and decommissioning. Table 1 summarizes them according to the type of the floater. Significant wave height, current and wind
165   speed restrictions apply to all marine activities. Some are more sensitive to this, but generally it is important to overcome this
restriction by precise weather monitoring and forecast (Emmanouil et al. (2020)) or using innovative ships and technologies.

Table 1: Advantages and disadvantages concerning installation, O & M and decommissioning of different floater types of FOWTs (Leimeister et al. (2018)), (James and Ros (2015)), (Liu et al. (2016))

Platform Type	Installation	Operation and Maintenance	Decommissioning
Spar-type	- High draught makes towing difficult - Requires heavy-lift vessels - Unstable motion of floater during mating - High installation cost - Tighter weather constraints - Requires deep water ports and sheltered areas	+ Similar to bottom-fixed wind turbines - Heavy-lift vessels might be required for major repairs - Needs deep water ports and sheltered areas for repairs	- Partially decommissioned in deep water - Requires heavy-lift vessels
Semi-submersible Type	+ Easy installation + Fully assembled at quayside + Cheaper mooring and anchoring system + Short installation time + Low installation cost - More sensitive to wave height limits during towing	+ Simple unhook from mooring system + Can be towed back to quayside for major repairs + No heavy-lift vessels required + Helicopter access possible	+ Can be completely towed back to shore for dismantling + Uses easily recoverable drag-embedded anchors + No heavy-lift vessels required
Tension Leg Platforms	+ Can be completely constructed onshore - Complex mooring and anchoring system - Slow and lengthy installation process - High installation cost - Bespoke barge required - High environmental impact	- Difficult to unhook, more onsite repairs - Mooring system highly susceptible to failure	- Difficult process due to complex mooring system - Difficult or non-recoverable pile-driven anchors

Key: + Relative advantage   - Relative disadvantage

3 Challenges and Opportunities

Marine operation is defined as "a generic term covering, but not limited to the following activities, which are subjected to
170 the hazards of the marine environment: Load-out/ load-in, Transportation/ towage, Lift/Lowering (Offshore/Inshore), Tow-
out/tow-in, Float-over/float-off, Jacket launch/jacket upend, Pipeline installation, Construction afloat (DNV (2011a))". Clearly,
many of the operations listed here are applicable for floating wind farms.

As mentioned before, the marine operations vary according to the type of the floater used. The challenge here is the
optimization of the unavoidable marine operations, throughout the life cycle of the wind farm. The installation locations of
175 FOWTs present considerable challenges in terms of harsh weather conditions and catastrophic events such as tsunamis. There
is a significant opportunity to transfer knowledge and technology from the mature O & G industry. For example, the optimized
marine operations, resource assessment and the prediction of offshore weather conditions. The general approach for planning
a marine operation is described in Figure 8.
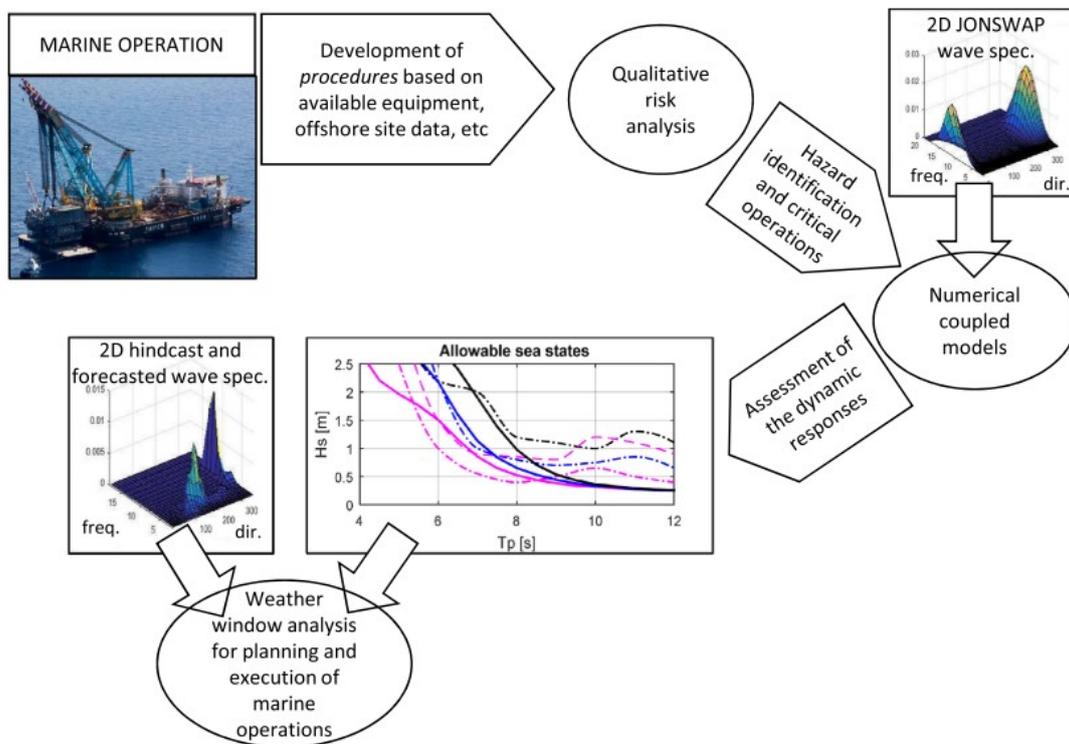
Figure 8. General procedure of assessing operational limits for an offshore marine operation (Acero et al. (2016))

There is lack of consensus on installation approaches, costs and time for each task for floating offshore wind farms.
180 Multiple installation, O & M and decommissioning approaches have been suggested for bottom-fixed wind turbines and many
of them can be adopted for floating wind farms. But FOWTs also present additional challenges, for example: dynamic cables,

mooring lines, longer real-world operational windows etc. The most significant challenges and the opportunities for addressing them are discussed in the following sections.

