Floating offshore wind turbine – Heavy construction requirements

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ABSTRACT: Floating offshore wind farms are becoming an option, for marine renewable energy production. They are anchored to the seabed, in water depths greater than those used by fixed bottom offshore turbines, where winds are stronger and more consistent further offshore. The large space required to build floating wind substructures will require changes to existing fabrication facilities. As turbines become larger then new lifting methods will need to be developed at the fit out quays. These floating offshore wind turbines will need to be fabricated, transported and installed in locations all over the world. To keep up with this progress, installation vessels and onshore cranes have to go through updates and new builds so that they can still be utilized in the installation of floating wind farms. This paper sets out the potential work in the design, construction and installation of floating offshore wind turbines.

1 INTRODUCTION

This paper assesses the inshore construction and the installation of floating offshore wind turbines. The motivation for this analysis is to determine the minimum requirements for construction equipment, port facilities and offshore installation vessels. The paper considers existing literature on the construction and installation of floating offshore wind turbines.

The construction and installation phases impose loads on the components of the floating offshore wind turbine, which may not be seen during the operational phase.

Scientific calculations are developed to consider substructure weight and hence floating drafts.

There are several floating wind types namely barges, semi-submersibles, tension leg platforms and spars and their capabilities and differences are discussed in section 2.

To realize the full potential of floating wind, efficient methods of constructing floating wind farms at scale must be found. Standardizing floater types and methods of installation will play a large part in this.

Fabrication yards are discussed in section 3 and load-out is covered in section 4. Offshore floating wind development has to date focused on prototype projects with limited scope and highly varied designs. Through standardized design principles and mass manufacturing strategies, construction can take place in parallel and economies of scale can be enjoyed that will lower the capital investments needed, making offshore floating wind more viable for more locations.

For a large scale floating wind farm, seeking to achieve the goal of load-out of for example one floating offshore wind turbine per week, every element of the fabrication, logistics and construction chain must be closely coordinated. Floating wind project scheduling is discussed in section 3.

If floating offshore wind turbines (FOWT) wishes to see the same success and cost reduction as Bottom Founded Wind turbines, then the supply chain must be effective from the beginning in terms of both cost and quality, (McMorland, et al, 2022).

The Crown Estate Scotland, (Crown Estate Scotland, 2022), has started the Scot-Wind and the Innovation and Targeted Oil and Gas (INTOG) processes which would deliver floating wind off the coast of Scotland. There are plans for floating wind farms in the Celtic Sea, which will provide via an export cable, electricity to the onshore electricity grid. However, the industry lacks experience with FOWT technology. The author calculates that about 0.10 GW, of FOWT, is installed and operational globally, by the end 2022.

Heavy maintenance is covered in section 4.Results are in section 5, a discussion is in section 6 and conclusions in section 7.

2 FLOATING WIND TYPES

2.1 *Floating wind options*

About 70% of world’s seas are deeper than 80m. The crossover from fixed to floating offshore wind turbines (FOWT) depends on the availability of jack up wind turbine installation vessels (The Carbon Trust, 2020). These floating structures have a large plan area, so storing them on land is realistically not an option and wet storage in sheltered waters will be limited. This means that the FOWT wind farms will have to be installed using just-in-time manufacturing processes that the renewables sector has not yet needed to use.

A floating offshore wind turbine (FOWT) platform is the concrete, steel or hybrid substructure on which the wind turbine is installed, providing it with buoyancy and stability. Wind power is stronger in the ocean than on land, hence the development of offshore wind in recent years. Turbines fitted on bottom founded structures, could not be installed in very deep or complex seabed locations, something that has changed with the advent of floating structures. These floating platforms are anchored to the seabed by means of flexible anchors, chains or steel cables or synthetic ropes. Floating offshore wind turbines can thus be installed further offshore in deeper water.

Floating offshore wind energy is a source of clean and renewable energy obtained by harnessing the power of the wind offshore, where it reaches a higher and more constant speed. Its high potential and strategic added value, both at an economic and environmental level, makes it one of the renewable sources that will play a crucial role in the decarbonisation process.

Among the advantages of floating offshore wind are the potentially low environmental impact. However manufacture and installation is challenging for floating offshore wind turbines. Barge and semisubmersible types can be built and assembled on land and then towed to the offshore installation site.

A floating offshore wind turbine platform (FOWT) can be concrete or steel or hybrid substructure on which the wind turbine is installed. The floating substructure is anchored to the seabed using one of the following for barges, semi-submersibles or spars:

- Catenary mooring
- Taut mooring
- Turret mooring

For TLP mooring vertical tensioned tendons would be used.

