CHALLENGES DURING INSTALLATION OF FLOATING WIND TURBINES

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SUMMARY

Floating wind turbine substructures are an expanding sector within renewable power generation, offering an opportunity to deliver green energy, in new areas offshore. The floating nature of the substructures permits wind turbine placement in deep water locations. This paper investigates the installation challenges for the various floating offshore wind types and suggests priority areas for future development to help reduce costs.

Specifically tailored design for installation includes expanding the weather window in which floating substructures can be transported to and from site and making mooring and electrical connection operations simpler. The simplification of installation methodology will reduce time spent offshore, by installation vessels, and minimise risks to personnel.

The paper reviews best towing practice for offshore installation and the possible return to port for maintenance. The installation process for a floating offshore wind turbine varies with substructure type e.g. Barge, semi-submersible, Spar and TLP which are discussed in detail. TLPs will need temporary buoyancy or specialised offshore crane vessels to enable installation of these substructures. Spars require deep water for construction and tow out. Return to port for maintenance is only feasible for Barges and semi-submersibles

Floating offshore wind structures require an international collaboration of shipyards, ports and installation vessels, The installation phases, in particular the maximum draft of the substructure, are affected by the construction materials i.e. steel or concrete. . Steel Semi Submersibles and Barges, have a smaller draft than concrete substructures, and thus require out-fit quays with less water depth.

In order to facilitate the installation and to minimize costs, the main aspects have to be considered strategically i.e., the required vessel types, the distance from fit out port to site and the weather restrictions. The fit-out port should be as close as possible to the offshore installation site to minimise weather downtime during tow-out. Of the main substructure types, the Spar has the greatest average installation cost, driven by the vessel requirements and the sheltered/calm conditions required for turbine assembly. The nature of the Semisubmersible substructure and its moorings lead to lateral movement of the turbine, which presents a challenge for the export cable connection.

This paper will be useful for researchers and stakeholders in the offshore wind and offshore engineering sector offering or considering technology solutions for floating offshore wind installations.

NOMENCLATURE

AHT	Anchor handling tug
FOWT	Floating offshore wind turbine
HTV	Heavy Transport Vessel
M	Metre
SSCV	Semi submersible crane vessel
T	Tonnes
TLP	Tension leg platform
WTG	Wind turbine generator
WTIV	Wind turbine installation vessel

1. INTRODUCTION

The challenges for floating offshore wind turbine (FOWT) depend on type of substructure, water depth, prevailing weather conditions, seabed soil and size of the wind turbine. To date, the largest turbine on a FOWT is 9.6 MW. Larger powered turbines, up to 13 MW are being ordered for new bottom fixed wind farms and it can be expected that future FOWT will also have wind turbines of up to 15 to 20 MW.

This paper describes the challenges identified for the installation of floating offshore wind turbines (FOWT). Section 2, considers why floating wind is a viable option for developing wind resources in deeper water. Options for floating wind are discussed in section 3. Installation requirements are considered in section 4. Section 5 considers mooring issues and section 6 is about the challenges of subsea cable laying and connection. Discussion and conclusions are given in section 7.

2.0 WHY FLOATING WIND

2.1 Introduction

The offshore wind industry has seen great growth in and around Europe, China and particularly around the waters of the UK, in recent years. In order to continue down the path of decarbonising the UK's energy supply more offshore wind farms are being considered. However, the shallow sites with agreeable seabed conditions have now been largely used and a move further offshore and/or to deeper water is inevitable for future offshore wind installations. The move to deeper water necessitates the use of floating substructures in order to be fully exploited, [1].

In these increased water depths, a fixed monopile / jacket substructure ceases to become a viable, cost-effective solution due to the loads imparted on the structure and the incurred sizes and costs required to counteract these. For these sites of water depth deeper than 60m a floating wind solution might be considered more viable. Table 1 gives some guidance on floating wind type water depths. Though wind turbine jack-up installation vessels, which can operate in up to 80 metres water depth are being developed which may change the economic cross over point between fixed and floating substructures. In addition articulated wind columns may be feasible.

Table 1 Operation water depth for floating substructures compared to fixed offshore wind turbines, based on technical limitation.

	Water Depth (m)			Upper limit basis
	Lower	Upper	Possible	
Fixed Monopile	0	40	50	Weight of monopile
Fixed jacket	10	60	80	WTIV water depth limit
Barge	50	100	125	No. of mooring lines
Semi Sub	60	250	300	Weight of mooring lines
Spar	80	350	400	Weight of mooring lines
TLP	70	300	350	Tendon length

2.2 Challenges during installation

The installation challenges centre around converting one off demonstration FOWT and a small number of pre commercial wind farms into full commercialisation. This will involve mass production, towout and installation of floating offshore wind turbines.

3.0 FLOATING OFFSHORE WIND TURBINES

3.1 General

There are many different floating substructure concepts, however they can be grouped broadly into four primary forms that have been tested to date. These are Spars, semisubmersibles, barges and tension leg platforms (TLPs) see figure 1. Barges and semisubmersibles may be grouped together though they have different motion characteristics.

