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FLOATING OFFSHORE TURBINES - INSTALLATION METHODS

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ABSTRACT

Floating offshore wind turbines are a possible source of large scale electricity. Fabrication and offshore installation design of these large floating structures is required to provide confidence to developers and insurers that they are constructed in a safe and cost effective manner. The design methods developed in this paper cover the substructure types such as Spars, semi submersibles, barges and TLPs. The engineering of mooring types includes catenary, taut and tension, plus turret mooring.

This paper details the preparation of engineering requirements for installation vessels and large onshore cranes used for the shipyard construction of substructures for floating wind. Each installation phase, for a floating offshore wind turbine, raises issues regarding existing construction methods and the need to develop revised installation works.

The engineering processes include mooring installation and connection. In addition consideration of load-out analysis, ocean transportation analysis including sea-fastening, intact stability and tow motion response. Installation analysis is required for lifting, up-ending, afloat construction, and cable lay methods.

Floating offshore wind turbines are offering a new approach to using marine resources and this

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paper will provide information on how naval engineering can be used to promote this development.

Keywords: Naval Architecture, Floating Wind, Offshore

1. INTRODUCTION

The future for floating wind is to turn the concepts from demonstration to fully commercial developments. This paper therefore reviews the effort required to reduce construction schedule and minimising capital expenditure (CAPEX) and lifetime cost of energy (LCOE).

Minimising costs during construction and will assist in reducing the CAPEX. Large floating wind farms will enable shipyards to develop construction industry and project management methods that will lead to rapid floating wind deployment.

Floating wind produce electricity for use onshore, via export cables. Some floating wind provides electricity to offshore oil and gas production facilities, to reduce their carbon emissions. The largest floating wind farm at present is about 100MW.

There is a desire to now develop commercial projects that are around 300MW in size, to prove the concept of mass production. This will move floating wind into a commercial phase, which will give opportunities that helps to continue to build market confidence.

It is predicted that by 2050 floating wind farms will be larger than 1GW each. Floating offshore wind turbines are being designed to generate electrical energy in water depths of at least 60 metres. This is the current maximum depth for fixed-bottom wind turbines. Maximum water depths for floating wind will be limited by the design constraints on mooring systems and dynamic array export cables.

Floating offshore wind turbines are complex and the options for structures are described in section 2. The requirements and facilities for construction are in section 3. Constructability is considered in section 4. Typical construction techniques are shown in section 5 and are further developed in the facilities construction facilities, section 6. Risks and reliability need to be considered, section 7. The discussion and conclusions are in section 8.

Floating wind turbines are not yet commercially viable as their construction costs are greater than for fixed-bottom turbines. As locations for fixed-bottom get used up then developers will consider going into deeper water and use floating wind structures. Naval architecture methods for floating wind are detailed in part in each section, Crowle & Thies (2022).

The method of analysis is by literature research, past construction experience of offshore structures and analysing current methods of floating wind fabrication.

2. STRUCTURES ARE COMPLICATED

2.1. SIZE AND COMPLEXITY

The complexity and large dimensions of floating offshore wind turbines, make them sensitive to the weather conditions during fabrication and offshore installation. The planning of the actual construction methods require turning the design into a real structure.

These construction activities use the overall term of constructability. The main types of floating offshore wind turbine are can be seen in Figure 1. The main types are the Semi-submersible, the Spar, the Barge, and the Tension Leg Platform (TLP) substructure types. In these cases the turbine rotates relative to the substructure, whilst the substructure does not rotate relative to the moorings.

Figure 1

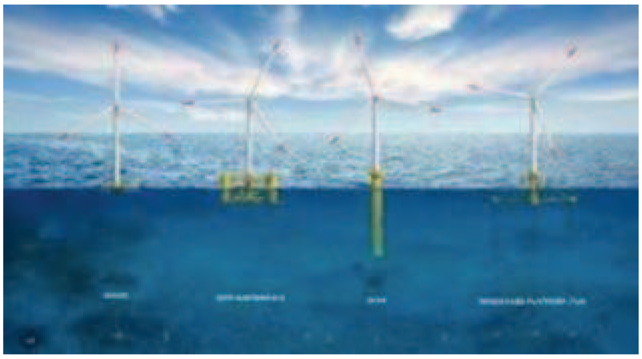

Figure 1 Floating Wind Types (Credit DnV)

There are alternatives mooring arrangements under development using a pivot buoy where the substructures rotates on a turn table, but the turbine remains fixed relative to the substructure.