The topside (tower, nacelle/hub and blades), the rotor nacelle assembly(RNA), are attached to the top of the substructure and the force of the wind turns the blades and the wind turbine converts the kinetic energy into electricity, which is transported by underwater cables to one of:

- Directly to shore if less than 50km
- To an offshore substation and from there to an onshore substation
- To offshore oil and gas platforms to minimise their use of hydrocarbons for electricity production
- To offshore or onshore facility for the production of green hydrogen

The installation of the subsea export cable requires the following:

- Detailed geophysical route survey
- Checking for wrecks, UXO, existing cables and pipelines.
- Burial of the cables by water jet trenching or subsea plough
- Possible protection by concrete mats
- Long term weather information for the route

At the offshore wind farm site similar surveys are required plus geotechnical, i.e. boreholes.

The choice of one type or another of FOWT will depend on sea and seabed conditions, the winds in the area, the size of the wind turbine, the water depth of the fit out harbours, the manufacturing facilities and the availability and cost of materials and equipment.

There are limitations on where a floating wind turbine can be moored, (Pendleton, 2019):

- Close to existing subsea pipelines
- Close to existing subsea cables (telecommunications and power)
- Military training areas
- Places where there may interfere with radar stations
- Dumping grounds for UXOs
- National marine sanctuaries
- Areas of low wind speeds
- Locations of bird migration routes
- Sea mammal feeding, breeding and transit areas
- Fishing grounds
- Underwater wrecks
- Commercial shipping routes

Floating offshore wind turbines installation, operation, maintenance and finally the decommissioning present challenges and opportunities (Ramachandran, et al, 2021) that can be overcome by targeted research (Crowle & Thies, 2021). With regards to construction and installation, of FOWT, there are lessons to be learnt from bottom founded wind turbines (Jiang, 2021)

Investigations, (Castro-Santos, et al, 2013) show that approximately 36% of the total floating project capital expenditure (CAPEX) costs are incurred during the installation, exploitation and dismantling activities. It has been revealed, (Castro-Santos, et al, 2016.) that the size of the floating wind farms has a considerable impact on installation costs and lifetime cost of energy (LCOE).

It was found that the CAPEX and LCOE reduces as the floating wind farm size increases.

2.2 *Calculation methodology*

The methodology for calculations includes weight, centre of gravity, drafts and intact stability values of which are not normally published. These items are key inputs into developing safe construction and installation methods.

Additional calculations have been developed for semi- submersible types for temporary buoyancy to minimize drafts. Bollard pull estimates have been developed.

2.3 *Wind turbine dimensions*

Typical values of offshore wind turbines are given in table 1. Existing FOWT are in range of 6 to 10MW turbines and it is expected that future FOWT will be up to15MW

Table 1 Turbine dimensions

Turbine Power	MW	6	19	15
Blade length	m	74	95	115
Rotor diameter	m	151	194	236
Hub height	m	106	127	148
Tower weight	t	195	310	450
Nacelle and hub weight	t	333	579	908
Each blade weight	t	54	83	109
Number of blades		3	3	3
Topside weight	t	691	1,138	1,684

These nacelle weights and their elevations above sea level are a challenge for existing onshore cranes as only a few are available.

2.4 *Barge*

The barge concept is a box shape where the beam and length are significantly larger than the hull depth, figure 1. The barge floating platform has a large water plane surface area in contact with the water, which is what gives it intact stability.

Typical weights and drafts for steel barges are given in table 2. Concrete barges will be of greater weight, and larger draft than steel barges during fit out and tow out.

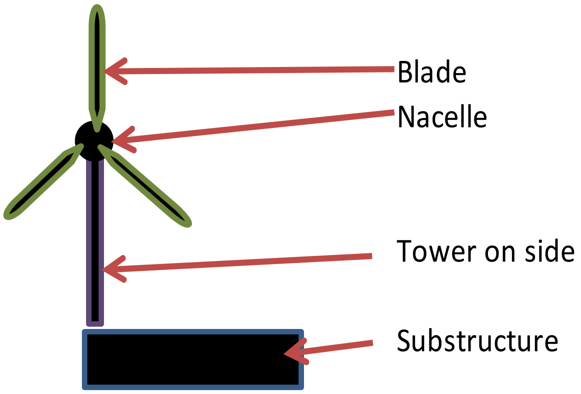

Figure 1 Typical barge

The barge FOWT advantages are:

- Shallow draft
- The turbine is on one side, hence maximum use of onshore crane during fit out

The barge FOWT disadvantages are:

- small freeboard
- higher motions in tow out

Typical weights and drafts for steel barges are given in table 2. These have been extrapolated by the author based on limited project data.