3.1 Metocean Assessment and Analysis

185 One significant challenge associated with FOWTs is predicting the optimum meteorological and ocean conditions for design as well as operation of FOWTs. In general, metocean data is required for planning installation, operation, maintenance and decommissioning activities by predicting the suitable weather window and associated costs based on wind, wave and current data (Jacobsen and Rugbjerg (2005)). Moreover, metocean conditions play an important role in site selection, calculation of design loads for floaters and mooring systems also. Wave and wind conditions also present safety concerns during the transfer
190 of crew to the floating platforms. The uncertainty associated with various environmental variables are of interest to all offshore operations concerning renewables as well as the O & G industry. The high complexity of the ocean environment makes it even harder to predict the operating conditions due to the presence of numerous variables. Also, the availability of metocean data for a particular location and time period affects calculations. It is very important to have a general understanding of the metocean conditions of a particular geographical area to plan the construction of wind farms. There are four main sources of metocean
195 data:

1. In situ measurements

2. Numerical modelling

3. Satellite measurements

4. Pre-existing statistics and reports

200 Among these, the in situ measurements provide the most reliable metocean data. Even though in situ measurements cannot provide long term data and incurs costs, it is advisable to start taking in situ measurements once the location is decided for a wind farm. Predictions using numerical models can be validated and augmented using in situ measurement data or satellite measurements. Long-term metocean data can also be generated using hind-cast data for a particular region. A careful combination of all these will serve as a reliable data-set for planning installation, O & M and decommissioning activities. Wind,
205 waves and current are the most important metocean parameters to be monitored and analysed for offshore wind installations. Wind, being the primary source of power, can be measured using LIDAR or satellite scatterometer ((Ahsbahs et al. (2018)), (Remmers et al. (2019))), the former has proved to be more accurate and continuous for a particular region of interest. Waves can be measured using multiple buoys deployed at a particular location, micro-wave radar systems (Teleki et al. (1978)) or using satellites. Current measurements are made using current meters mounted below buoys or using micro-wave radars. Large scale
210 geostrophic currents can be measured using satellites (Dohan and Maximenko (2010)). Shore-mounted HF (High Frequency) radars can measure winds, waves and currents in coastal waters over a range of 120 km from the shore (Wyatt (2021)). Various numerical models exist for the precise calculation of metocean conditions. SWAN (Booij et al. (1999)) is a third-generation wave model that can calculate random, short crested waves in shallow waters and ambient current.

3.2 Environmental limits for installation, O & M and decommissioning

The installation, O & M and decommissioning activities require precise monitoring and assessment of metocean conditions in the planning phase itself. FOWTs are installed far offshore to utilize the higher wind speeds. As wind speed and wave heights are directly related, the installation and O & M of a floating wind turbine can be more challenging compared to a bottom-fixed wind turbine. Many pre-hook-up activities like site inspection surveys, installation of anchors, cable laying etc. are possible only during calm sea states. Periodic maintenance and repairs also depend on the weather conditions for safe crew transfer. Special operations, such as the mating of a spar-type platform with wind turbine is difficult when the platform is unstable. The installation of TLPs also pose similar challenges as the platform itself is relatively unstable before the connection to the tendons.

Significant wave height and wind speed are two major factors that affect workability. Transfer of crew for maintenance activities becomes difficult in high wave heights. Beyond a significant wave-height of 1 m, marine operations become difficult and most operations halt at a swell of 1.5 m (Lange et al. (2012)). Raising this limit is essential for all marine activities concerning offshore structures. Table 2 shows the significant wave height (Hs) and wind speed limits for various vessels used for marine operations involving FOWTs. These limits can be raised by developing innovative ship designs that have better hydrodynamic performance in rough seas. Walk-to-work vessel is one example. The possibility of outfitting existing vessels with motion compensated gangways should also be investigated. At the same time, specialized vessels are expensive to hire, which would raise the costs.

Table 2. Operability of various vessels used in the FOW domain (Paterson et al. (2018), Ahn et al. (2017))

Vessel Type	Purpose	Max. sea-state, Hs (m)	Max. wind Speed (m/s)
AHTS	Installation of anchors & moorings	2	20
Tug boats	Towing	1-1.65	14
Cable laying	Installation of cables	3.5	15
Heavy-lift Vessel	Mating of spar-type platforms	1.8	15
Offshore Supply	O & M	2	11
Monohull	Crew transfer, O & M	1	-
Catamaran	Crew transfer, O & M	1.2	10
SWATH (Small Waterplane Area Twin Hull)	Crew transfer, O & M	1.5	-
Jack-up barge	O & M	1.65	16

Marine operations, such as the installation of mooring and anchoring systems, upending and mating of spar-type platforms, towing of platforms to the location etc. have to be carried out in calm sea conditions. Figure 9 shows the metocean limitations during assembly, transit and installation of different kinds of platforms. Waiting for suitable weather conditions can
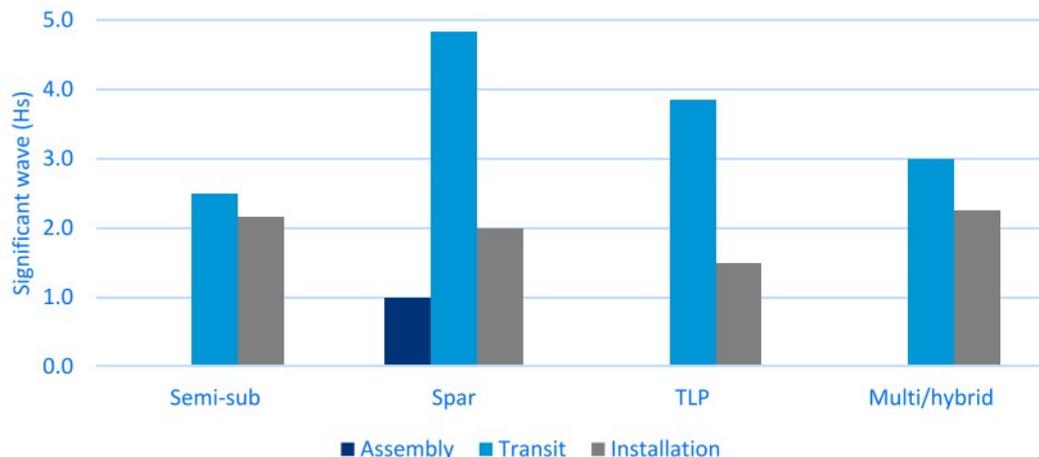
Figure 9. Significant Wave Height limitation during assembly, transit and installation (James and Ros (2015))

raise the costs, so a precise weather forecast is essential. Currents also affect the installation, O & M and decommissioning
235   activities concerning floating platforms.

DNV (DNV (2011a), DNV (2011b)) classifies marine operations into weather restricted and weather unrestricted. The
operation period T_R is defined as:

$$T_R = T_{POP} + T_C \tag{1}$$

T_R is the operation reference period, T_{POP} is the planned operation period and T_C is the estimated maximum contingency
240   time for the marine operation. Weather restricted operations are marine operations with T_R less than 96 hours, and T_{POP} less
than 72 hours. This is the maximum time period for which the weather forecast is sufficiently reliable. Precise weather forecast
and continuous monitoring are required for weather restricted operation. Towing operations must be analysed based on this
(DNV (2011a)). For the Kincardine project the towing took approximately 9-10 days (Bridget Randall-Smith). This can be
considered as a weather unrestricted operation (DNV (2011a)). Statistical extremes of metocean conditions must be considered
245   for planning such an operation according to Table 3.

