NAVAL ARCHITECTURE METHODS FOR FLOATING WIND TURBINE INSTALLATION

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SUMMARY

Floating offshore wind turbines are becoming an important part of 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 presents the naval architecture design methods requirements for the installation of floating offshore wind turbines.

It is expected that floating offshore wind turbines will become an important part in the production of renewable energy. Naval architects have a role in the design, construction and offshore installation of floating offshore wind turbines. This paper considers the installation phase of floating offshore wind turbines, including the load-out, fit-out, tow-out and connection of moorings and dynamic cable. The results show that port facilities for the construction and fit out are limited by alongside water depth, laydown area and quay strength for large onshore cranes.

Keywords:
Naval architecture, weight control, inshore construction, offshore installation

Abstract:

This paper covers port requirements, different floating offshore wind turbine substructures and various installation vessel requirements (FOWT).

Most existing floating offshore wind turbines are barge, semi submersible and spar types and their installation use methods developed for offshore structures. Naval architecture calculations considered are weight control, ballasting intact stability, one compartment damage stability, ocean tow motions and bollard pull. In addition there are mooring calculations required for temporary conditions plus installation of export and dynamic cables. The Tension Leg Platform (TLP) floating wind turbine are being considered as an option but have minimum water plane area and hence have low intact stability during ocean tow and thus TLPs may require modified crane vessels for offshore installation or temporary buoyancy which improves intact stability.

The weather window limitations for the various substructure types for the transportation to and from the offshore site and during the connection of mooring lines and electrical cables are included in the paper. The paper will present recent advances in the installation of floating offshore wind turbines.

1. INTRODUCTION

The method of research used to develop this paper has been carried out by the application of standard naval architecture methodologies and a review of the industry state-of the-art. There is limited literature on the construction and installation of floating offshore wind turbines (FOWT), so the method of writing this paper depends on lessons learnt from the offshore oil and gas industry and also the fixed bottom offshore wind turbines. Naval architecture calculations are required for the inplace condition of the FOWT to understand operation limiting weather conditions. The calculation must consider intact stability, motions and structural integrity. For the installation phase of the FOWT, calculations are required to assess the limitations of construction locations and the requirements for installation vessels.

The purpose of the naval architecture calculations is to ensure a safe way of installing floating offshore wind turbines. This paper proposes an approach to analyse the assembly and temporary phases, of the floating structures. The installation starts with the loadout (or floatout or launch from a slipway) from the substructure shipyard. It continues when the turbine is assembled at the fit out quay and then the following tow out phase from sheltered waters to the offshore operational wind farm. Finally the mooring are connected to the floating structure. A framework is proposed where criteria, standards and environmental and loading conditions are discussed.

Section 2 covers floating offshore wind types and their installation phases. The design input is considered in section 3.0. Marine warranty services are discussed in section 4.0. Construction options are in section 5.0 and completion activities in section 6.0,

2.0 FLOATING WIND INSTALLATION

2.1 Floating wind types

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 barges, semisubmersibles, spar buoys and tension leg platforms (TLPs) see figure 1.

Figure 1 FOWT Wind Options (DNV website, 2022)

2.2 Installation phases

The main installation phases can be identified, as follows:

- Movement of the substructure from shipyard into the sea. Most have been built on land and are moved from trailers onto heavy transport vessels. A few have been built in a drydock with subsequent float out either complete or with further construction work to be carried out. An alternative is that the substructure is launched from an inclined slipway into the sea,

- Transport of substructure from the shipyard to fit-out quay
- Turbine installation on the floating support structure: this phase is composed of the platform construction, the procedure of turbine positioning on the substructure (when the structure is still either in a dry dock or in a basin), the inclining tests and the sequence of ballasting and of de-ballasting the support structure. This phase ends when the towing tugs start to pull the completed structure away from the fit out quay.
- Transport phase from the fit-out quay to the operational site: this phase consists of the procedure of towing the entire structure (already built and floating) from the sheltered harbour to the offshore wind farm where the turbine will be operative. Some parts on a TLP may still need to be (re-)assembled.
- Commissioning at operational site (final assembly and mooring): this phase is composed of the procedures that take the floating wind turbine into its operational condition. This consists of mooring the platform to the seabed and linking the dynamic electrical cable to the turbine. The phase ends when the support structure is correctly positioned, moored and the wind turbine is ready to work