Table 2 Typical steel barge weights

Turbine Power	MW	6	19	15
Length	m	49	52	55
Width	m	49	52	55
Depth	m	12.5	12.5	12.5
Dry weight	t	2,633	3,153	3,636
Draft before fit out	m	1.7	1.7	1.7
Topside weight	t	691	1,138	1,684
Ballast	t	8,895	10,884	12,633
Draft after fit out	m	7.5	7.5	7.5

2.5 *Semi-submersible*

The semi-submersible design minimises the surface area exposed to the water, but always maximising the volume, figure 2. The volumes that provide buoyancy are divided into several vertical columns which are joined by braces to create a structure where the turbine can be installed. The size and the distance between the columns determine the intact stability, i.e. they second moment of water plane area.

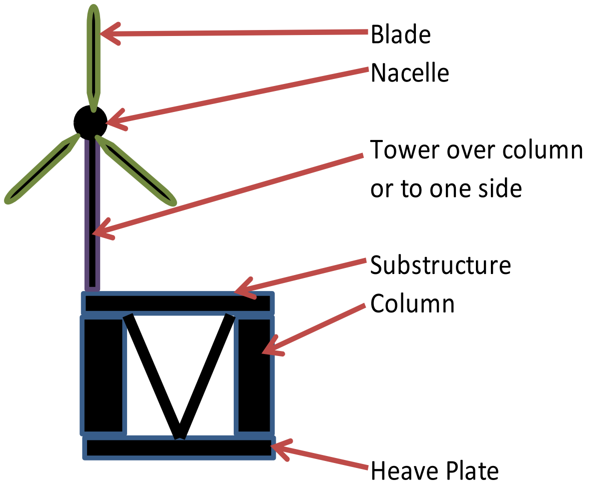

Figure 2 Typical steel Semi-submersible

The Semi-submersible FOWT advantages are:

- Large 2nd moment of water plane area, hence good intact stability in tow out
- The turbine is on one side or over a column, hence maximum use of onshore crane during fit out

The Semi-submersible FOWT disadvantages are:

- High steel weight
- If constructed in a dry dock temporary buoyancy may be required to minimise the draft.

Typical steel Semi-submersible weights and drafts are in table 3. These have been extrapolated by the author based on limited project data.

Table 3 Steel Semi-submersible weight

Turbine Power	MW	6	19	15
Nacelle only weight	m	333	579	908
Nacelle above sea level	m	106	127	148
Blade tip height	m	181	224	266
Number of columns		3	3	3
Column diameter	m	13	15.6	18.8
Heave plate diameter	m	21	25	30
Width of structure	m	71	83	98
Depth of sub structure	m	26	29.2	33.2
Dry weight substructure	t	3,000	5,469	10,052
Draft of substructure	m	7.5	9.5	12.0
Zero trim ballast	t	691	1,138	1,684
Topside ballast	t	691	1,138	1,684
Displacement	t	4,383	7,746	13,410
Draft after fit out	m	11.0	13.5	16.0
Option buoyancy tank	m	170.8	284.6	421.0
New draft a	m	8.6	10.5	13.0

Most semi submersibles have the tower over a column, rather than in the middle. This means that sea water ballast needs to be added to the other two columns to bring the structure to zero trim and heel.

An alternative to add temporary buoyancy to the heavily loaded column. This reduces the draft alongside the fit out quay. The temporary buoyancy can be removed when deep water has been reached in the tow out operation.

2.6 *Spar*

In the Spar, most of the weight is placed at the lowest possible point to provide stability, figure 3. As turbines become larger and larger, it requires very long cylinders to compensate for the weights, which makes this solution very difficult to manufacture, transport and install. Solid ballast is based on the base of specific gravity 2.5 to 4.0 tonnes/m^3. Water ballast is added on top of the solid ballast to achieve the required draft during tow out is given in table 4. These have been extrapolated by the author based on limited project data.

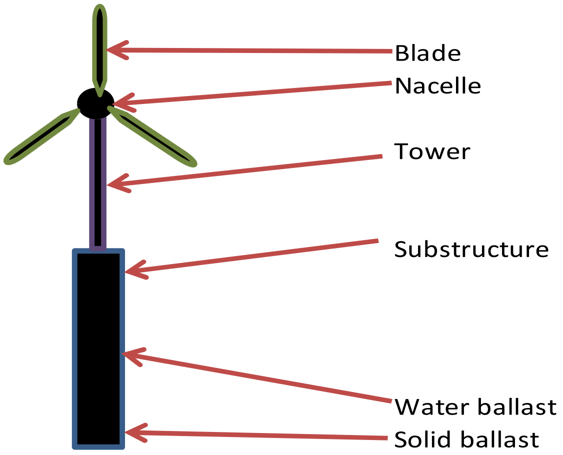

Figure 3 Typical steel spar

Table 4 Typical steel Spar weights

Turbine Power	MW	6	19	15
Column diameter	m	14.5	15.9	17.6
Topside weight	T	691	1,138	1,684
Dry weight substructure	t	2,300	3,456	4,996
Solid ballast	T	7,240	9,528	13.017
Trim water ballast	T	2,973	2,568	2,124
Displacement	t	13,204	16,691	21,821
Draft after fit out	m	78	82	87