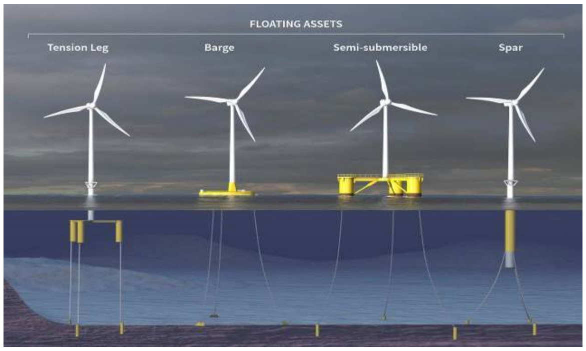

Figure 1 Main floating wind types ref [15])

There are several other options under consideration as shown in Figures A2 (multi wind turbine generators on one substructure) and A3 (suspended ballast weights). The main elements of a floating offshore wind turbine are shown in Figure A1.

3.2 Design and construction

Table 2 shows the current deployment of floating offshore wind farms and those under construction and their material of construction.

Table 2 Floating Wind Farms

Name/type	Sub structure	Turbine Outfitting	Final location
Wind float /semi-sub	Spain / Steel	Netherlands	UK (East Scotland)
Wind float /semi-sub	Spain / Steel	Portugal	Portugal
Wind float /semi-sub	France / Steel	France	France
Hywind /Spar	Spain / Steel	Norway	UK (East Scotland)
Damping Pool Barge	France / Concrete	France	France
Damping Pool Barge	Japan/ Steel	Japan	Japan
Hywind /Spar	Norway/ Concrete	Norway	Norway

Floating wind projects have the potential to make a significant contribution to the global low carbon electricity demand, as it:

- Opens access to new sites in deeper waters – 80% of Europe's offshore wind resource is located in waters of 60m or deeper
- Accesses higher average wind speeds and allows for optimal spacing
- Increases yield and capacity factors leading to competitive costs of energy.
- Minimises or eliminates the visual impact from the coastline as locations are further out to sea.
- Are well suited to locations where deep eater is close to the shore e.g. off the West coast of the USA.

4.0 INSTALLATION REQUIREMENTS

4.1 General

4.1.1 Types

The installation process for a floating wind turbine varies with substructure type; however, there are some overarching benefits relative to fixed wind that are seen in almost all cases. Generally, the installation cost for floating wind is lower than that of fixed wind turbines.

Intrinsically the installation of mooring lines and anchors is fundamentally easier to achieve than a large monopile/jacket structure and the tolerance in position is larger for a FOWT.

The connection of the turbine to the structure should be completed in port wherever possible.

4.1.2 Semi submersibles and Barges

Floating wind systems can simplify the overall installation work since turbine assembly and commissioning can take place at the quayside, with the whole unit being towed to site for connection In most cases floating wind allows more operations to be conducted onshore/port-side than with fixed wind. Fewer offshore operations results in fewer weather-constrained operations, reducing the requirement for expensive offshore vessels. Additionally, key assembly steps, see figure 2, can be performed onshore in safer, more controlled environments. Given that the turbine is coupled with the substructure, there is potential for operations and maintenance in larger sea states and therefore larger weather windows than for fixed substructures, where this is often limited to ~1.5m Hs. The option to retrieve the turbine and substructure in larger sea states than this and complete works in a safer, inshore environment is also an attractive benefit of floating wind. The construction work flow is:

- Construct substructure components
- Join substructure components close to shipyard quay
- Use self propelled modular tarnsporters (SPMT) to loadout the completed substructure onto a heavy transport vessel (HTV)
- In parallel pre-instal the moorings and subsea cables offshore
- Ocean transport the substructure to the to the fit-out yard
- Float off substructure from the HTV and moor to the fit-out quay
- Use a land based crane to fit the tower, nacelle and blades to the top of the substructure
- Tow the completed Semi Submersible to the offshore location
- Connect the moorings and tension
- Connect the inter-array subsea cables

Figure 2 Semisubmersible assembly (ref [13])

It should be noted that to date, floating wind towing and installation operations have faced restrictive weather limits. The environmental impact of installing anchors and moorings is much lower compared to piling of the seabed, with far less seabed penetration and a lower impact upon marine life. As can be seen in Table 3 there are certain operations that must happen offshore (electrical connection, anchor installation and mooring connection). In these activities the challenges for floating offshore wind remain.

Table 3 Typical operations for FOWT installation (Based on research for fixed offshore wind turbines and comparing with semi submersible and barge floating offshore wind turbines)

Item	Work	Port Laydown and Storage Time	Offshore Installation Operation Time
Substructure	Shipyard	95%	5%
Electrical Cables	Storage	25%	75%
Anchors	Storage	15%	85%
Mooring	Storage	35%	65%
Tower out-fit	Inshore	85%	15%
Nacelle out-fit	Inshore	80%	20%
Blades out-fit	Inshore	80%	20%

Semi submersibles and barges can in theory be returned to port for major maintenance.