These design and construction steps are shown in figure 2

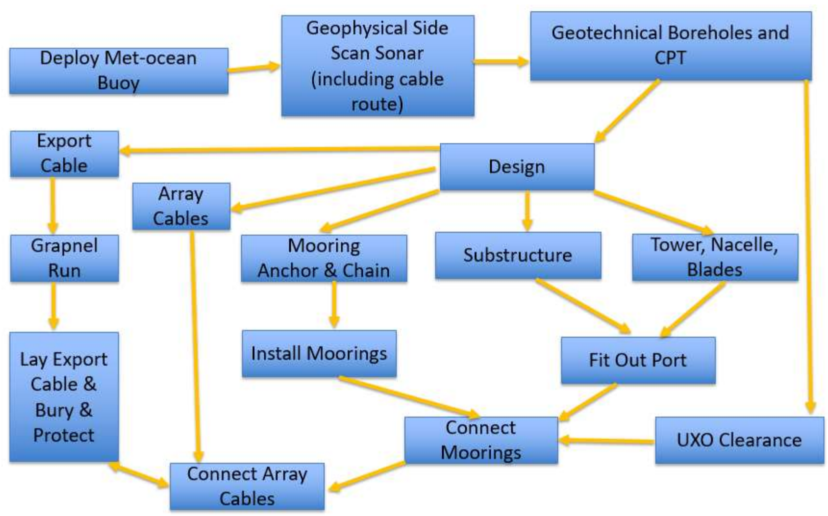

Figure 2 Design and construction sequence

3.0 DATA REQUIRED

3.1 Input data

The input data required for the Floating offshore wind turbine (FOWT) is:

- Weight, Centre of Gravity, radii of gyration
- Detailed drawings of FOWT
- Ballast tanks of FOWT
- Transportation vessels details
- Water depths at fabrication yard, ocean routes, fit out yard, tow route and offshore site
- Weather data at fabrication yard, ocean routes, fir out yard, to offshore site

Guidelines on design are available from classification societies, e.g. ABS, DNV, Class NK, BV.

3.2 Design spiral

A design spiral is a common way of showing the design process for a ship, and this section describes how the process might work for floating offshore wind turbines. The naval architecture design spiral, see Figure 3, (Hirdaris, 2021), serves the iterative design logic of designing a floating offshore wind turbine (FOWT). The spiral comprises of 4 phases of design namely,

1. The concept design stage is the translation of the requirements to the FOWT..
2. The preliminary design stage comprises of iterations that help refine concept design. Some properties defined during concept design do not change (e.g. type, external dimensions, weight, and turbine size)
3. Contract design stage involves an iterations where the major characteristics of the FOWT are unchanged. The contract design stage continues with weight control, intact stability, motions and moorings.
4. In the design phase, the production drawings are made.

Naval architecture calculations are required for the in-place condition of the FOWT to understand operation limiting weather conditions. The calculation must consider intact stability, motions and structural integrity. For the temporary condition of the FOWT, calculations are required to assess the limitations of construction locations and the requirements for installation vessels.