Floating offshore wind turbine (FOWT) structures are quite expensive to fabricate and install offshore. In addition dynamic array cables which connect the floating wind structure to the subsea export cable require more development in order to reduce their very high capital costs, Ramachandran et al. (2022). Construction costs and their development schedule need more detailed consideration. The installation is very weather dependent and so is often on the critical path, for the renewable energy project. Good planning and good project management in order to minimise construction and installation time. During the design stage constructability and installation options needs to be considered so that the FOWT is fabrication time is minimised.

2.2. CONSTRUCTION PLANNING

Each type of floating offshore wind turbine substructures effects the selection of construction and installation methods. In particular the substructure type results in the water depth requirements at the load-out shipyard and at the vertical integration fit out quay.

The overall schedule includes procurement, fitting together of components and prefabricated items. The training of workers, the organization and the supervision of the workers need to be developed with works councils. Quality control, safety on site, cost estimating, work scheduling and cost control are all part of construction engineering.

Weight control is very important for all phases of fabrication, tow out and offshore installation of the floating wind turbines. Table 1 shows the fabrication constraints per type are presented. Table 2 shows the status of floating offshore wind turbines, with number deployed in brackets.

Construction planning considers heavy lift cranes, yard labour, high level access and transport of materials, Shu (2022). In addition the fit out of electrical, piping and mechanical items within the structure needs to be scheduled.

Constructability uses standard methods in order to overcome the difficulties in complicated construction. Its scope includes ocean transport of components, fabrication, tow-out and installation. Towing ashore for maintenance, possible relocation to another site, or extreme event of salvage are also part of the constructability. Eventual decommissioning of all the offshore components is also to be considered in the design constructability meetings.

Table 3 compares fabrication and offshore installation of floating offshore wind turbines (FOWT). The main components of a floating offshore wind turbine are given in Figure 2.

Table 1

Table 1 Construction Restraints for FOWT

	Construction/installation constraint
TLP	Low intact stability during tow
Spar	Deep draft
Barge	Motions during tow
Semi-submersible	Heavy substructure

Figure 2

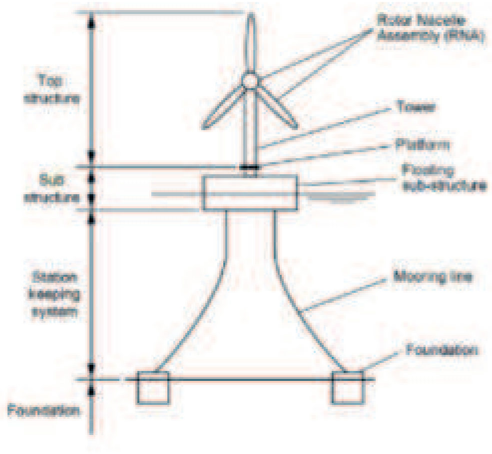

Figure 2 Floating Wind Turbine (Credit DnV)

Table 2

Table 2 Status of Deployed Floating Wind

Type Country (no off)	Material
Semi-submersible, Portugal (3)	Steel
Semi-submersible, Scotland (5)	Steel
Spar, Scotland (5)	Steel
Spar, Norway (11)	Concrete
Pivot Buoy, Portugal (1)	Steel
Pivot Buoy, Concrete (1)	Spain
Suspended ballast, Norway (1)	Steel

Table 3

Table 3 Comparison of Installation Ease

Type	Comment
TLP	Complicated installation
Spar	Requires solid ballast
Barge	Low freeboard
Semi-Submersible	Installation method well known

3. FLOATING WIND CONSTRUCTION

The distinct stages that a floating offshore wind structure goes through are:

- Fabrication
- Load-out (or float-out)

- Vertical integration of topsides
- Commissioning and completion afloat,
- Ocean tow transport
- Mooring connection
- Subsea cable hook-up.

In constructability planning, it is essential to develop detailed schematic drawings of each stage. Further subdivision is required of each stage to develop small work packages that can be carried out by a small group of workers. Structural design reports on the structural capacity under differential loads need to be calculated. Where the substructure is afloat then intact stability calculations are required for each stage.

Items to be considered in the planning include:

- Substructure draft, trim and heel
- Available water depth
- Solid ballast requirements
- Water ballast requirements
- Intact stability
- Tie-down sea-fastenings on HTV
- Hydrodynamic response during tow,
- Transport fatigue
- Effect of temperature on valves
- Wind loads at all stages
- Wave and current forces during tow
- Snap loads of mooring lines
- Clearance under the keel
- Damage cases
- Poor ballast control

- Vortex shedding
- Welding temporary attachments

An overall check needs to be made of the whole construction sequence to ensure integration. The coordination of all steps and stages are required during subassembly, construction, offshore installation and commissioning.