The Spar FOWT advantages are:

- Low centre of gravity, so good intact stability in tow out
- A small water plane, hence the turbine can be in the middle, making maximum use of crane during fit out,

The Spar FOWT disadvantages are:

- Deep draft, hence requires deep sheltered water during fit out
- Needs solid ballast for intact stability during fit out and tow out

Water ballast is added on top of the ballast to achieve the required towing draft.

2.7 *Tension Leg Platform (TLP)*

TLPS are the most technically risky as the platform has very low intact stability during TLP tow out. The aim is to reduce the dimensions as much as possible in order to lower the manufacturing costs. To prevent the platform from capsizing during tow out various options are possible:

- Float at low draft with large 2nd moment of water plane area. Then by tensioning the tethers the platform is pulled to a deeper draft. See figure 4.

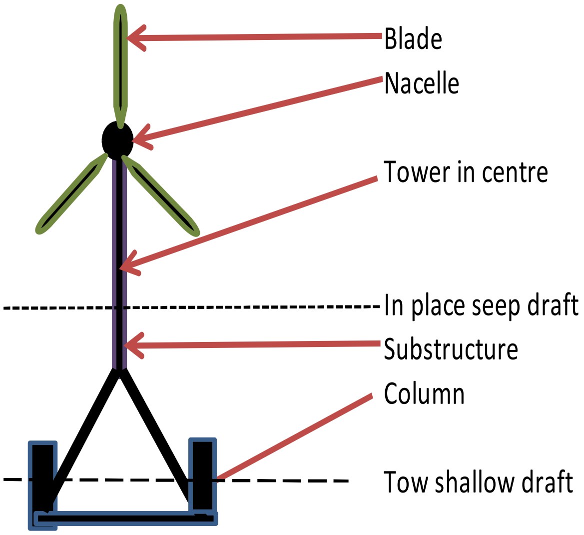

Figure 4 TLP with variable draft

- Fit temporary, reusable buoyancy tanks to the TLP substructure, figure 5, which in turn allows it to be towed to the offshore location. Once there, tensioned tendons are connected and the temporary buoyancy tanks are disconnected for reuse on the next TLP platform to be installed.
  Offshore cranes would be required to remove after completion of the mooring tension.

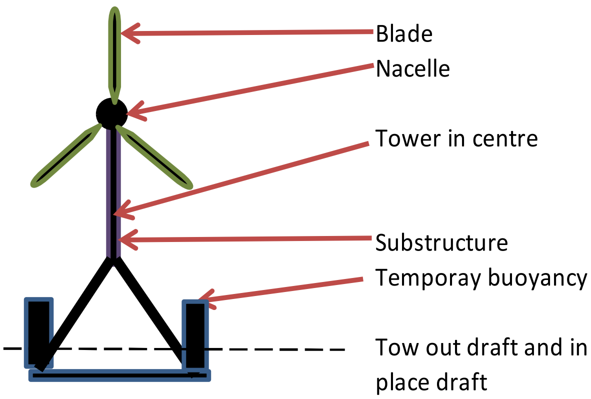

Figure 5 TLP with temporary buoyancy

- Building the TLP piece small offshore using a large crane vessel with DP (dynamic positioning) and active heaver compensation.

The TLP FOWT advantages are:

- Small area on the seabed
- Low steel weight

The TLP disadvantages are:

- Very low intact stability during tow out
- Turbine is in the centre so reducing crane capacity during turbine fit out
- Installation of tethers is weather restricted and time consuming
- Drag anchors not possible
- Requires piles for mooring
- May need temporary buoyancy for tow out
- May need crane vessel to assist offshore mooring connection or to construct the TLP offshore

2.8 *General design considerations*

It is important to have good weight control, (ISO, 2015) which covers:

- Accurate weight
- Centre of gravity
- Buoyancy at various draft and trim
- Centre of buoyancy
- Radii of gyration for tow out condition and in place position

The weight and centre of gravity of the floating offshore wind turbine structure is an important input into intact and damage stability, (Thiagarajan & Dagher, 2014). Weight control is needed for each stage of installation, (Crowle & Thies, 2022).