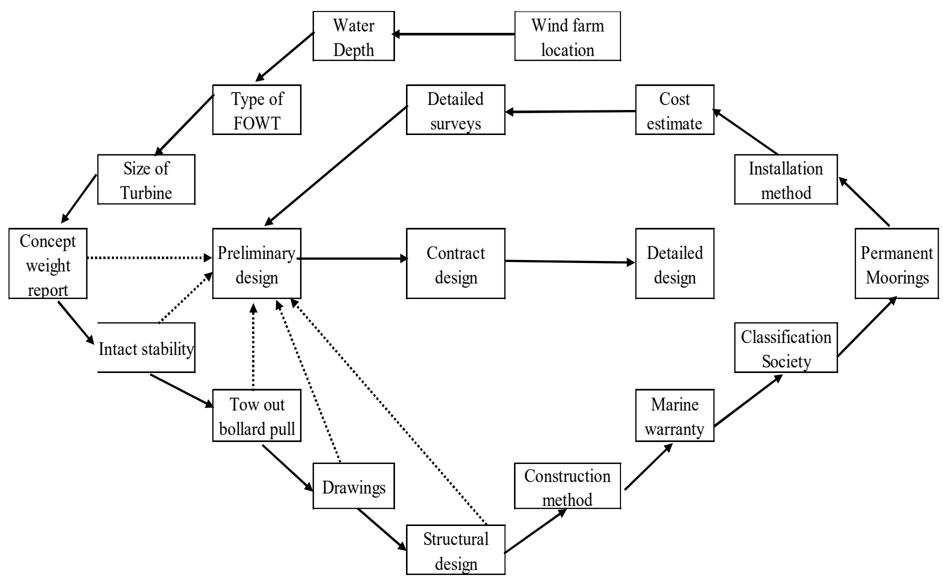

Figure 3 FOWT design spiral

3.3 Weight Control

Weight control in all phases of design and construction is vital. The weight related constraints are summarised in in table 1. Weight considerations are a critical design driver, as the assembly weight influences the key naval architecture analysis parameters (DNV marine operations, 2021):

- Draft
- Intact stability
- Damage stability
- Ballasting
- Dry transport of components
- Wet transport of the substructure
- Tow out of completed structure

Table 1 Weight related constraints for various types of FOWT

TLP	SPAR	BARGE	SEMI SUBMERSIBLE
Very Low intact stability during tow-out, so probably requires temporary buoyancy for tow out of large variation in draft.	Needs solid ballast after upending. Deep water required for inshore construction	many mooring lines	Heavy construction. Temporary buoyancy in dry dock

3.4 Weighing

The tower, nacelle and blades are weighed separately before fitting on the substructure.
It may not be possible to weigh a substructure in a drydock due to access or dock strength issues. A draft survey will be required after floatout, to compare floating condition with hydrostatics.
The quay area needs to be checked to confirm the strength of high point loads from substructure weighing.

4.0. INSTALLATION CRITERIA

4.1 Typical marine warranty criteria for a FOWT may include:

- Wind speeds (at specified heights and gust durations) for critical lifts.
- Any restrictions on current speeds or wave heights and wave periods
- Degree of acceptable damage to ballast tanks
- Any restrictions on helicopter or vessel movements within the offshore wind farm
- Any restrictions on transfer of people and equipment onto floating installations.
- Requirements for disposal cuttings removed from drilled piles
- Driven piling operations – sound effects on sea life.

4.2 Vulnerable locations

Typical vulnerable items may include:

- J-tube entry holes being covered with debris.
- External fittings (including anodes, J-tubes, etc.) being damaged by mooring lines.
- Operations of divers

4.3 Marine Vessels

There are a large variety of installation vessels are described below.

4.3.1 Tugs

Tugs are required for all the operations

- To tow a FOWT out of a drydock
- To assist mooring of heavy transport vessel (HTV) at the loadout quay
- After floatoff of the FOWT from the HTV wet storage area

Large anchor handling tugs are required for:

- To tow the substructure to and from the fit out quay

- To lay drag anchor moorings
- To connect moorings lines to the FOWT

For ocean tows, mooring laying and mooring connection large anchor handling supply tugs (AHTS) are required. For moving the FOWT in restricted waters highly manoeuvrable harbour tugs are required.

4.3.2 Crane vessels (seagoing)
It is expected that an offshore crane vessel is required for TLP construction completion.

4.3.2 Inshore crane vessels and barges
Inshore crane vessels may be used as an alternative to land based cranes for fit out.

4.3.4 Cable lay vessels
- Cable lay vessels are required for:
- Route clearance for export cable and dynamic cables
- Installation of export cable
- Burial of export cable
- Installation of protection covers for export cable
- Connecting the FOWT dynamic array cables

4.3.5 Offshore support vessels
Offshore support vessels are required
- Crew transfer or accommodation vessels with proprietary crew access arrangements.
- Escort and stand-by vessels can be needed in some areas to warn off other vessels

4.4 Onshore cranes

Large onshore cranes are required if the tower, nacelle and blades are lifted from a crane on the quay. For barges and semi submersible types, in order to maximise crane capacity the turbine tower is not in the centre of the substructure. Quay strength needs to be confirmed for the onshore cranes. Figure 4 shows the typical height of hub and the weight of components is plotted against turbine rating in figure 5. For a 15MW wind turbine expected values are:

- Height of hub above sea level, 148m
- Height of blade above sea level, 266m
- Weight of tower, 450 tonnes
- Nacelle including the hub, 907 tonnes
- Each blade length, 115m
- Each blade weight, 109 tonnes

There are a limited number of onshore cranes that can lift these loads to the height required. An alternative might be to use a very large wind turbine installation vessel (WTIV), and such vessels that can lift 15MW nacelles under construction. For Spars an option is to use a large semi submersible crane vessel to lift the topsides onto the substructure.

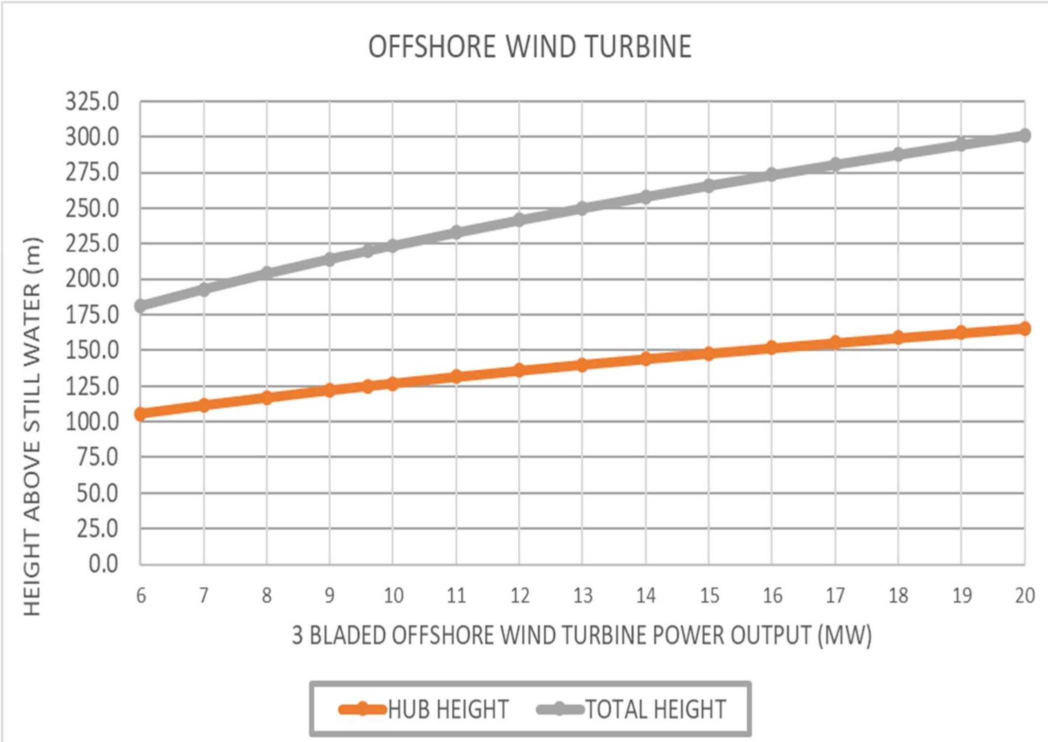

Figure 4 Height of hub and total height, (Vestas website, 2021)