In floating offshore wind turbine construction, there is a need for development of lifting equipment and any special instrumentation. New temporary steel structures and rigging arrangements will need to be engineered.

Table 4 shows the dimensions and hence the required crane capacity and hook height requirements to install the nacelle and blades. The crane size and it's hook load determine the bearing capacity of the fit out quay.

Table 4

Table 4 Offshore Wind Turbine Dimensions			
Power of turbine(mw)	10	15	20
Blade length (m)	91	109	125
Nacelle to waterline (m)	123	150	161
Nacelle weight (t)	550	850	1200

4. PRINCIPLES OF CONSTRUCTABILITY

Lessons learnt from previous renewable energy offshore projects, plus oil and gas projects, will help reduce the cost and schedule of fabrication.

Subdivision of the main substructure into large components needs to be considered as it may reduce overall project costs. Parallel fabrication of major sub components, if carried out in the best location, can minimise schedule construction. How the flow of components arrive at their assembly site needs to be included in the project design phase.

At the final fabrication site there must be adequate space for local transport, storage, and access. Specialised equipment include such items as cranes, self-propelled modular transports (SPMTs) floating cranes, dry docks, very strong quays and construction wet docks.

Reducing the number of steel grades helps to reduce construction time, by minimising welding procedures. Where possible standardization of structural details should happen where practicable. Excessive tight tolerances should be avoided. There needs to be provision for flexibility and adjustment in connections, especially in mechanical system piping which can reduce construction schedule.

Efficient working requires a uniform worker requirement which helps for better about relations. Indoor prefabrication and painting of sections which are sensitive to the weather need covered areas.

Thus, each FOWT substructure type results in specific port and installation vessels requirements.

5. FACILITIES FOR FABRICATION

5.1. EARLY STAGES NEAR SHORE

Floating wind substructures, are built next to the sea, Efthimiou & Mehta (2022). Large areas are required to store and lay down the main parts of the floating structure. It will also require strong load-out quays, access roads, support buildings and infrastructure utilities. Floating offshore wind structures are large in weight, area and volume. Many skilled personnel are required over a long period of time to construct floating wind substructures.

Dredging may be required at the load-out quay and in the channel leading to the open sea.

Adequate lighting is required to enable 24 hour working during construction. Most work needs to continue even in bad weather, e.g. rain or snow, and so some covered areas are required. During high winds work will need to stop in outside locations. Enclosures must be provided for welding and painting. Changing rooms are required for the personnel.

Adequate roads must be constructed, around the laydown areas and FOWT fabrication location, with adequate drainage installed. Good railway access would be an advantage. The shipyard must have high ground bearing capacity to support the new FOWT substructure and the construction equipment, especially the large cranes. The soils in the yards may require stabilization and piling. Account needs to be considered from jack-up spots where weighing equipment is used. Large crawler cranes cause on high soil loadings, when they lift the maximum loads.

Cleanliness is important in the workplace, to maintain efficient access and safety. Clean working also prevents damage to sensitive equipment. As the structure will move from the onshore shipyard onto a heavy transport vessel it will requires strong quay bulkheads. In addition mooring dolphins are required for the safe transfer of the structure from land onto the transport vessel.

5.2. FROM SHORE TO SEA

5.2.1. FLOAT OFF - HTV

The substructure is loaded out horizontally from the construction yard quay on to a heavy transport vessel.

The HTV is towed or more likely self-propelled for the voyage to the fit out quay where the FOWT is floated off close to the fit out yard. Intact stability during of the HTV after submergence needs to be considered. The free-surface effects of the ballast in the water tanks, of the HTV needs to be taken into account to calculate the intact stability. To minimise free surface effects most ballast compartments are either full or empty, so that only a few ballast tanks will have a free surface. Unequal loading due to different ballast conditions can effect global and local structural effects on the transport vessel. At deep drafts of submergence the floating wind structure lifts off. The HTV is low when submerged resulting in low intact stability. To provide intact stability, the HTV is fitted with stability columns at both ends, which give enough water plane second moment of inertia to provide intact stability. These stability columns also allow the HTV draft to be accurately controlled.

Float-off of the substructure follows the safe submergence of the heavy transport vessel (HTV).