Table 3. Acceptable return period for unrestricted operations (Berg (2017),DNV (2011a))

Duration of towing	Return period of metocean parameters
Up to 3 days	Specific weather window to be defined
3 days to 1 week	1 year, seasonal
1 week to 1 month	10 year, seasonal
1 month to 1 year	100 year, seasonal
More than 1 year	100 year, all year

3.3 Cost modelling of floating wind marine operations

Installation, O & M and decommissioning costs depend on a variety of factors and stakeholder engagements. It is very important to model the costs accurately over the whole life-cycle of wind farms. Figure10 shows the important factors and inputs to be considered while modelling the costs of a floating wind farm. In order to optimize marine operations, precise modelling of
250   the associated costs is required. Many good models exist for bottom-fixed wind turbines. Figure11 shows the breakdown of costs associated with a floating wind farm compared to a bottom-fixed wind farm. They can be extended into floating wind depending on the type of floater and the methodology of the various operations. The floating wind costs are less developed at the moment, hence new and improved models are required for precise calculation of the costs.
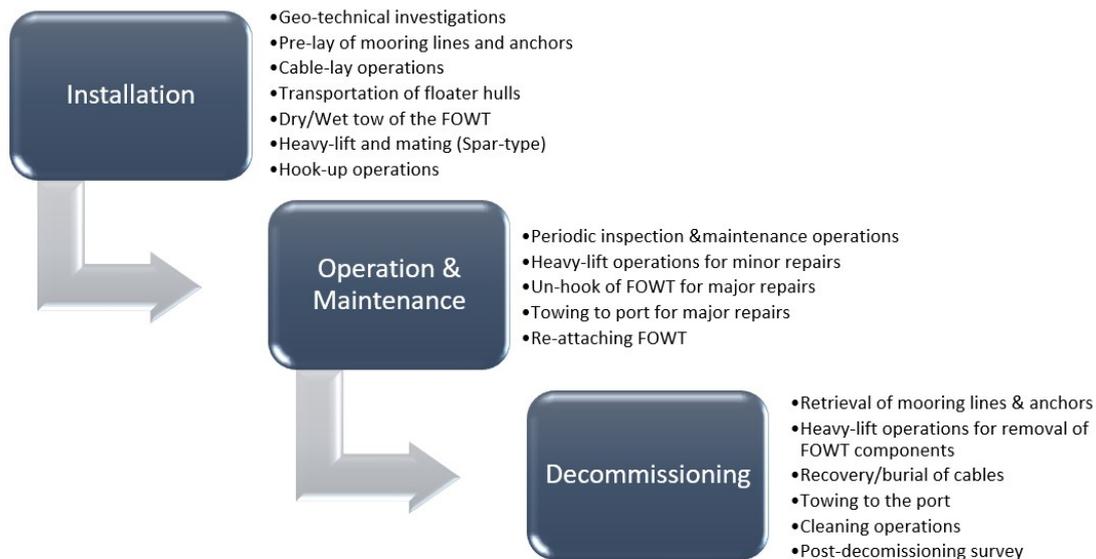
Figure 10. Important factors to be considered for the financial modelling of FOW marine operations (Judge et al. (2019))

      The installation costs consist of costs incurred for the installation of the wind turbine, floating platform, electric system,
255   mooring and anchoring systems and the start-up cost (Castro-Santos et al. (2016)). The installation costs of the floating offshore wind platform depend on the port and shipyard costs, transportation/towing costs and site installation costs. Draught restriction applies to many ports depending on the type of the floater used. The spar-type platforms and TLPs have higher draughts compared to semi-submersibles. In such cases they have to be stored in a special storage area (Castro-Santos et al. (2018b)) or the port is needed to be dredged. This incurs additional costs. The electric system installation costs are composed of cable
260   installation costs and sub-station installation costs. For the installation of mooring and anchoring system it is economical to use an Anchor Handling Vessel (AHV) compared to using barges and tugs (Wayman et al. (2006)). The costs vary according to

the number of anchors used in the wind farm. By the end of the installation of all the systems, the wind farm is commissioned and start-up costs are also incurred during its connection to the electrical grid.
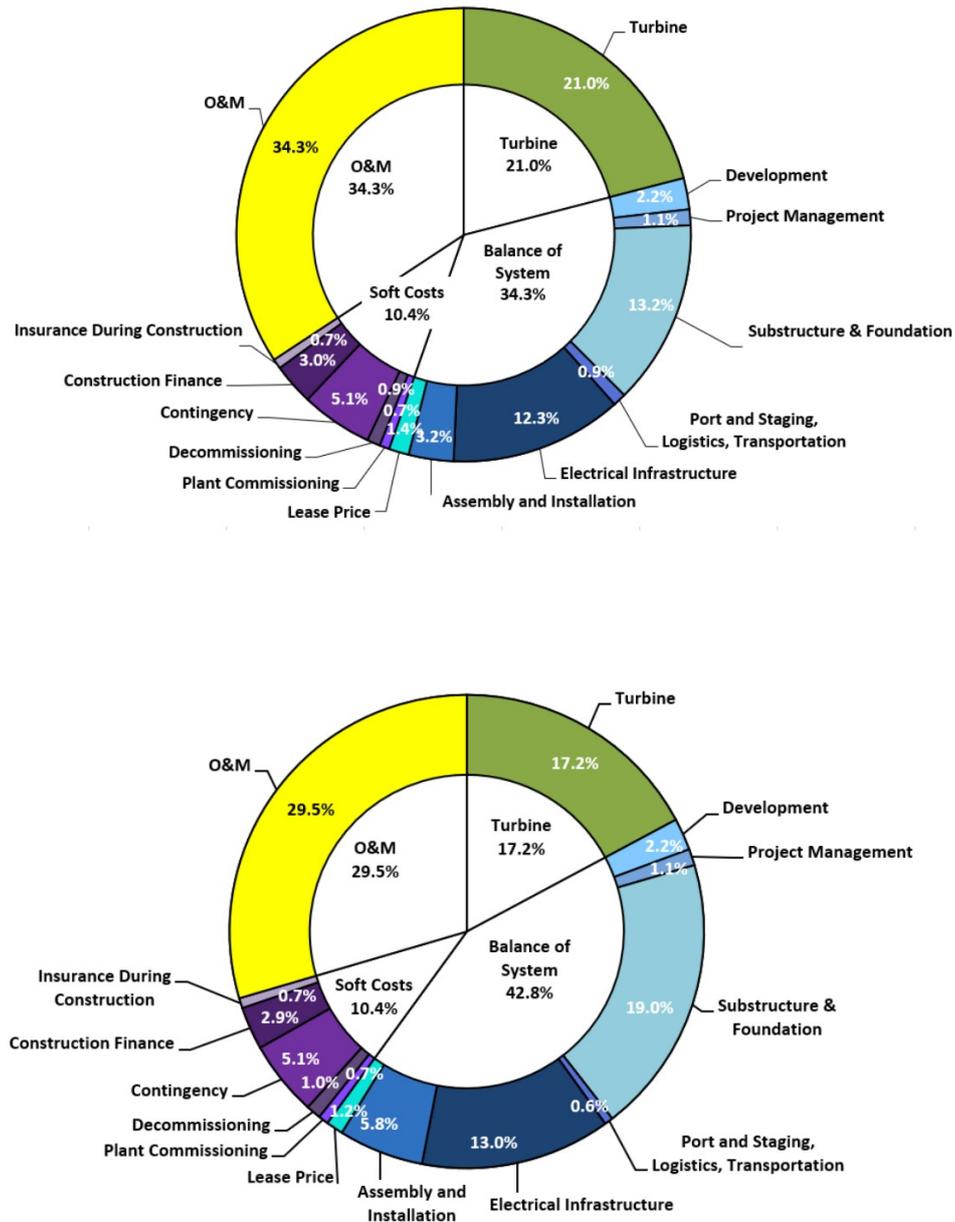
Figure 11. Comparison of component level LCOE contribution for fixed-bottom (top) vs floating wind (bottom) farms operating for 25 years (Stehly et al. (2020))