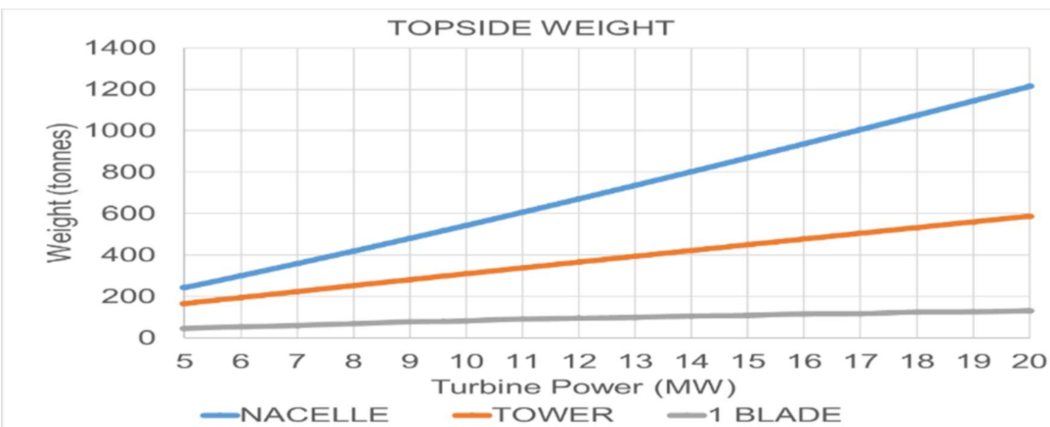

Figure 5 Weight of components versus turbine power, (Vestas website, 2021)

4.5 Cargo vessels

Cargo ships are required to transport components to the mooring assembly port from their manufacturing locations, namely items are:

- Anchors
- Chain
- Possible wire rope for the mooring line above the seabed
- Possible synthetic rope for the mid water mooring line
- Buoyancy chambers
- Clump weights

Cargo ships are also required to transport topside components to the topside fit port namely from their fabrication factories located on their own quaysides, namely:

- Tower sections
- Nacelle, including hub
- Blades

4.6 Laydown areas

Large laydown areas are required at:

- The manufacturing mooring component sites
- In the substructure shipyard
- At the topside fabrication factories
- The mooring assembly location
- The topside fit out quays

The export cable manufacture is a specialised function and the area required depends on the length of cable. For the inter array dynamic cables there is one required for each floating offshore wind turbine, with some being stored onshore waiting for offshore installation.

4.7 Procedures

Technical documentation is to be completed for all marine installation operations. In general, this should include:

- The anticipated timing and duration of each operation, including contingencies.
- The limiting wave states, wind speeds and currents, and where applicable any visibility/day-light,
- Temperature and precipitation limits, as well as the site-specific equipment or methodology prescribed for
- Measuring each limit-state.
- The transport route including shelter points.
- The arrangements for control, manoeuvring and mooring of barges and/or other craft alongside
- Installation vessels.
- Effects on and from any other simultaneous operations
- Contingency and emergency plans.
- Design standards for each individual phase.

4.8 Weather restricted operations

A weather restricted operation is one planned to be executed within a reliable weather window. Marine operations with a reference period less than 96 hours and a planned operation time less than 72 hours may normally be defined as weather restricted. However, in areas and/or seasons where the duration of the reliable weather forecast is less than 96 hours, the maximum allowable period is the duration of the reliable forecast.

If the weather restricted design environmental condition is too low, severe waiting on weather delays can occur. The design environmental condition should be selected based on an overall evaluation of operability i.e. there should be an acceptable probability of obtaining the required weather window.

For areas with high tidal currents there can be additional restrictions on operations due to the need to wait for slack (or slacker) tides for current-sensitive operations such as:

- Installing equipment on the seabed
- Bringing cargo vessels alongside installation vessels
- ROV deployment
- Diving operations

Operations that could be carried out within the maximum allowed period may be planned. The following are be taken into account:

- Increased risk for halting (and re-starting) due to additional operations.
- Increased risk due to the nature of the “temporary” safe position of the object.
- Increased weather risk due to an increased total operation period.

4.9 Site and route survey requirements

Having chosen wind farm site it is important to carry offshore surveys as soon as possible:

- Metocean for wind, waves, currents, tides
- Bathymetry of export cable route and offshore wind farm location
- Environmental baseline surveys
- Geophysical, top layer of seabed
- Geotechnical, boreholes for better understanding of the seabed
- Seabed features survey to check for UXO, wrecks

As well as ensuring that all positional, bathymetric, soil and current surveys are performed using the same datum and coordinate systems, various requirements to ensure sufficient accuracy like the frequency of survey equipment calibration (for salinity, temperature etc.) are required.

The “as built” locations of structures, cables and subsea equipment is recorded accurately on charts using a common survey datum used by all parties. These charts are updated, including all jack-up footprints as soon as they are made and issued to all vessels operating in the field. “No anchoring” zones are to be well marked.