4.1.3 Spar

Spar buoys require specialist vessels to first upend the substructure in sheltered water on site and then install the turbine. The Spar FOWT requires more installation vessels than semi-submersibles FOWT during the inshore phase, During the inshore construction phase where a large Semi Submersible Crane Vessel (SSCV), solid ballast delivery barge and outfitting barges are required. Construction of steel spars substructure is completed in a shipyard as shown in figure 3a


Figure 3a Spar substructure (ref [12])

The Spar is loaded out horizontally onto a Heavy Transport Vessel for ocean transport, figure 3b,


Figure 3b Ocean transport on HTV (ref [12])

The downside for Spars is the large water depths needed for inshore construction and towing to the offshore site. Onshore wind turbine generator (WTG) is shown in Figure 3c, whilst Figure 3d gives typical turbine installation onto a spar. Note that temporary moorings are needed inshore for the Spar, too.


Figure 3c WTG Construction (ref [12])


Figure 3d SSCV WTG installation (ref [12])

It is expected that for a Spar maintenance will need to be done at sea because of the restricted number of inshore sites with deep water.

4.1.4 TLP

Many TLPs require temporary buoyancy for tow out, see figures 4a and 4b. Temporary buoyancy on the substructure, is shown in red.


Figure 4a Temporary buoyancy on substructure at end of tow out (ref [14])

Figure 4b Temporary buoyancy on substructure removed after ballast down. (ref [14])

Alternative installation methods include fitting the turbine offshore, which requires heave compensated crane hooks, see figure 5a and 5b, on a large floating crane vessel.

TLPs requiring, on average, more installation vessels than semi-submersibles. If a TLP has to return to shore for major maintenance then refitting temporary buoyancy will be difficult and would require very good weather conditions.

An alternative is to construct the TLP offshore using a floating crane vessel, figure 5a and 5b.

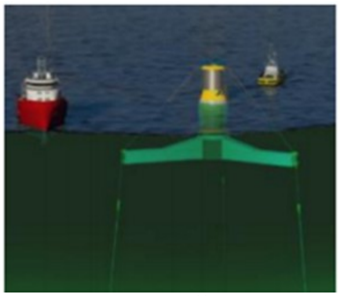

Figure 5a TLP installation (courtesy Bluewater)

Assume lift installation of the substructure.

Heave compensation device attached to crane hook on the floating crane vessel

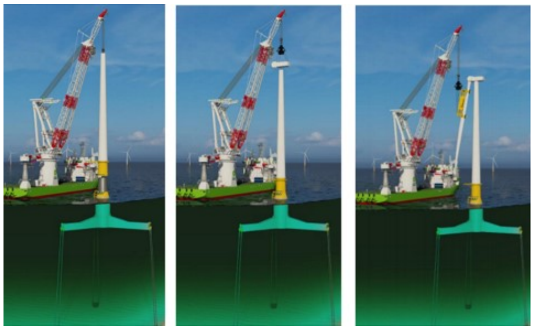

Figure 5b TLP topsides (courtesy Bluewater)

Returning a TLP to port for maintenance would be extremely difficult and is perhaps the reason why TLP concepts are yet to be developed in pre commercial units.

4.1.5 FOWT development

It should be noted that FOWT is still at an early development stage and that the marine operations, equipment and vessels, table 4, will be refined as the sector grows. Semi submersibles, damping barges and steel spars are in pre commercial operation. In contrast TLP installation methods are challenging. All of the major substructure types will continue to be developed and deployed, each suited to their own weather conditions, the local supply chain, available port infrastructure and installation vessel development.

Another significant limitation affecting installation and maintenance activities is the ability to tow these substructures to and from site. The large structural fabrications involved in floating wind platforms are inherently very large and bulky and have significant drag, making towing difficult. Additional complexity comes from very large semi-sub substructures with their distributed buoyancy and the inherently unstable tension leg platforms (TLP).

Table 4 Minimum installation vessel requirements

Vessel	Work	Average Number Of Vessels Required		
		Spar	Semi-Sub	TLP
			Barge	
Water depth	In port	80m	8m	12m
Crane vessel	Inshore	1		
Anchor handling vessel	Drag anchors	1	1	
Offshore crane vessel	Suction piles or drive piles	1	1	2
Heavy Transport Vessel	For ocean voyage of substructure	1	1	1
Harbour tug	Yard assistance	2	2	2
Anchor Handler	Installation	3	3	3
Cable Lay		1	1	1

At present, towing operations have been limited to ~1m Hs for TLPs and ~2.5m Hs for semi submersibles. For future commercial sites this level of restriction could slow the deployment of projects and cause a blockage in the supply chain with substructures in port awaiting deployment. The towing limitation has further ramifications for any return to port maintenance strategies for semi submersibles and barges. If the wait time to tow a turbine back to port for significant maintenance is of the order of months downtime losses will be very costly.