Installation costs strongly depend on the site location of the wind farm. Maienza et al. (2020) investigated how the factors
265 like distance from the coast, distance from the nearest port, and the sea depth influence the total cost of a wind farm in the
Italian waters (Maienza et al. (2020)). A cost map for the Italian national waters was produced, indicating the total costs for
a wind farm consisting of 12 TLP FOWTs. Preliminary analysis showed that the number of wind turbines has a considerable
effect on the total cost. Doubling the number of turbines increased the cost by 35%, but quadrupling or increasing eight folds
increased the costs by 60% and 80%, showing a decrease in the rate at which the total costs increase. The LCOE was found
270 to decrease with increase in the farm size (Castro-Santos et al. (2018a), Myhr et al. (2014)). According to Castro-Santos and
Diaz-Casas (2015), the distance from the shore has 36.3% influence on installation cost and 14.2% on dismantling cost. As the
wind turbines move further into the sea, it is expected that they will grow in size too, to fully utilize the higher wind speeds. 15
MW wind turbines are predicted to be used from around 2030 and 20 MW turbines from 2037 in the UK floating offshore wind
sector (OREC (2015)). The wind turbine diameter is found to have 15.9% influence on the dismantling cost (Castro-Santos and
275 Diaz-Casas (2015)).

O & M costs mainly consist of the corrective and preventive maintenance costs throughout the whole life-cycle of the
wind farm (Castro-Santos (2016), Sperstad et al. (2016)). To minimize these costs, it is important to design reliable systems and
efficiently monitor the health conditions of the turbine system, floater, electrical installation, mooring and anchoring system.
This is of high importance as the failure of main components could result in a considerable downtime, as the FOWT might
280 not be accessible due to lack of suitable weather windows. A preliminary analysis by Dewan and Asgarpour (2016) considered
using Service Operation Vessels (SOV) and towing vessels for O & M of a floating offshore wind farm consisting of fifty
8MW semi-submersible wind turbines and investigated the costs and downtime. The availability was found to be 91.4%, which
was lower that fixed-bottom wind turbines, because of the towing of the platform to the shore for major repairs. Detailed
investigation is pending in this area to improve the downtime by using better vessels (eg: Walk-to-Work vessels), helicopters
285 (Maples et al. (2013)) etc. for different types of floaters. Easy coupling and decoupling systems should be developed to facilitate
easy attachment and detachment of FOWTs during major repairs. Advancements in robotics have paved the way for usage of
robots for inspection and maintenance. iFROG (Offshore-Engineer) is an amphibious robot developed by InnoTecUK, ORE
Catapult, TWI Ltd. and Brunel University London, which can clean corrosion and bio-fouling from monopile surfaces.

Decommissioning is an environment-sensitive activity. It is better to incorporate decommissioning studies in the design
290 phase to avoid complications in the final years of the wind farm life-cycle (20 years or more) ((James and Ros (2015), Castro-
Santos (2016)). A reverse-installation approach can be used for calculating the decommissioning costs of a wind farm (Topham
and McMillan (2017)). The main components are the dismantling costs of the wind turbine, floating platform, electric system,
mooring and anchors. Some anchors, eg: drag-embedded anchors, are easily recoverable, which would save costs and time
(González and Diaz-Casas (2016)). There is an additional cost due to the cleaning of the wind farm site which is of environ-
295 mental concern (Castro-Santos et al. (2016)). Some materials can be sold as scrap eg: steel from the floater and copper from
the electric cables, which would result in a negative cost (income) (Castro-Santos et al. (2016)).

Various stakeholders are involved in the construction of an offshore wind farm. Proper planning and optimum utilization
of resources are very important in bringing down the costs. Weather restrictions during the marine operations would cause

Table 4. Day rates of different type of vessels used in the FOW industry (Jiang (2021), Sperstad et al. (2017), Foxwell (2019))

Vessel Type	Approximate typical day rate (€)
Tug	1000-4500
AHTS	20000-50000
Cable Lay Vessel	70000-115000
Barge	80000-180000
Jack-up	72000-130000
DP Vessel	50000-200000
Bespoke vessel	200000
Crew Transfer Vessel	1750
Service Operation Vessel – Large (W2W)	52000
Service Operation Vessel – Medium (W2W)	35000
Semi-submersible crane vessel	200000-360000

the logistic costs to increase exponentially (Lange et al. (2012)). Often hiring offshore support vessels from abroad invites

300   large hiring costs. Specialized vessels also raise the costs. Depending on the location, optimized used of local vessels and port facilities would help bring down the associated costs.

3.4   Health, Safety and Environment (HSE)

One of the non-technical challenges that needs to be addressed, is improving the HSE conditions during the complete life-cycle of floating offshore wind farms. HSE factors must be considered during all phases of the development of the wind farm, but only

305   the installation, O & M and decommissioning phases are considered in this section. Since the floating wind technology is in infancy, there is a shortage of dedicated applicable rules and standards. Until the development of such standards it is advisable to follow component/process specific standards used in the fixed wind industry or O & G industry (Hutton et al. (2016)). Marine operations in general, can follow the various safety standards, codes and classification society rules accordingly.

Theoretically, the installation of FOWTs is less environment-sensitive compared to fixed offshore wind turbines, as most

310   of them are constructed completely onshore and towed to the offshore sites. Again, the type of the floater is a deciding factor here. The installation of anchors and mooring lines can have a negative impact on the environment. Spar-type platforms and semi-submersibles employ catenary moorings with long mooring lines that have a larger footprint on the seabed, while TLPs don't, because they employ taut mooring lines (James and Ros (2015)). Heavy-lift vessels are used during the installation of spar-type platforms which invites additional safety issues, but there are well-defined guidelines and standards available for

315   this operation. The installation of drag-embedded anchors has less environmental impact compared to suction or pile driven anchors. The noise impact during hammer piling is also an issue. The effects on fish population and marine mammals need to

be studied separately. Protected marine areas, migratory birds' paths and migratory marine life paths should be avoided while selecting sites for offshore wind farms (Díaz et al. (2019)).