The transitional conditions due to construction, transportation and installation, in particular with regards to intact stability are as follows, (Collu, et al, 2014):

- Towing the substructure from a dry dock to fit quay
- Towing the substructure after offloading from a heavy transport vessel (HTV) to a fit out quay
- Wet storage of the substructure before fit out
- The positioning of the wind turbine on board the floating unit
- Wet storage of the completed structure, whilst waiting on weather
- The tow out of the completed to the operational site
- The final installation on site, i.e. connection of mooring lines
- Connection of dynamic array cables and final commissioning

Marine warranty rules are provided by:

- International Standards Organisation (ISO), (ISO 2016)
- Det-Norske-Veritas (DnV), (DNVGL, 2021)

There are guidelines for the design of floating offshore wind turbines from classification societies namely:

- ABS, (ABS, 2020)
- Bureau Veritas, (Bureau Veritas, 2019)
- Class NK (Class NK, 2012)
- DnV, (DNV, 2020)

3 FLOATING WIND PROJECTS

3.1 *Project schedule*

Floating offshore wind turbines are relatively new types of offshore units for the offshore renewable industry, which come in a range of designs, with a new logistics philosophy, as well as congested subsea spaces and small fabrication/assembly sites. There are many factors in floating platforms that need to be considered, such as the seabed type, tidal current, wind, waves, distance to shore and equipment fatigue. Constructability meetings and reports are required at early stage of the design.

The initial planning is the most critical phase for the success of the project and where there is the best chance of realising any cost saving opportunities.

This is where the ability to impact the project is highest. As time passes throughout the project life cycle, the cost of changes to the design goes up significantly, (Castro-Santos, et al, 2018), (Castro-Santos, et al, 2018), as illustrated in figure 6.

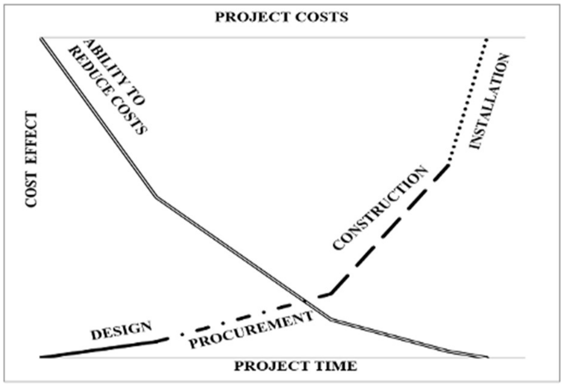

Figure 6 Cost impact for FOWT project

The capital expenditure cost (CAPEX) of a floating wind farms reduces as deployment increases, (Andersen, 2016), (Katsouris, 2016), (Ury & Kylesearman, 2021), (Kausche, et al, 2018). This assumes that there is a design learning curve and mass production of components leads to cost savings.

Also for operations and maintenance (O&M), as more floating offshore wind turbines are installed offshore so maintenance methods will be become more advanced and operations expenditure (OPEX) will be reduced.

3.2 *Wind turbines*

With the increasing size of Wind Turbine Generators (WTG's), (Castro-Santos, et al, 2013), the transportation and installation of offshore wind farms is becoming a big challenge. Currently turbine capacity is around 9.6MW, per installed turbine, which is expected to increase to 11MW in the near future. Furthermore, the latest turbine models being displayed by the major manufactures will increase output further to 15MW.

The challenge comes from the sheer size of the components. For example, the blades, though not relatively heavy, are heading towards 130m length, which becomes challenging to store, lift and transport on cargo ships. The blades are normally transported longitudinally, on the cargo ship.

Furthermore, the next generation nacelles are expected to weigh up to 1,000 tonnes, and have to be hoisted to heights of up to 150m above sea level. To keep up with this progress, in wind turbine size, installation vessels have had to go through multiple updates since launch so they can still be utilized in the latest installation of wind farms. Large wind turbine installation vessels and onshore cranes are currently under construction which will be able to lift the 15MW turbine components.

3.3 *Project Planning*

Challenges during planning of a floating offshore wind project are:

- What is the most efficient installation sequence? Consider weather window, port limitations, marine equipment availability
- What are the offshore wind farm conditions? Consider soil conditions, water depth, wind speed, wave height, wave period, local regulations, marine traffic
- What is the field layout? Consider exclusion zones, substation location, distance between turbines and moorings
- What is the best mooring solution? Consider flexibility requirements, anchor pattern, mooring line composition, tensioning requirements
- What are the associated logistics? Consider the timeline of equipment and floating structure production, fabrication, onshore storage, wet storage, and commissioning
- How will the interfaces be managed? Consider creating a value chain, syncing schedules and ensuring accountability
- Where are people involved? Consider floating structure accessibility, passengers boarding restrictions, diving requirements
- What size of wind farm can the value chain support? Consider timeline, bottlenecks, equipment availability
- How are power cables being installed? Consider how to connect to the grid or to offshore oil and gas platforms.
- How will the wind farm be maintained? Consider in-port versus offshore maintenance, turbine accessibility, moorings inspection, contingency plans and maintenance patterns, navigating the congested area by fishing boats and subsea dynamic cable array layout

3.4 *Fabrication*

Fabricating floating substructures will present significant laydown area challenges for existing facilities. The scale of substructures also limits the number and type of fabrication facilities that can be used.