For example, assuming operations for mooring and electrical connection/disconnection limit of 1.5m Hs and a towing limit of 1m Hs, then the average wait time for a weather window long enough to disconnect a turbine and tow (at an assumed speed of 3 knots) results in long waiting on weather time periods. The 1.5m Hs value is dependant on tugs operating close to the FOWT.

Understandably there is significant seasonal variation with shorter wait times during the summer and some significantly long periods over winter months.

Another limitation that exists for the operation and maintenance activities for floating wind is the safe transfer of equipment to the turbine/substructure, such as transformers or generators, using cranes from a floating crane vessel. The risk here is considerable as there are many factors that affect the safety of the workers, such as relative motion of vessel/platform. This can result in uncontrolled dynamic effects, and the user unable to lift off or put down the equipment safely.

4.2 Mooring installation

The installation of drag embedment anchors requires a tug with a large bollard pull as it is required to correctly tension the anchor and test the moorings. Anchoring in more challenging conditions is highly site specific and represents a technical riskat each new site. It is essential that the navigational and health and safety regulatory expectations for the mooring systems are set in proportion to the potential risks with a view to develop a safe and sustainable industry for the long term.

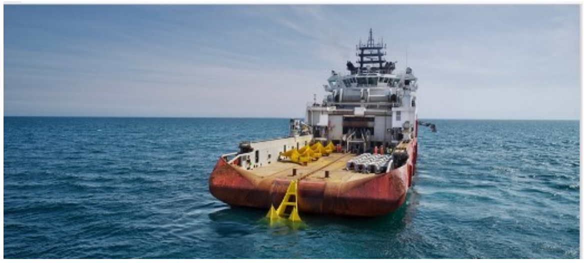

Figure 6 Anchor handling tug (, ref [10])

Using a suction pile a medium size offshore crane vessel is required, 2,000 t capacity. An anchor handling tug is also required to lay the anchor chain on the seabed. Using a driven pile a medium size offshore crane vessel is required, of say 2,500 t capacity. An anchor handling tug is also required to lay the anchor chain on the seabed.

4.3 Outline Installation Procedure

This is a high-level procedure that varies somewhat for each substructure type, the strategy chosen by the developer, and the availability of installation vessel and port facilities.

- Load-out of the floating substructure from the fabrication yard. Typically, by either flooding the dry dock, using a slipway, or using a heavy transport vessel to transport the substructure to the water.
- Installing the turbine assembly onto the substructure using onshore cranes (not the case for spar-buoys, see below)
- At site, the anchors and moorings are pre-installed by an anchor handling vessel and a work class ROV. It is typically required at this stage to test the moorings to 100% load to prove the structural integrity.
- The electrical cables are pre-installed at the site using a cable laying vessel, prior to the arrival of the substructures.
- The substructures are towed to site using tugs/barge as required by the specific substructure type.
- Spar buoys will be towed to a sheltered area to be ballasted and have the turbine installed onto the substructure (using a crane vessel), before final transit to site.
- Connection of mooring lines to the substructure.
- Electrical connection to the turbine is made.
- Ballast added to further stabilise the substructure (if required).
- Mooring lines tensioned as required.
- Final commissioning of turbine and substructure systems

4.5 Inshore mooring

For barges and semisubmersibles moorings are required against the outfitting quay. Fenders are required to keep the FOWT just off the quay. A similar mooring arrangement is required where the TLP is fitted with temporary buoyancy tanks. See Table 5 for a comparison of inshore moorings per FOWT type.

The Spar requires temporary moorings in deep sheltered water as is found in fjords in Norway. In addition, outfit barges will also need temporary moorings. The need for inshore marine activities will mean that Spars are unlikely to return to port for major maintenance.

Table 5 Inshore moorings

FOWT TYPE	Semi Submersible or Barge	Spar	TLP
Inshore moorings	Quay mooring	Inshore (Fjord) mooring in 100m of water	Quay moorings if fitted with temporary mooring

4.6 Hull construction

Hull construction is based on traditional shipyard methods where a small number of similar units are produced in series. Table 6 shows the construction of various types of FOWT. For full commercialisation a large number of substructures needs to be constructed in parallel.

Table 6 Substructure hull construction

TLP FOWT	Fit with temporary buoyancy	Install by crane vessel
Loadout	Loadout onto HTV	Loadout onto HTV
Transport to fit out quay	Transport to fit out port	Lift off at offshore location by crane vessel
Float off from HTV	Float off vertically	

Turbine fit out requires large onshore canes. For the Spar a large semi submersible crane vessel (SSCV) is required, see figure 3, and deep water in a sheltered location.

Table 7 Turbine inshore fit out

FOWT Type	Barge or Semi Submersible	Spar
	Topsides	Topsides
Topside construction on quay	Large land based crane lifts onto the substructure	Complete tower built on land
Inshore		SSCV lifts turbine off quay and installs turbine tower on to Spar in deep water
Inshore alternate	Floating sheer leg crane vessel	Use a spacer barge with a large onshore crane, in a Fjord

4.7 Offshore work

Table 8 gives comparison of installation methods for different FOWT types.