The most challenging safety concern is access and egress of personnel to and from FOWTs during repair and maintenance activities. The FOWT and the vessel form a floating-floating couple which makes access and egress challenging. Bump and jump can only be safely accomplished in low wave heights whereas walk-to-work systems increase this wave height limit while providing safer means of access/egress. Precise weather forecast is also required for planning O & M operations to avoid difficulties during the operations. Aboard an FOWT, even the small motions of the floater get amplified into large displacements at the nacelles and blades. This contributes to severe motion sickness or reduced efficiency of the personnel working on such structures. In the long-term these factors have to be considered in the design phase of the FOWT itself to reduce the dynamic response in waves. Remote O & M can also be considered to reduce the O & M visits. FOWTs can be towed back to shore for O & M which makes them attractive from a HSE point of view.

After decommissioning, it is important to leave the site in a similar condition as it was before the deployment of the wind turbines. After the wind turbines are transported to the shore, the mooring lines and anchors have to be removed. Certain types of anchors offer easy removal, while others are difficult/impossible to remove. Extreme care should be taken while removing cables from the sea. The complete removal of cables can cause severe damage and disruption to the sea-bed and in most cases, they are left buried at site (Topham and McMillan (2017)). Post-decommissioning surveys are conducted to ensure that no debris is left behind and the buried remnants are not causing obstructions.

4 Innovations applicable to Floating Offshore Wind Turbines

Significant research is currently being conducted in the development of efficient and optimal floating wind turbines. To decrease the costs associated with installation, O & M and decommissioning operations, many innovative designs, procedures and technologies along with established best practices are required. Some aspects can be adopted from the O & G industry, however, the unique nature of FOWTs requires dedicated research and development. Some of the innovations applicable in this domain are discussed in this section. These innovations are targeted on improving the operability of vessels, widening weather windows, improving HSE factors and reducing the need for complex marine operations.

4.1 Shared mooring and anchoring systems

For large floating offshore wind farms, the mooring lines and anchors can be shared with multiple FOWTs, reducing total mooring line length, saving construction material for anchors and reducing the need for marine operations by optimising utilisation of installed infrastructure. In a shared mooring system (Figure 12), the FOWTs are inter-connected using mooring lines, reducing the frequent connections to the sea bed using anchors. In a shared anchor system, a single anchor takes multiple mooring lines and the number of anchors can be reduced. Both these systems are practical for large wind farms and significant cost reductions are achievable due to the savings in material costs.

Many researchers have worked on these concepts for the application in the floating offshore wind domain. The technical know-how of integrated mooring systems can be transferred from the O & G industry. They have been employed in the floating
350   O & G platforms and the technology is relatively mature. Musial et al. (2004) has observed that individual mooring and anchor costs are significant for single-turbine systems compared to a shared system.

Fontana et al. (2016) investigated the hydrodynamic performance and loading analysis of shared anchors for various FOWT configurations and found that shared anchors must be structurally strong enough to handle loading from unexpected directions. Anchors with a directional preference in their holding position and capacity are generally not suited for multi-line
355   moorings but they can be adapted by extra structural outfitting for handling mooring loads in various directions (Diaz et al. (2016)). The type of floater is also found to have a significant influence on the anchor forces. (Balakrishnan et al. (2020)) analysed and compared the anchor forces on a semi-submersible floater system and a spar-type floater system and found that the anchor forces on the latter was lesser. This is because spar-type platforms have lesser surface area interacting with waves compared to that of a semi-submersible.

360   Goldschmidt and Muskulus (2015) investigated the performance of coupled mooring systems involving 1, 5 and 10 floaters in various configurations. Semi-submersible floaters were arranged in row, triangular and rectangular configurations separately and the system dynamics was studied. It was found that mooring system cost reductions up to 60% and total system cost reductions up to 8% were achievable using shared moorings. However, it was noted that the displacements of the floaters were higher when the number of floaters in the system increased, which would be a problem for large wind farms. Further
365   investigation is required to improve the behaviour of floaters in larger wind farms. One of the main challenges in adopting a multi-line system for FOWTs is the reduction of system reliability. Failure of the multi-line system components can cause a large number of FOWTs to detach and stay adrift. Hallowell et al. (2018) investigated the reliability of a multi-line system (100 wind turbines in 10 rows and 10 columns configuration) compared to a conventional single line system. It was found that the reliability of a multi-line system reduced considerably in extreme load conditions due to progressive failures. Further research
370   is required in this area to increase the reliability of multi-line systems for FOWTs.

Geo-technical investigations are carried out at the anchor site prior to the installation of anchors. Dedicated geo-technical investigation vessels are used for this. The cost of geo-technical investigations is a function of water depth, site conditions, pre-existing survey data and method of investigation. The geo-technical site investigation costs are also dependent on the number of anchors (Fontana (2019)). In a wind farm with shared anchors, there is a significant reduction in the number of anchors.
375   This would help to bring down geo-technical site investigation costs. (Fontana (2019)) compared the costs of installation and geo-technical site investigation for different farm sizes. It was found that a multi-line configuration reduces the installation cost for wind farms with 36 or more wind turbines. The geo-technical site investigation costs also get reduced with increase in the size of the wind farm but tapers due to the diminishing of the perimeter effect (anchors in the perimeter share less FOWTs). In a shared mooring system, mooring lines can be inter-connected instead of connecting to the sea-bed. The optimized installation
380   procedure for shared mooring and anchoring system and its effect on costs and time are yet to be investigated.
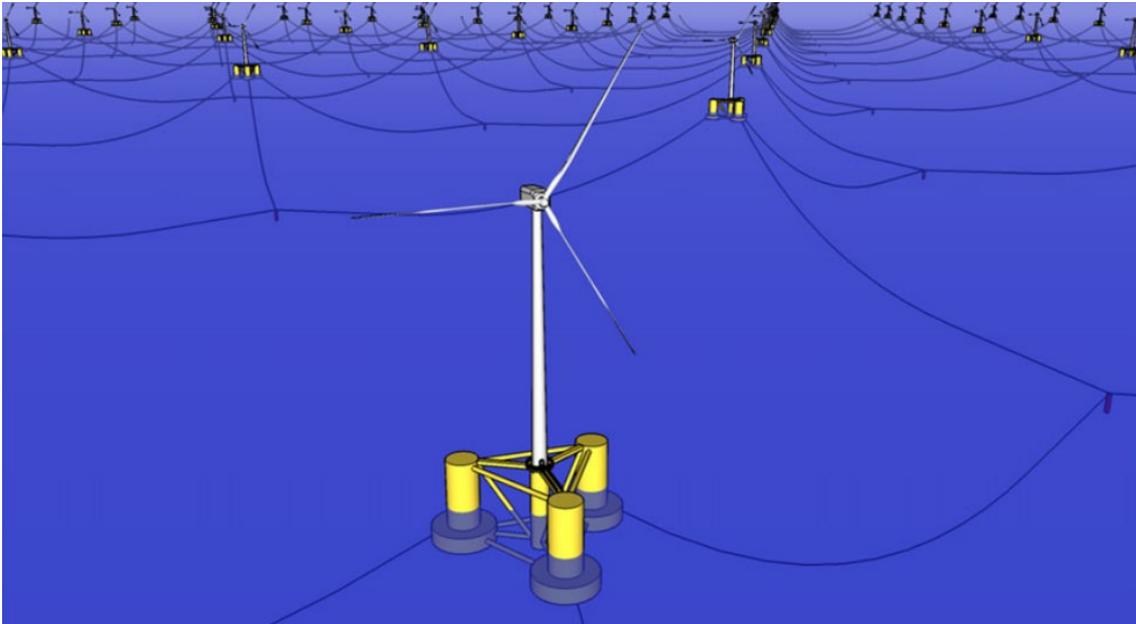
Figure 12. Shared anchor system (Fontana et al. (2018))