For the spar sheltered deep water is required close to shore, e.g. as per some Norwegian fjords. Spars also require very large crane vessels to install the topsides on the substructure, or large onshore cranes mounted on spacer barges.

It may not be possible to construct a TLP at an inshore location due to low intact stability during tow out.

For barges and Semi-submersible types most of the fabrication and assembly work can be done in port, with the unit then being towed to the offshore site. This avoids the use of the installation vessels required for fixed structures, such as jack-up or dynamic positioning vessels (very expensive and scarce vessels that condition the installation times and costs of these substructures). The installation of floating platforms, on the other hand, mainly requires relatively frequent and cheaper tugboats and cable-laying vessels.

One option is construct the substructure in a dry dock. There are limited dry docks of suitable size to get these structures in the water, neither is a slipway launch appropriate for such huge objects. So, fabrication sites will need a large water depth alongside the load-out quay, so that the substructure is built onshore before load-out onto a submersible barge or heavy transport vessel (HTV). As the market opens up to these new entrants, the right construction approach will be crucial to a project's success. Designing substructures so that they can be built, transported and shipped in the most efficient way shortens overall schedules and lowers whole-project costs.

Ensuring an efficient production line at ports to keep projects moving will be a critical step in the floating wind industry reaching a mature model. To achieve this, facilities will need to put in place additional infrastructure to load-in, store and load-out components. Due to their size, large real estate areas with good maritime access and sufficient ground capacity will be needed. Amongst the key criteria to meet will be the space to handle the increasing size of floating substructures

It will be a challenge to find enough ports worldwide that can provide this, and infrastructure upgrades will be contingent on a reliable pipeline of projects being planned. However, with the right equipment, facilities located almost anywhere can enter the floating wind market.

Project-based upgrades that can deliver the required capabilities using operational rather than capital expenditure will be preferred. To achieve this in an efficient and cost-effective manner, providing additional port space and lifting capability without interrupting existing activity. Major ports need to develop their facilities with offshore wind in mind, providing additional space and ground reinforcement to marshal and store offshore wind components.

3.5 *Load-out*

With weights of anything between 2,000t and 10,000t, the load-out of floating substructures uses techniques developed in the oil and gas industry. The key challenge is to find a safe, cost-efficient and scalable method for placing large units in the water. One common approach has been the use of submersible vessels, with components rolled onto the vessel using self-propelled modular trailer (SPMTs). The submersible vessel maybe a barge towed by tugs or a self-propelled heavy transport vessel (HTV).

3.6 *Substructure Transport*

The substructure needs to be sea-fastened to the deck of the submersible vessel or HTV for the ocean tow. The ocean voyage on a submersible vessel or HTV will be with unrestricted weather conditions, which are typically the 10 year return wave condition.

3.7 *Float-off*

To discharge the substructure form the submersible vessel the following needs to be considered:

- Water depth sufficient for the submersible vessel or HTV to be ballasted down for the substructure float off, without the submersible vessel or HTV touching the seabed
- But not too deep water, so that if the ballasting of the submersible vessel or HTV goes wrong that the vessel does not sink.

3.8 *Wet Storage*

Wet storage of the substructures is required in case of delays due to weather, fit out quay not being ready or if installation vessels are not available. The wet storage areas could be as follows:

- For substructures waiting for the topsides to be fitted
- For completed structures waiting to be towed offshore

3.9 *Assembly At Fit Out Quay*

Floating offshore wind turbines are growing in size, height and weight as developers seek larger power yields from higher wind speeds. So much so, that they are rising beyond the reach of all but the tallest cranes.

Bottom founded wind turbine maximum water depth limits are determined by the availability of jack up wind turbine installation vessels (WTIV). Large high capacity WTIV are under construction.

For TLPs one option is to build them offshore using a floating crane vessel fitted with active heave compensation on the crane hook. This method is currently under development.

The topsides of a FOWT is expected to be installed against a fit out quay for barge and semisubmersible types, using one of the following methods:

- Very large onshore crane

- Use a jack-up wind turbine installation vessel (WTIV).
- Large floating sheer leg crane
- Semi-submersible crane vessel (SSCV)

All these lifting options would lie dormant for long periods between topside fit outs.