Pre installation
- ROV survey before installation
- check for debris on seabed

Tow out
- Tug to Tow to site
- 2nd tug for safety tug, but not connected
- 3rd tug for mooring connection

During installation 3 anchor handling tugs are required:
- 2 tugs to hold FOWT position
- 1 tug to connect the moorings

Table 8 Offshore work

FOWT Type	Semi Submersible	Spar	TLP (temporary buoyancy)
1st	Connect catenary moorings	Connect catenary moorings	Connect tendon moorings
2nd	Adjust moorings	Adjust moorings	De ballast hull Tension tendon moorings Remove temporary buoyancy
3rd	Cable connection	Cable connection	Cable connection

4.8 Spar installation

The installation challenges specific to spar configurations are focused on the large draft of the buoy. This necessitates that the substructure is towed horizontally to a sheltered site. Solid ballast is added and topped up with seawater. Then the turbine is installed via a large floating crane vessel. This process not only adds some steps and complexity to the installation but adds time. It should be noted that the process of installing a turbine onto a substructure is not trivial, with up to many bolts bolts needing to be installed and tensioned. Although a significant proportion of the assembly (~70%) happens in sheltered waters, the weather windows are still larger than that for fixed offshore wind.

From the sheltered location the assembled turbine and substructure can be towed to site and connected to the pre-laid moorings and electrical cable. The additional processes result in an overall installation time of ~50h (20 to 24h targeted for commercial deployment) and dictate that there is a tighter weather window when compared to other floating substructures. If the Spar can be towed in a ballasted state, then this opens-up the weather window considerably as the structure is very stable. Of the main substructure types, the Spar has the greatest average installation cost, driven by the vessel requirements and the sheltered/calm conditions required for turbine assembly.

The catenary mooring used by most spar-buoy configurations are longer than those used in TLPs, typically due to their length and mass. However the mooring base for a TLP is more complex than that required for a Spar or Semi submersible.

The nature of the Spar substructure and its moorings lead to lateral movement of the turbine, which presents a challenge for the export cable connection.

4.9 Semi submersible installation

Typically, Semi submersible substructures have been the simplest to install and are based upon a large amount of learning form the oil and gas sector. The majority (~60%) of the assembly happens on/near-shore and the reasonably shallow drafts allow for the turbine-substructure assembly to be towed to site using anchor handling tugs, for connection to the pre-laid moorings and the electrical cable. The total installation time is ~60h (again, 20 to 24h targeted for commercial deployment) and can be carried out in up to 1.5m to 2m Hs. The relative simplicity of the installation process makes this the cheapest format of floating substructure to install and therefore very easy to deploy demonstration turbines and pilot arrays as the technology progresses. These substructures typically use catenary mooring systems of similar cost to spars although present applications have seen a few additional mooring lines (typically 3 to 6). The nature of the Semi submersible substructure and its moorings lead to lateral movement of the turbine, which presents a challenge for the export cable connection.

4.10 TLP Installation

The installation challenges for tension leg platforms are different from the other substructure types as they are usually unstable until connected to the mooring system. This lack of buoyant stability can reduce the weather window for the installation of these substructures to below ~1.5m HS. TLPs also often rely upon a bespoke crane vessel or large temporary buoyancy tanks for installation that has features specific to that substructure type for transport and positioning.

The use of tensile mooring lines to hold the TLP in place, puts a greater requirement on the anchor system and, as such, these are typically more expensive than conventional mooring for other floating substructures. TLPs tend to have a large amount of offshore assembly work (although this is highly concept dependent), but an installation time of ~65h (~40h targeted for commercial deployment). When this long installation time is coupled with the calm weather requirement, it leads to a relatively high installation cost for TLPs.

It should be noted that some TLP concepts that use gravity anchors like GICON-SOF are able to do full mooring tension-up prior to leaving port and install everything in one go, by lowering the base to the seabed once on site. This means only the electrical connection needs to be made offshore. On the other hand, no significant deployment of TLP substructures has taken place yet. Thus a barrier to the installation of TLPs in large numbers is the requirement for bespoke installation vessels which do not make sense commercially for small deployments.

However TLP tensile mooring systems result in just a few metres of linear excursion and virtually no pitch or roll; this reduces the requirements and fatigue concerns for the dynamic export cable, as well as providing more stable loading on the turbine itself. In addition the TLP has a smaller footprint than the catenary moored Spars and semi submersibles.

4.11 Installation comparisons

There are many challenges facing the installation and major maintenance operations of commercial floating offshore wind arrays.

The major benefits of floating offshore wind are the ability to access deep water sites and the potential for more cost-effective substructure installation activities. To help realise these benefits for the renewable industry the offshore operations are a key to success. There is a need to develop cost effective methods and technologies for easy connection and disconnection of floating offshore wind turbines.

The most important cost drivers for installation are time and vessel requirements. Reviewing the expected costs of the installation of the different types shows that semi-submersibles are expected to offer the most cost competitive installation solution. This is not because they claim the shortest installation time, but because they make use of simple vessels throughout the installation process.