4.2 Dynamic positioning for FOWTs

The FOWTs are generally positioned in the deep sea using mooring lines. They have to be pre-installed using offshore support vessels which are expensive and the process is time-consuming. Precise engineering calculations are required to design the mooring lines and anchors for offshore structures.

385   The water depth is a decisive factor that determines the length of mooring lines and the costs associated with them. In many cases the sea-bed has to be analysed and prepared depending on the type of the anchors used for installation. Semi-submersibles and spar-type floaters are moored using longer, but simpler mooring system compared to TLPs, but the TLPs employ complex anchors and vertically loaded mooring lines with high load bearing capacity. They are considered impractical and uneconomical for water depths greater than 1000 meters (Yamamoto and Morooka (2005)). At the moment, researchers

390   agree that the practical water depth limit for floating wind turbines should be between 700 m to 1300 m (Musial et al. (2016)). Developing a cable system for transferring electricity from such depths is difficult and impractical. But with the development of better electricity storage technology, eg: efficient hydrogen production and storage (Cummins and McKeogh (2020)), FOWTs can be deployed in deeper waters. Mooring systems will be less effective for station-keeping in such cases.

    Dynamic positioning has been often used for station-keeping of ships and offshore structures in the O & G industry

395   for years. Offshore support vessels actively employ Dynamic Positioning Systems (DPSs) for a variety of offshore activities. Employing DPS can be considered for FOWTs in deeper waters. The water depth and sea-bottom conditions do not affect the DPS, hence it can save mooring line, sea-bed preparation and anchoring costs. The disadvantage of the DPS is that, it consumes

a considerable amount energy the turbine produces. Xu et al. (2021) proposed the feasibility of a dynamically positioned semi-submersible 5 MW floating wind turbine in their paper. It was found that the DPS utilized approximately 1/2 of the total generated energy when the current forces are not considered and the ratio becomes 4/5 when current forces are taken into account (Xu et al. (2021)). The concept has not been experimentally evaluated and the economics of the DP system have not been optimised.

Another scenarioO & M activities. Even with the mooring lines attached, the platform is subject to motions which makes the transfer of personnel difficult. In such cases, the DPS would help to stabilize the FOWT and help safe transfer of the crew. Heavy-lift vessels can also employ the DPS during heavy-lift operations in the deep sea (eg: mating of spar-type platforms, O & M). The economics of using such systems for FOWTs are yet to be investigated.

4.3 Walk-to-work for FOWTs

Operation and maintenance of offshore platforms are often challenging due to the difficulty in accessing the platforms. Safe transfer of crew is essential for all kinds of maintenance activities concerning offshore structures. Access of O & G platforms and fixed wind platforms has always been challenging. In the case of floating platforms, it is even more challenging as the platform and the crew transfer vessel are in relative motion during transfer. Since floating wind technology is relatively new, it is necessary to use the knowledge acquired in the O & G and fixed wind domain for floating platforms (Santos et al. (2016)).

Walk-to-work (W2W) vessels (Figure 13) are equipped with motion compensated gangways (MCG) that enable crew transfer in higher wave heights. They help to widen operational weather windows and eliminate the waiting time, which saves time and expenses. They can also be employed during installation activities for the transfer of crew. The MCGs employ a technology known as active motion compensation (Chung (2016)). Accurate motion sensors detect vessel motions and counteract them using a sophisticated hydraulic hexapod on which the gangway is mounted. The motion detection and hydraulics are governed by an automated control system. MCGs allow crew transfer in significant wave heights up to 3.5 m and wind speed up to 20 m/s (Salzmann et al. (2015)).

Guanche et al. (2016) investigated the hydrodynamic performance of a catamaran crew transfer vessel (CTV24) with a fender and a Platform Support Vessel (PSV80) with an MCG and the operating significant wave height conditions were compared. It was found that access was theoretically possible with wave heights up to 2m using the catamaran and 5m using the PSV in head seas (Guanche et al. (2016)). In a separate study, accessibility was calculated for a semi-submersible located off the coast of Portugal using hind-cast data from 1980-2013. Safe access was possible up to 20% and 76% percent of the time using the catamaran and PSV respectively (Martini et al. (2016)). Li (2021) further investigated the operability of such systems by taking second-order drift motions also into consideration. It was noticed that the general wave-height limit reduces to 2-3m when nonlinear drift forces were involved. Both investigations revealed that beam seas are to be avoided in all cases when employing W2W vessels for access. However, all these studies indicate that W2W vessels equipped with MSGs are considerably advantageous over conventional access systems for floating wind platform access. The complex motion of the multi-body system requires further studies to ensure the safety of the crew during such operations.

Figure 13. Walk-to-work vessel in operation (4C-Offshore)

4.4 Specialized ships for FOWT installation

Even though many FOWTs do not need specialized installation vessels, innovative vessel designs that could simplify the installation processes are worth investigating. Many of the floater types can be constructed onshore and towed to the location by using tugs. An exception to this are the spar-type platforms. They need heavy-lift vessels for the platform-turbine mating pro-

435 cess. There is potential for developing innovative ship designs that can facilitate cheaper and safer marine operations compared to the existing methods. One public competition we can examine to give insight into this, happened in 2014, when Statoil (now Equinor ASA) presented the 'Hywind Installation Challenge (Equinor (a))' that sought out innovative installation technologies and methods for the installation of the Hywind wind turbines.