Also 1,000t nacelles need to be installed 170m in the air. For barges and semisubmersibles with the turbine to one side or one corner the lift radius is about 25m. However if the turbine is in the centre of the substructure the lift radius could be 60m.This means that when assembling from dry land, only the world's largest crawler or super heavy lift cranes will be able to complete the fit out of the topsides.

Spars need to be fitted out in deep sheltered waters. Onshore fit out facilities will be required as part of the sequence.

3.10 *Pre Lay Of Moorings*

The mooring system for barges, semisubmersibles and spars, consists of drag anchors, or piles to which chains, are attached, which are in turn connected to the floating offshore wind turbines. Chain is required at the seabed end where it touches the seabed. Steel wires or polyester lines might be used for the mid water part of mooring. The type of anchoring system depends on the water depth, the size and weight of the floating wind turbine, soil conditions and the weather conditions.

Anchors may be

- Drag anchors, of high holding capacity, which are installed with AHTS. Drag anchors are not suitable for TLPs
- Suction piles or driven piles or drilled piles all of which require DP2 (dynamic positioning, level 2 or 3) for installation plus at least one AHTS (anchor handling tug supply) to lay out the moorings on the seabed.
- All the pile options are suitable for all types of floating offshore wind turbines.

During the anchor laying phase they are proof load tested and then the mooring lines are pre-laid and sometimes buoyed off, ready for the turbines to arrive on site for connection. In a floating wind farm with multiple FOWTs, with 4-6 mooring lines each, there is going to be a lot of subsea mooring lines.

It is essential that manoeuvrability for the AHTS vessels carrying out installation is considered during planning to ensure minimised risk of damage to any mooring equipment.

From an installation point of view it is important to minimise the types mooring lines used, otherwise it will potentially lead to more port calls or additional vessels.

3.11 *Offshore Towing*

During tow out the floating offshore wind turbine is towed out to the fit out port by harbour tugs. The FOWT is towed an initial distance to carry out ballasting operations, in sheltered waters. The completed FOWT is towed to the installation site using a large AHTS tug and an escort tug. A primary concern is for availability of the required installation vessels and equipment for a seamless transition from integration of the turbine and floating structure to the offshore wind farm. To ensure alignment, flexibility and cost minimisation, the right interface management in this phase needs to be considered during planning.

This tow out takes place an average speed of about 3 knots. The tow cannot sail too fast because of the large wind, wave and current forces that are exerted on the turbine and substructure.

Table 5 shows the tug bollard pull requirements for a steel Semi-submersible with a 10 MW turbine and at a draft of 13.5m. For an ocean tows the blades are expected to be feathered to minimise the towing wind load. There is possible requirement for a temporary diesel generator to turn the turbine into the wind during tow. In addition power may be required to minimise humidity in nacelle.

The scope of work for the towing company includes:

- full project management
- engineering
- hiring of harbour tugs
- wet storage moorings
- liaising with local authorities
- using local pilots
- mooring assembly site management
- pre-installation and pre-tensioning of mooring lines, prior to arrival of the FOWT offshore
- towage of floating offshore wind turbines (FOWT) to the offshore site,
- connection of the FOWT platform to the pre-installed mooring lines

Table 5 Semi-submersible bollard pull

FOWT Type	Semi Submersible		
Turbine Power	MW	10	10
Blade condition		Open	Feathered
Wind speed	m/s	10	10
Wind force	T	59.2	40.9
Current speed	m/s	1.5	1.5
Current force	T	101.2	101.2
Significant wave height	M	1.0	1.0
Wave force	T	6.5	6.5
Total force	T	167	149
Tug efficiency		0.75	0.75
Tug bollard pull	t	222	198

3.12 *Hook Up of moorings*

The hook up phase involves connecting the floating offshore wind turbines to the pre-laid mooring system. This is then followed by tensioning the mooring system in place to withstand the environmental conditions.

At least 3 AHTS are required for the mooring hook up. However for a TLP a dynamic positioning 2/3 (DP) crane vessel may be required to assist in connecting the tendon tension moorings.

3.13 *Cables*

The export cable installation contract includes the export cables laying, cable burial and cable protection.

Dynamic inter-array cable installation is part of the final hook up. The dynamic inter-array cable installation requires vessels than can manoeuvre easily between the floating platform and the seabed.

The dynamic cable may be connected to one of the following:

- Directly to the export cable
- Into a subsea substation
- Into a floating substation
- Into a fixed substation
- To a another floating offshore wind turbine, i.e. a daisy chain
- To a local bottom founded wind turbine

3.14 *Commissioning*

When the floating offshore wind turbine is connected to the moorings and the dynamic inter- array cable, then commissioning of the whole system is carried out. Construction support vessels will be required to assist.