5.2.2. CONSTRUCTION IN DRY DOCK

When constructed in a dry dock, the offshore wind turbine substructure is floated out, possibly with temporary buoyancy added. The advantage of dry docks is that structural loads are minimised during float-off, which is offset by the costs to rent the dry dock.

Dry docks are restricted by width and float out draft. It may be necessary to fit some temporary buoyancy to the FOWT substructure to have zero list and trim and to minimise float out draft from the dry dock.

Where the dry dock is not of sufficient width then the substructure needs to be built on a strengthened quayside followed by load-out by SPMT onto a HTV or a submersible barge. The HTV then goes to the fit out quay where it submerges and the FOWT structure is floated off

5.2.3. MOORING

Prior to arrival of the floating offshore wind turbines the anchor and mooring line are pre laid on the seabed. The export power grid cables and array power cables are laid after the mooring lines and well clear of the mooring lines.

Offshore moorings can be

- Drag anchors
- Suction piles
- Driven piles
- Drilled piles

Mooring lines use chain on the seabed and at the connection with the floating offshore wind turbine. At mid water level the mooring line can be wire or synthetic fibre or chain.

5.2.4. POWER CABLES

Dynamic inter array cables are connected to the FOWT. They are limited to about 66KV. A substation connects the dynamic array cables from multiple FOWT to the export cable. The substation can be subsea, floating or fixed to the seabed via a jacket structure. However dynamic export cables from a floating substation have not yet been developed.

The export cables can be:

- HVAC, limited to about 235KV
- HVDC, limited to about 515KV

The export cables are buried in the seabed to minimise damage from fishing equipment.

5.2.5. FIT OUT QUAY

The towers, nacelles and blades are manufactured in factories next to jetties. They are transported on modified cargo ships to the fit out quay. The substructure is floated off close to the fit out quay and may be anchored on temporary sheltered moorings wet storage.

The fit out quay requires large storage areas and strong ground conditions for large cranes. Vertical integration of the topsides takes place, by cranes, onto the substructure. This is followed by commissioning and then towing out the completed floating structure to the offshore wind farm.

5.3. EXAMPLE OF CONSTRUCTION

5.3.1. BARGE TYPE

The steel barge construction is as follows:

- The steel barge in a dry dock Figure 3.
- The tow to the outfitting yard, Figure 4
- Nacelle installed, Figure 5

- The tow out, Figure 6

Figure 3

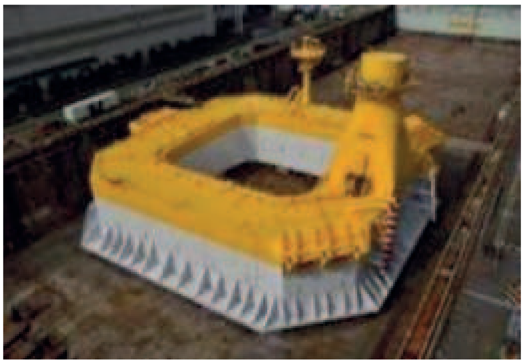

Figure 3 Steel Barge (Credit BW-Ideol)

Figure 4

Figure 4 Steel Barge Tow (Credit BW-Ideol)

Figure 5

Figure 5 Lifting Blades Martini et al. (2016) (Credit BW-Ideol)

Figure 6

Figure 6 Steel Ring Barge Martini et al. (2016)

5.3.2. SEMI-SUBMERSIBLE TYPE

A typical sequence is shown as follows:

- Loaded out onto a HTV Figure 7
- Transported to the fit-out yard Figure 8
- Nacelle installed by crane, Figure 9
- Tow out of the structure Figure 10

Figure 7

Figure 7 Load-out HTV (Credit Principle Power)

Figure 8

Figure 8 Dry tow (Credit Principle Power)

Figure 9

Figure 9 Fit Out Quay (Credit Principle Power)

Figure 10

Figure 10 Wet tow (Credit Principle Power)

6. INSTALLATION SEQUENCE

6.1. STEEL SEMI SUBMERSIBLE FOWT

The installation operations are carried out with the assistance of harbour tugs, inshore, and several AHTSs (Anchor Handling Tug and Supply) at the offshore location. AHTSs can be used for floating wind farm work. In particular they are used for the installation of drag anchors, tow out of the FOWT offshore and to finally to connect the preinstalled moorings. The floating wind industry may require new AHTS with large chain locker capacity.