Stavanger based Windflip AS proposed an innovative vessel design that can be used for the installation of floating offshore

440 wind platforms (Maritime-Journal). The proposal was based on a specialized barge than can transport a fully assembled spar-type platform to the location and unload by flipping. The turbine is loaded in an almost horizontal position and the barge is towed to the offshore location. The aft side of the barge is then ballasted taking the whole barge-turbine system into a vertical position. The turbine is then connected to the mooring lines and the barge is towed back to the quayside for reloading. Figure 14 explains the main stages in the installation of a wind turbine using the barge. Windflip AS claims that the vessel can operate

445 in shallow waters which is an advantage when it comes to the installation of spar-type platforms.
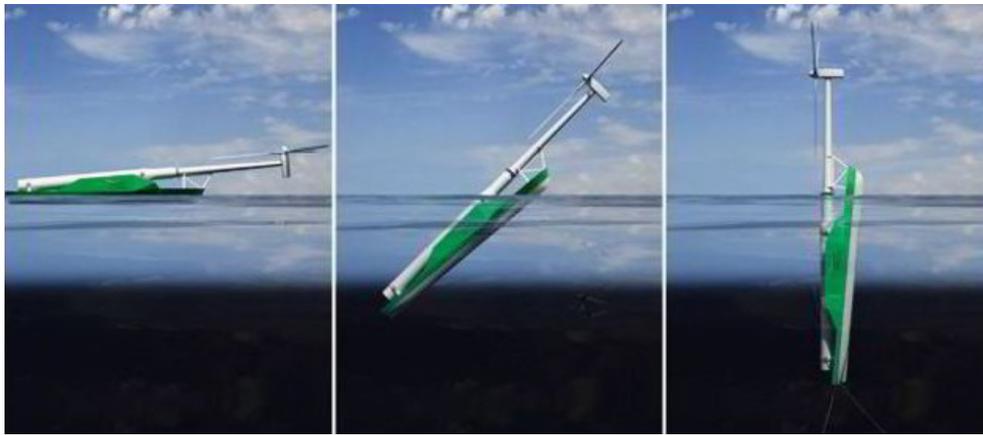
Figure 14. Installation of wind turbines using a WindFlip vessel (Maritime-Journal)

Another concept was proposed by Jiang et al. (2020) to aid the installation of spar-type platforms. A floating dock was specifically designed for shielding a wind turbine during the installation of the tower, nacelle and rotor onto a spar-type platform. Hydrodynamic evaluation showed that the floating dock was able to reduce the platform-pitch response of the spar-type platform which aids mating of the blades.
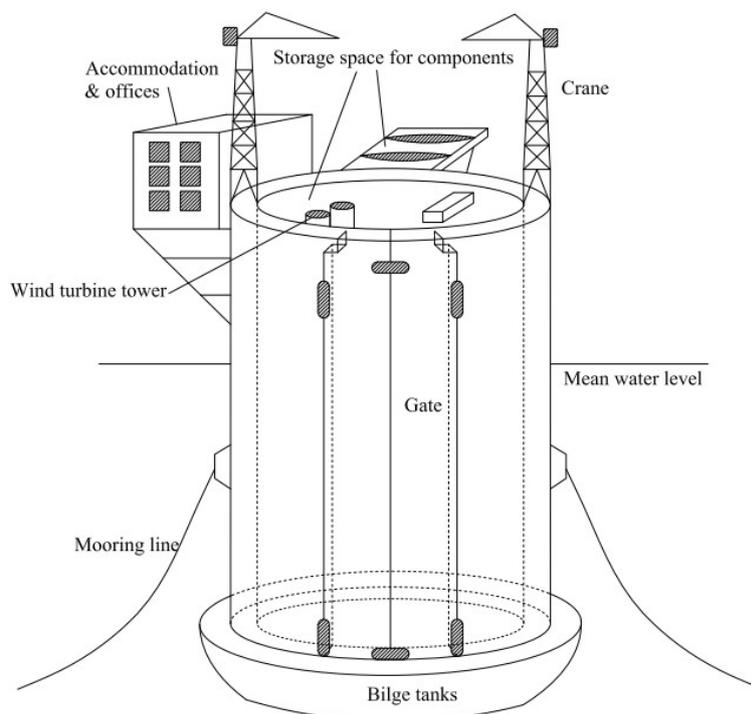
Figure 15. Floating dock concept (Jiang et al. (2020))

450   Jiang et al. (2018) investigated another concept, a catamaran wind turbine installation vessel equipped with grippers that aid installation of spar-type platforms. The vessel can carry a maximum of four wind turbines. This vessel can minimize or eliminate the use of heavy-lift vessels and thereby reduce installation time. Figure 16 explains the various stages in the installation of a spar-type platform using the catamaran vessel. The disadvantage here is the complex mechanical structural arrangement and various dynamic loads acting on the system.
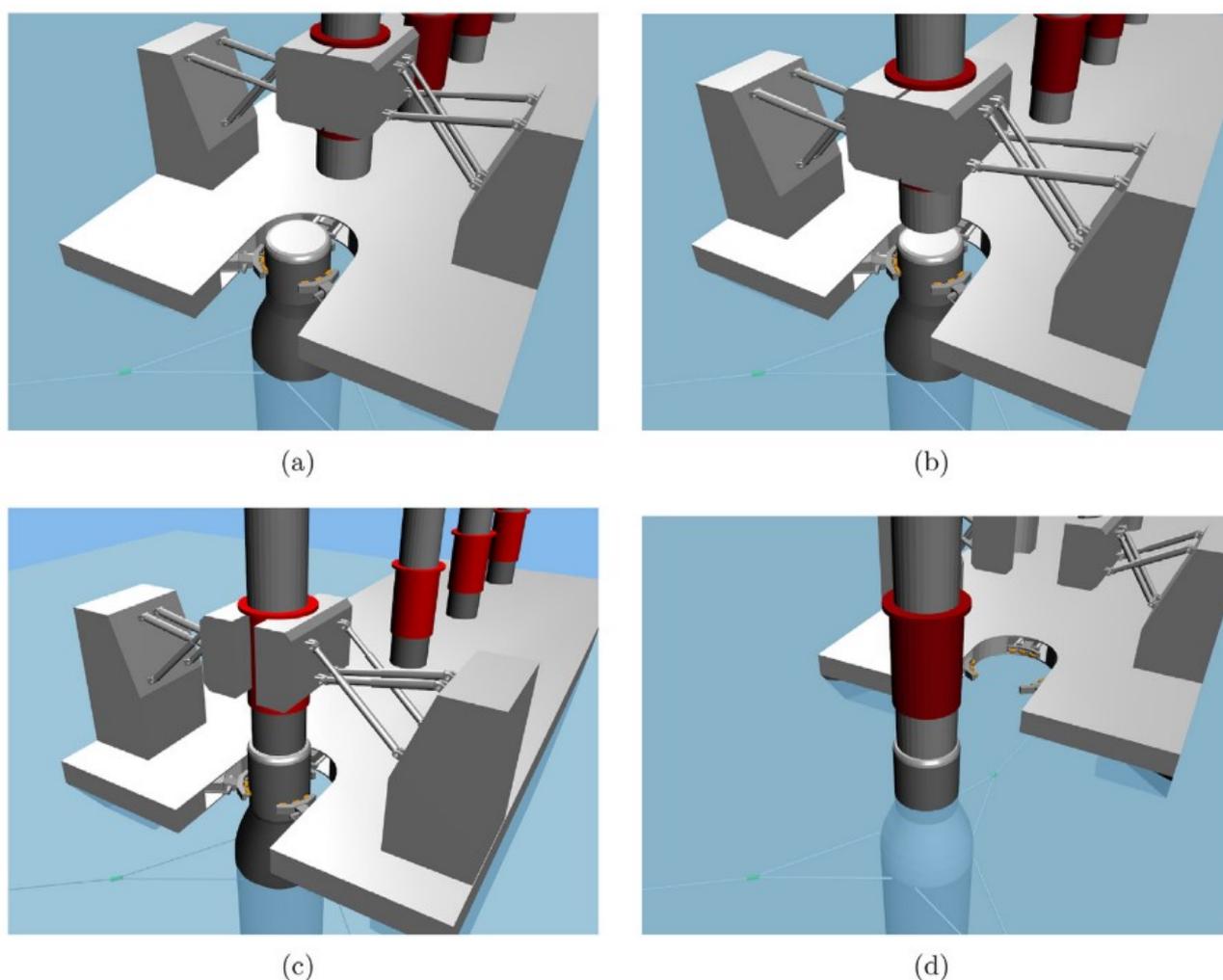
Figure 16. Stages in the installation of a wind turbine using the catamaran vessel (a) transfer of the assembly (b) monitoring of relative motion (c) mating of the tower with the floater (d) release of the foundation (Jiang et al. (2018), Hatledal et al. (2017))