The floating wind farm commissioning requires complex logistics and planning, (James, and Ros, 2015). There may be weather restrictions on the construction vessels that can be used.

4 MAINTENANCE

The advantage of barge and semisubmersible floating offshore wind turbines substructure types is that they can be disconnected relatively easily, unless the dynamic array cables are daisy chained between platforms, (Kolios, 2019). However Spars and TLPs will require heavy maintenance to be carried out at the offshore location, for which techniques are being developed.

There is a strong interest in floating wind off the west coast of the USA (Banister, 2017) as deep water is close to the shore. Maintenance of floating wind will thus be easier than where floating wind farms are a long way offshore.

In addition to turbines and floating structures, mooring system maintenance also needs to be considered. Subsea inspection of moorings take place at a minimum of every 2-5 years, depending on the system. New mooring lines and anchors may need to be procured and installed over time. A contingency plan needs to be in place for emergency repair in response to worst case scenarios such as mooring line or dynamic cable breakage, (Rinaldi, et al, 2021).

5 RESULTS

The fit out equipment, whether onshore cranes or installation vessels with large cranes, used to connect offshore wind turbine to the substructure, is just keeping pace with the industry requirements of taller and more powerful wind turbines. Existing shipyards and fit out quays may not have enough space to carry out the construction of multiple FOWT units simultaneously.

Fit out quays require:

- No overhead obstructions (i.e. no bridges and no overhead cables) between the fit out quay and offshore wind farm
- Sufficient ground strength for very large onshore crane support
- Enough water depth alongside the fit out quay so that the FOWT stays afloat in all stages of the tide
- Mooring bollards of sufficient strength to hold the FOWT in expected inshore storm conditions
- Onshore storage space for blades, nacelles and towers
- Approach channels of sufficient width and depth for heavy transport vessels and cargo ships
- Departure channels of sufficient width and depth for the completed structures to leave the fit out port safely in moderate sea conditions
- Wet storage areas close by with good holding ground for temporary anchor systems and of sufficient water depth
- Taking note that the tow out of the completed structure is expected to be a weather restricted operation
- Fit out port within 3 days sailing time of the offshore wind farm. At present a 3 day weather forecast can be expected to be fairly reliable.

Regarding moorings and their assembly this can be done at a location away from the fit out quay. However to minimise transit time and frequent return to port to pick up moorings, it should be within about 7 days sailing time of the offshore wind farm.

The manufacture of the components i.e. blades, nacelles, towers, substructure, export cables, anchors, mooring lines, export cables and dynamic array cables can be built anywhere in the world.

6 DISCUSSION

Floating offshore wind projects require the construction and installation of many structures. This is so that major onshore and offshore equipment does not have long periods of being idle. The key challenge is to achieve efficiency at scale, being able to install many FOWT units in steady succession. Success in the construction and offshore installation depends on:

- Using existing offshore experience as early as possible in the design process
- Reducing interfaces and ensuring clear accountability between developers, engineering designers, construction companies and installation vessel operators
- Creating trust and aligning incentives across the supply chain.
- Involving major subcontractors, such as crane suppliers and installation vessel operators with early contracts so that they can be involved in the design process.
- The preliminary design and detailed design phases should hold frequent constructability meetings to minimise manufacturing schedule and costs.

7 CONCLUSIONS

Construction and installation of floating offshore wind turbines (FOWT) requires both heavy duty onshore construction equipment, in particular very large onshore cranes, and large installation vessels.

Ports locations need large areas in which to carry out their functions. Wet storage areas are required close to the fit out ports.

Each FOWT structure is large in dimensions and if many are to be fabricated, for an offshore wind farm, then logistics on a big scale is required.

Component parts need to be delivered from around the world for assembly at the mooring and fit out ports.

The fit out port needs to be relatively close to the offshore wind farm because the tow out is a weather restricted operation and hence should be completed within a short weather window.

The detailed design of a floating offshore turbine structure needs include construction and installation requirements from the start.

8 ABBREVIATIONS

AHTS	Anchor handling tug supply
CAPEX	Capital expenditure
DnV	Det Norske Veritas
DP	Dynamic positioning
FOWT	Floating offshore wind turbine
HTV	Heavy transport vessel
INTOG	Innovation and Targeted Oil and Gas
ISO	International standards organisation
LCOE	Lifetime cost of energy
MWS	Marine warranty surveyor
OPEX	Operation expenditure
O&M	Operations and maintenance
RNA	Rotor nacelle assembly
SPMT	Self propelled modular transporter
SSCV	Semi-submersible crane vessel
TLP	Tension leg platform
WTG	Wind turbine generator
WTIV	Wind turbine installation vessel

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