This does not mean that Spar and TLPs are unfeasible concepts; they make their cost savings elsewhere (lower grade steel and simple construction for spar-buoys and reduced steel weight for TLPs. What this does highlight is the different installation challenges with each substructure type. Some solutions that will benefit semi-submersible substructures, will not have the same value to spar buoys, due to the different installation challenges.

4.12 Weight Considerations

A weight comparison for platforms supporting a 5MW floating offshore wind turbine is given in Table 9 for steel substructures. The latest Windfloat Semi submersible, for Kincardine, has a 9.6M turbine and larger 14MW turbines are being used on the Dogger Bank fixed offshore wind turbines and thus the FOWT substructures will be heavier than shown in Table 9.

It is noteworthy that the next phase of Spar development is using concrete substructures. Concrete substructures are heavier than steel substructures and thus have deeper drafts.

Table 9 Weight considerations (5MW)

		Semi-Sub	Spar	TLP
Material		Steel	Steel	Steel
Substructure weight	t	3,800	1,400	1,000
Solid Ballast	t	0	3,600	0
Water ballast	t	3,700	2,500	0
5MW wind turbine	t	500	500	500
		8,000	8,000	1,500

5.0 MOORING INSTALLATION CHALLENGES

5.1 Design considerations

Mooring lines and anchoring systems are defined by factors such as the weather and seabed conditions, the floating substructure motion and forces, the loading from the turbine (mostly thrust loading) and the materials chosen for the mooring lines. Typically, mooring anchors and in the case of catenary moorings, the mooring lines are preinstalled and left on the seabed for when the substructure arrives on site. Then, once the substructure is on site, a work class ROV will be used to find and connect the individual pre-laid lines to ropes/chains on the anchor handling tug. Then these lines need to be connected to the substructure top connection. To date, top connections are cumbersome and this has had a significant influence on the initial connection and any disconnection procedures used in through-life maintenance.

Moreover, connecting lines one by one adds time to the offshore operations and requires sea conditions with <1.5m Hs. It is considered possible to develop a more focused, lower cost solution for floating substructures.

There is also the issue of the potential failure rate of mooring lines, with a significant number these failures due to installation damage or issues. Simplifying installation to eliminate these issues would greatly increase the confidence in moored floating wind turbines.

5.2 Mooring Systems

It should also be recognised that reducing offshore risks makes an offshore wind farm a more attractive investment prospect.

The installation of the anchors will likely be the most expensive part of the mooring system; however, this is dependent on the site geotechnics and cannot be significantly reduced across all seabed conditions with a single solution. Table 10 gives some indication of FOWT mooring systems. However, there is also a significant amount of time (and therefore cost) attributed to connecting up to the mooring arrangement once a floating offshore wind substructure is on site. If this connection time could be reduced the costs associated with vessels and labour could be reduced. Figure 7 and Table 11 shows different anchor systems.

Table 10 Typical FOWT mooring criteria

Item	Lower range	Upper range
Mooring Tensioning	Only during installation, not available during operation	
Mooring lines each	3	12
Spars, Semi-sub barges	Catenary moorings	
TLPs	Vertical tendons	

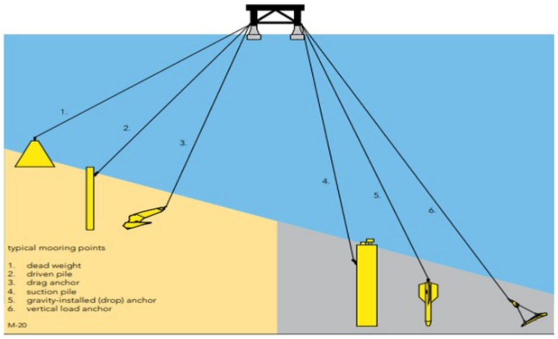

Figure 7 Anchor options (Ref [11])

Table 11 Installation of anchor systems

	Anchor Type	Vessel for anchor	Advantages	Dis-advantages
1	Gravity-base anchor	Floating crane vessel	OK for temporary moorings in sheltered waters	Very heavy
2	Driven pile anchor	Floating crane vessel	All types	Underwater vibrations
3	Drag-embedded anchor	AHT	Experienced	Not for TLP
4	Suction anchor	Floating crane vessel	Some experience	
5	Vertical loaded anchor	AHT	Lightweight	Limited experience
6	Torpedo embedded anchor	AHT	Lightweight	Limited experience

Currently, for spars and semi-subs, the moorings are pre-installed and laid on the seabed. Once the substructure arrives on site these are lifted from the seabed by ROV fitted leader line for connection to the substructure. The time, equipment and skill required for this operation highlights an area that could be simplified to help reduce costs. A shorter operation time offers an increased weather window in line with that mentioned for electrical connections above. In the case of mooring lines there is also the requirement for anchor handling tugs and Remotely Operated Vehicles (ROVs). If these factors could be reduced the installation costs could be reduced. Operations that do not involve personnel accessing floating platforms in an offshore environment are intrinsically safer and lower risk. Personnel safety in the operation and maintenance of floating offshore wind farms is a top priority.