In advance of the final detailed design being carried out for the FOWT structures, the seabed material, geophysical, and geotechnical surveys of the sub-bottom profile should have been carried out, as well as magnetometer surveys for ferrous objects, including UXO. The Cone Penetrometer Test results and other appropriate survey details for each substructure location needs to be documented.

4.10 Turbine support towers

The following items need to be addressed:

- Access for de-rigging
- Partial bolting
- Lifting points certification for multiple use (load-out, installation, maintenance, decommissioning)
- Verification that there will be no ovalisation of structure tubular members due to local seafastening forces
- In higher sea states
- Transport frames
- Requirements and criteria for upending from the horizontal to vertical mode.

4.11 Nacelles

The following items are to be addressed:

- Lift points
- Tugger lines arrangement
- Access for de-rigging
- Partial bolting.

4.12 Blades

The following items required:

- Infra-red release systems are to be reliable in releasing and, more importantly, not liable to early release from any cause
- Limiting weather criteria.
- Boom tip motions
- Partial bolting.

5.0 SUBSTRUCTURE CONSTRUCTION

5.1 Floatout from a drydock

The FOWT may be constructed in a dry dock figure 6. If completed with topsides then the FOWT can be towed directly offshore. Though any temporary buoyancy needs to be removed just before leaving the sheltered harbour (Ramachandran, 2021).

Figure 6 Semi submersible constructed in dry dock, (Principlepower website, 2022)

If only the substructure is constructed, without turbine, in the drydock then it can be floated onto a heavy transport vessel (HTV). Alternately the substructure can be towed to a local quay for outfitting. Temporary buoyancy may be required for the substructure if it is expected to float on zero trim and zero heel.

Accurate assessment of expected draft, trim, heel and stability needs to be made. Contingency plans need to be developed if the substructure does not float as expected
Intact stability during floatoff from the dock floor is to be assessed.

Specific information is required as follows for floatout from a drydock:

- Water depth at LAT (lowest astronomical tides)
- Range of tides
- Height of dock bottom below LAT (height over the sill)
- Width at the gate entrance
- Length of the drydock
- Craneage over the drydock

Weather limits are as follows during floatout is

- Wind maximum = 16 knots (8m/s)
- Current = 1 knots (0.5m/sec)
- Waves = Hs < 0.5m
- Wave period, Tp < 8 seconds

Naval architecture calculations are:

- GM > 1.0m
- Under keel clearance > 1.0m
- Clearance to dock side > 1.0m
- Trim <0.5 degree
- Heel <0.5 degree

5.2 Loadout from a quay

Specific information is required as follows for loadout:

- Water depth at LAT (lowest astronomical tides
- Range of tides
- Height of quay above LAT

The structure is fabricated on a suitable grillage, under which a combination of multi-wheeled hydraulic trailers i.e. self propelled modular transporters (SPMT) are positioned. The trailers then pick up the weight of the structure and are pulled or driven onto the transportation vessel. The trailers then jack down and position the structure on the transport grillage, figure 7 and figure 8. Specific naval architecture checks for a SPMT loadout operation include:

- Number of axles required
- Quay ramp strength
- Stability of the transport vessel
- Overall strength of the transport vessel
- local strength of the transport vessel
- Mooring loads on quay and transport vessel

Figure 7 Semi submersible loadout onto HTV(Principlepower website, 2022)

Figure 8 Spar loadout onto HTV (Equinor website, 2022)

Weather limits are as follows during loadout:

- Wind maximum = 20 knots (10m/s)
- Current = 1 knots (0.5m/sec)
- Waves = Hs < 0.5m
- Swell = no swell i.e. wave periods < 10 seconds

The following checks are made:

- Mooring loads
- Fender loads
- Fender size to prevent allusion
- Under keel clearance > 1.0m

Loadout calculations are required for

- Ballast calculations for loadout
- Design of the transport vessel grillage
- Temporary seafastening design after loadout
- Transport seafastenings
- Moorings during loadout
- Fenders

For each loadout ballast step calculate for the HTV:

- Draft
- Trim
- Heel
- Under keel clearance
- Quay height to barge/vessel distance
- Free surface effects
- Intact stability
- Longitudinal bending
- Transport vessel local strength check

Following loadout onto the HTV there is an ocean tow. If the ocean voyage is on a self-propelled semi-submersible vessel assume a speed of 10 knots. If the ocean voyage is on a towed vessel assume a speed of 5 knots. The 10 year return wave is used for motion analysis.