455   Vågnes et al. (2020) proposed an improved system using winches and wires, instead of grippers. This system can reduce the structural requirements of the lifting system and improve the handling of the wind turbines. The system will be installed aboard a catamaran vessel which can be used for the installation of spar-type platforms. The low height lifting system is controlled by an active heave compensation system and tension tugger wires to ensure the balance of the tower during the mating process. Figure 17 shows the various components of the low height lifting system. Preliminary hydrodynamic analyses

460   of the system under various weather conditions and operational layouts showed that the system is feasible and can be efficiently used for the installation of spar-type platforms. However, detailed analyses and experiments are pending.
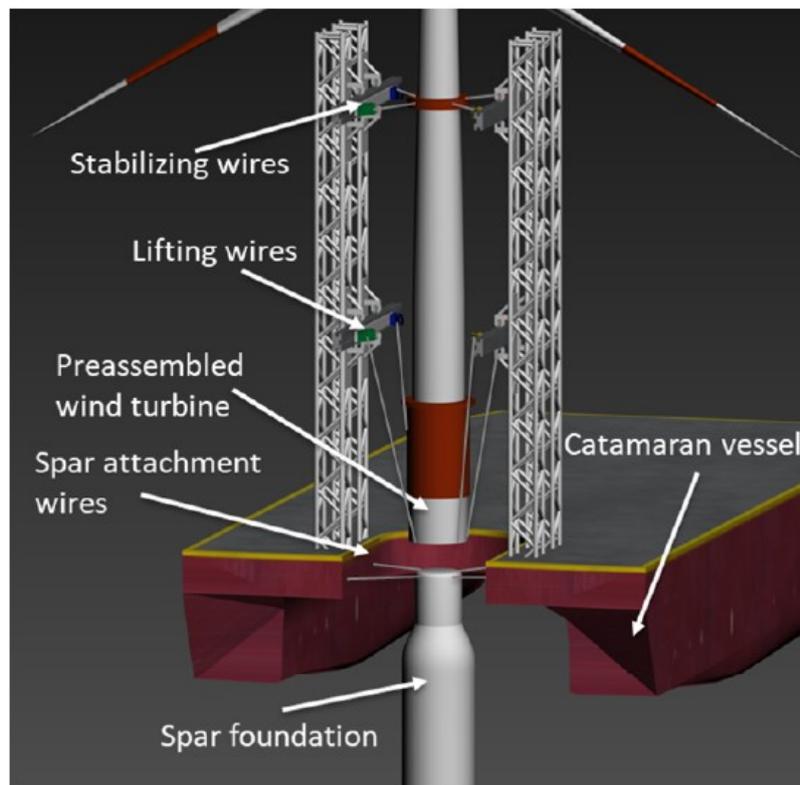
Figure 17. Catamaran OWT installation concept (Vågnes et al. (2020))

5   Conclusions

The importance of focussing research on the installation, O & M and decommissioning operations is discussed in this paper. As the industry matures, much research is needed to frame innovative methods and technologies to reduce the costs and LCOE.

465   Compared to the O & G industry, offshore wind turbines provide opportunities for batch production and deployment. These opportunities should be utilized for the full commercialization of floating wind farms. Semi-submersibles are observed to be the most cost-efficient design from an installation, O & M and decommissioning point of view, but broader research is needed

to consider all the factors applicable to the whole life-cycle of the wind farms. Several challenges are yet to be addressed to reduce the costs concerning spar-type platforms and TLPs. It is very important to consider the ease of installation, O & M and decommissioning in the design phase of the floater concepts for the practical realization of these concepts. There is also plenty of room for innovation to cut costs, reduce environmental impact and improve safety of the personnel associated with the industry.

Many challenges need to be addressed and much research is pending in the FOW domain. Some of the challenges are specific to the type of floater but others apply generally. There is much research to be done for the easy and cost-effective installation, O & M and decommissioning of TLPs. It is important to introduce and implement innovative and cost-effective methods and technologies in this domain. Marine operations, due to the involvement of human life, environment and marine life, are of paramount importance. They are most dependent on metocean conditions, so accurate prediction is important. In situ measurements should be encouraged for getting accurate weather data throughout the life-cycle of the wind farm. Sharing of these data across multiple platforms should be also be encouraged for the metocean analyses of upcoming wind farms and for further research. Marine operations can be improved in two different ways i.e., either by developing better metocean prediction models, for example, analytical models augmented by in situ measurements, or improving the operability of vessels in harsh seas by implementing innovative technologies and methods. Specialised vessels are expensive, but by reducing costs in other areas they can lead to reductions in the overall LCOE. Generally, O & M operations have stricter weather restrictions compared to installation operations (eg: towing). Emphasis should be given in this area and the O & M weather conditions should be used as limiting cases for the metocean assessments. As the industry matures, it is very likely that there will be a huge demand for Offshore Supports Vessels (OSV), AHTSs, SOVs etc. in the near future. The industry should be able to supply the vessels according to the demand or else the costs will rise. Marine operations and vessel utilization must be optimised to reduce the LCOE of floating offshore wind and increase competitiveness with other energy sectors.

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Competing interests. The authors declare that they have no conflict of interest

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