Preparing the design for installation of a mooring system for a floating offshore wind turbine is complex. Important aspects, ref [3] are as follows:

- Previous experience
- Type of FOWT
- Applicable regulatory codes and standards.
- Site-specific metocean environmental conditions and geotechnical properties
- Ease of fabrication
- Installation vessel availability, accessibility, and capability.
- Local staging and mobilisation yard accessibility, availability, and capability for

mooring equipment and offshore operations support.
- Logistical requirements and constraints for shipping, importation and the receipt of mooring and installation equipment.

Many concepts and ideas are being pursued to develop different anchoring devices and mooring configurations. Some involve multiple floaters that are moored together (i.e. lines connecting adjacent floaters) and multiple mooring lines anchored with shared anchors.

Low stiffness synthetic lines like nylon are being augmented and constructed in ways that make them more fatigue-resistant to accommodate long design lives. Traditional mooring components are being combined in varying ways to achieve composite stiffness that achieve preferred station-keeping performance characteristics. Mechanical devices that offer a more compact way of providing design specific stiffness characteristics and load monitoring capability are also being developed e.g. ref [8} and [9].

Regarding installation, off floater tensioning devices and techniques are also created to minimise the capital expenditure associated with the housing and installation of winches and fairleads on the floater and to facilitate long-term mooring maintenance and repair work with minimal operational expense. Methods and products that can be installed in shorter time are also being developed. Saving even a short amount of time on a given operation can translate into large savings on commercial wind farms as that operation may take place hundreds of times during a campaign.

6.0 ELECTRICAL CONNECTION CHALLENGES

6.1 Electrical Connection

Electrical installations are completed by personnel on the floating turbine itself. The subsea cable is laid beforehand and then winched up into the substructure, where it is clamped, and the electrical connection completed by personnel on board. This requirement for personnel on board not only requires skilled electrically qualified personnel, but also a crew transfer vessel and access to the floating substructure.

Access to floating substructures is not that well understood at present. If this requirement could be completely removed from the installation process, not only would the installation be safer, the weather window would be greater and the cost of installation lower.

6.2 Possible return to port for maintenance

With almost all floating substructures the ability to tow the structure back to port for major maintenance is cited as a major benefit for semi submersibles and barges. However, return to port for a TLP is very complex and very weather sensitive. For a Spar the requirement for deep water inshore, with temporary moorings makes their return to port for maintenance difficult.

Since the turbines in an array are typically connected together in a chain, removal of one turbine would lead to the entire farm being down. The alternatives are lifting the cables and connecting a temporary piece of cable to maintain the continuous chain or installing temporary equipment to provide electrical continuity, or allowing for the possibility of turbine retrieval in the cable layout.

The act of breaking and making the electrical connection, as well as installing temporary equipment to allow the array to keep running is a costly process requiring specific vessels, personnel and limited by access weather windows.

7.0 DISCUSSION

7.1 Installation Procedure

The installation procedure of a FOWT after manufacturing generally consists of load-out, transit to site and hook-up to mooring lines and dynamic cable. To facilitate the installation process and minimize costs, the key logistical aspects have to be considered:

- Installation vessel requirements
- Shipyard location
- Fit out port distance from shipyard
- Distance from fit out port to site
- Weather downtime during installation
- FOWT type

The weather mainly impacts the installation procedure due to sensitivities of required marine operations to wave height and wind speed. This weather impact increases for larger distances. Furthermore, the floater towing speed, draft and other requirements, mooring and dynamic cable hook-up times and procedures and other technical aspects greatly influence installation, particularly for TLPs.

For floating wind substructures, there is only limited information about the decommissioning process available. Barge and semisubmersible floating substructures will be detached from the mooring lines and towed to the shore for further decommissioning. Mooring lines may be recovered while pile anchors remain in the sea bed. TLPs are very unlikely to be returned to shore for maintenance. Spars are also unlikely to be taken back to shore for maintenance.

7.2 Offshore operations

The installation procedure of a floating offshore wind turbines consists of shipyard, fit-out yard, towout and offshore moorings and cable connection. Generally, shore side work implies the fabrication of the FOWT and the assembly and mounting of the wind turbine onto the floating substructure. It is further assumed that both dynamic cable and mooring system are pre-laid and not part of the installation process focussing on the substructure.

The float out as the first part of the installation procedure of the floater is port specific. For example, in the case of a dry-dock, the dock is flooded, and the FOWT is towed out, while in the case of a Heavy Transport Vessel (HTV), it is submerged in order to initiate the installation. After the FOWT is prepared for the transit to the offshore wind farm site, typically involving temporary changes of the ballast, it is moved by anchor handling tugs. These tugs are sufficient for self-stabilizing FOWT, namely barge, Spar and semisubmersible and appropriate proximity from port to site. Projects in regions with more severe weather conditions or larger distances from port to site might require more resistant and specialized vessels. This does not apply for TLPs or other complex FOWT types, which are not self-stable. For these FOWT types, individual transport strategies and specialised installation vessels are required.