For a tow on a barge tugs require to have sufficient power to maintain the tow at zero forward speed using the following criteria.

- Wind 40knots (20 m/s)
- Wave Hs=5m
- Current = 0.5 m/s

6.0 COMPLETION

6.1 Float off

Assuming the use of a Heavy Transport Vessel the substructure is floated off requiring the following calculations, figure 9 and figure 10:

- water depth no more than 25m
- minimum water depth governed by 1m of under keel clearance
- stability of HTV when submergede.g. GMt>1m
- minimum freeboard of 2m maintained, when partly submerged

Figure 9 Semi submersible floatoff from HTV (Principlepower website, 2022)

Figure 10 Spar floatoff from HTV (Equinor website, 2022)

6.2 Fit out quay

Fenders are used to:
- Absorb berthing loads
- Maintain the FOWT gap off the quay

Calculations required:
- Under keel clearance, minimum 1m at low tide
- Intact stability, GM > 1.0m, of the FOWT at shallow draft
- Horizontal clearance between underwater parts of the FOWT and the quay wall > 2.0m
- Strength of the quay wall for cranes

This assumes that the fit out quay is sheltered from the open sea, either in an estuary or with breakwaters, with assumed weather conditions
- In the absence of 10 year return data assume 60knot (30m/s) for a 1 minute wind speed
- Assume current 2knots (1m/s)
- Assume wave height of Hs=1.0m.
- Assume wave period =10 seconds

Calculations required:
- Check strength of quay mooring bollards
- Check strength of mooring wires
- Check strength of FOWT mooring connections

6.3 Ocean tow to offshore site

Naval architecture calculations are required for
- weight and centre of gravity
- radii of gyration

- hydrostatics
- ballast
- draft
- trim
- heel
- free surface effects
- intact stability, GMs i.e. metacenric height
- intact stability, GZ, i.e. righting arms
- wind load
- tidal current loads
- wave loads
- bollard pull in a storm
- bollard pull in tow conditions
- static angle of heel due to wind
- motions and accelerations in waves

6.4 Connection of moorings & subsea cables

The moorings are installed prior to tow out of the completed FOWT from the fit out yard. The moorings are pre laid on the seabed and located with mooring buoys.

The export cables are installed after the FOWT has been installed. The subsea inter array cables are laid after the FOWT has been installed and the export cable has been installed.

7.0 DISCUSSION AND CONCLUSIONS

7.1 Discussion

Naval architecture checks required include:

- Condition and suitability installation vessels,
- Load-out attendance including equipment, rigging and ballast pumps
- Towage including vessel audits, tow gear inspections and route planning reviews.
- Transportation including acceptable weather

7.2 Conclusion

For water depths of over about 80 metres and onwards, floating wind technology can be utilized. It is connected to the seabed by anchors, by moorings, but the structure itself is floating. Floating wind technology has the potential to harness previously unavailable wind power at greater ocean depth. With increased installed capacity, offshore floating wind costs are expected to be falling. Cost reduction is driven by technology improvements, more effective manufacturing, economies of scale, broader supply chain efficiencies and, not least, competition. Naval architecture is playing an important part in the development of floating offshore wind turbines.

8. ACKNOWLEDGEMENTS

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9. NOMENCLATURE

[Symbol]	[Definition] [(Unit)]
υ	Kinematic viscosity (N s m^{-2})
ρ	Density of water (kg m^{-3})
P	Pressure (N m^{-2})
AHT	Anchor handling tug
COG	Centre of Gravity
CUM	Cubic metres
Deg	Degree
DP	Dynamic positioning
FOWT	Floating offshore wind turbine
GM	Metacentre above COG
GZ	Righting moment
HTV	Heavy Transport Vessel
LOA	Length overall
M	Metre
ROV	Remotely operated (underwater) vehicle
SPMT	Self propelled modular transporter
SSCV	Semi submersible crane vessel
T	Tonnes
UXO	Unexploded ordinance
WTIV	Wind turbine installation vessel

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