After the arrival at the wind farm site, the actual installation is initiated. The mooring lines are picked up by an anchor handling tug (AHT). Conditional upon the chosen technology, the hook-up is made. After the FOWT is connected to the mooring system, its ballast is adjusted in order to reach stable and safe operating conditions. Then the mooring lines are tensioned. Afterwards the FOWT is connected to the grid by attaching the pre-laid dynamic cable. Finally, the installation is terminated by testing and confirming the floating offshore wind turbine functionality and operation.

7.3 Economic choices

The choices, which are made within the installation procedures, affect other phases of the project or are influenced by them. In order to facilitate the installation process and minimize its costs the optimum installation vessels need to be chosen. While less specialized vessels are both better available and also less cost intensive due to lower charter rates, they can only be utilized, if the boundary conditions are suitable. This directly relates to the other two main aspects, distance from port to offshore site and weather limitations during installation, Ref [7].

The weather influences the installation procedure primarily by governing the timeframes when installation vessels can operate, and necessary marine operations are performed, such as the connection of the FOWT to the mooring lines. This influence increases if larger distances have to be covered and therefore require more time. This leads to increased risk regarding the accuracy of weather forecasts and higher contingency considerations. Smaller distances between fit out port and offshore site therefore reduce the weather impact and reduce risk and cost. Differences arise in terms of the installation times and costs.

8. CONCLUSION

Floating offshore wind is an expanding sector within renewable power generation. The floating nature of the substructures permits turbine placement in previously unattainable (or prohibitively costly) sites. As this sector of the industry has been growing, various substructure concepts have been developed. However, to date much of the focus has been on proving the compatibility with large offshore wind turbines. Whilst this was a valuable starting point for the industry, it is now entering a new phase where the installation, operations and maintenance procedures surrounding these substructures assumes a more critical role both in the running of a wind farm and in the reduction of the lifetime cost of energy production for floating offshore wind turbines.

Design for installation and maintenance activities are seen as priority areas for the cost reduction of floating offshore wind projects. Studies and future developments should focus on the following aspects:

- Expanding the weather window in which substructures can be towed/transported to and from site
- Making mooring and electrical connection operations more weather tolerant
- Simplification of installation methodology to reduce time spent offshore by construction vessels
- Reduce risks to personnel working offshore during installation and maintenance
- Easy mooring and electrical connection and disconnection
- Ease of towing of the completed substructure
- Return to port for maintenance for semi submersibles and barges is feasible. This would encapsulate maintaining electrical continuity throughout an array.
- Technologies should be developed to allow for a greater range of maintenance activities at sea, including floating crane vessels and installation of key components, blade repair and replacement and safe crew transfer for maintenance.
- Integrated wind turbine and floating substructure certification to improve investor confidence.
- Advanced structural monitoring is required to evaluate fatigue damage during tow to site.
- Increasing the maintenance service intervals, where possible, as Spars and TLPs are unlikely to be returned to port for repairs.

Table 12 shows how various FOWT compare for construction and installation

Table 12 Qualitative Overview of FOWT installation characteristics

	TLP	Spar	Semi Submersible
Construction Land Area	Medium	Medium	Large
Ease of onshore construction	Medium	Medium	Medium
Seabed area	Low	Large	Large
Intact stability in tow	Low	Large	Large
Attachment of moorings	Complicated	Standard	Standard

8. ACKNOWLEDGEMENTS

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10. APPENDIX OTHER FOWT OPTIONS

10.1 FOWT definitions

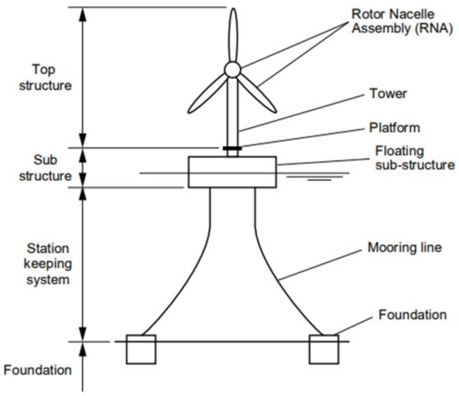

Figure A.1 FOWT definitions Ref [4]

10.2 Multi WTG

Figure A2 Dounray-Tri Ref [5]

10.3 Suspended ballast weights

Figure A3 Suspended weight Ref [6]

10.4 Vertical axis

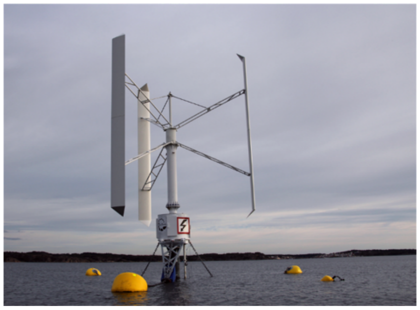

Figure A4 Vertical axis Ref [16]