The export cable can be installed in parallel with the main structure fabrication and installation. The marine operations for a steel Semi-submersible are:

- The pre installation of moorings.
- Construct, vertically, onshore
- Load-out onto HTV, using SPMT
- Ocean voyage HTV
- Float-off from heavy transport vessel
- Wet storage of substructure
- Rotor assembly fitted with crane
- Pre commission systems
- Towing out to the offshore location
- Connect the mooring and tension
- Connect the dynamic array cable

Light maintenance activities can be carried-out offshore. The periodic inspections, preventive maintenance and repair activities will be performed in situ (i.e. at the offshore wind farm). In case of large heavy maintenance or repair activities the Semi-submersible platform can be towed to a sheltered port Salzmann et al. (2015). However, this requires procedures to be developed for disconnection and laydown of mooring lines and dynamic cables. The low draft means that there are a few ports available for fit out and for heavy maintenance.

The Semi-Submersible substructure has a large advantage regarding Capital Expenditure (CAPEX because the turbine installation and commissioning can be done in a sheltered port. The towing is straight forward due to the inherent stability of the assembled system and the low draft. The operations needed at sea is connecting the complete structure to pre-installed anchors. The dynamic array cables require a specialised cable installation vessel after the moorings have been completed.

The anchors are with catenary mooring lines, and thus become very long and expensive in deeper waters. In deeper water part of the chain can be replaced by wire rope of synthetic cables.

The turbine is usually in one corner to maximise onshore crane capacity during fit out at a quay. The technical challenges, Lewis & Laskowicz (2023), for floating wind structure during installation, namely:

- Large area for the construction
- Very wide channel needed to for tow
- Large tug to tow offshore.
- Large anchor handling tugs
- Large steel content

6.2. SPAR TYPE FOWT

6.2.1. GENERAL

The Spar substructures have large drafts which require the use of fit out in deep water, as can be found in several Norwegian Fjords. The deep water location also requires sheltered coastal waters. The maximum significant wave heights are to be less than to 0.5 m, with associated wave period less than 10 seconds, and wind speeds less than 10m/s, for inshore lifting operations.

6.2.2. STEEL SPAR

The marine operations for a steel spar are, Kaiser & Snyder (2011):

- Pre installation of mooring
- Construct steel cylinder, horizontally,
- Load-out steel cylinder onto a HTV
- Ocean voyage of substructure on a HTV
- Float-off from heavy transport vessel
- Upend with seawater ballast
- Solid ballast added to the base

- Seawater ballast added to increase draft
- Tower assembled onshore with nacelle
- Blades added onshore
- SSCV lifts the tower assembly
- Tower assembly bolted to substructure
- Pre commission systems
- Towed complete structure offshore
- Connect the mooring lines and tension
- Connect the dynamic array cable

6.2.3. CONCRETE SPAR

The marine operations for a concrete spar are, Kaiser & Snyder (2011):

- The pre installation of mooring.
- Construct concrete partial cylinder,
- Float partial cylinder to deep water
- Slip form the concrete cylinder
- Solid ballast added to the barge
- Add water ballast to get to required draft
- A spacer barge on the quay
- The tower assembly is mated by crane
- Pre commission systems
- Tow to the location of the wind farm.
- Connect the mooring and tension
- Connect the dynamic array cable

6.3. PIVOT BUOY

The X1 pivot buoy was built as a semisubmersible, but is moored as a single point mooring system, Figure 11.

Figure 12 shows the demo Sath concrete substructure with pivot buoy mooring system

Figure 11

Figure 11 X1 Pivot (Credit X1)

Figure 12

Figure 12 Sath Pivot (Credit Sathech)

7. RISK EVALUATION

7.1. TYPICAL RISKS

Construction and installation risks can be identified. Thus an evaluation can be made of their safety needs and ultimately reliability, Gerwick (2007). Each procedure or one off operations all require full risk evaluation. Human error often has a significant impact on construction and installation risks and this needs to be considered in the hazard identification.

Risks which have been identified on previous wind farms construction and installation methods include:

- Weight control procedures
- Delay in approvals
- Flooding due to external damage
- Overtopping of hull due to waves
- Free-surface water
- Structural cracking
- Mooring line failure during bad weather
- Dragging anchor
- Explosion or fire
- Storms such as wind, waves,
- Acceleration loads
- Sea-fastenings failure
- Failure of tugs
- Towline broken
- Ice jamming on structure or towline
- Excessive sway or yaw during tow
- Large roll during tow
- Going aground
- Towed structure overruns tug
- Loss of intact stability
- Malfunction of instrumentation
- Seafloor irregularities,
- Excessively stiff soil or hard layers,

- Excessively soft soils
- Storm during installation
- Bad visibility, fog
- No resistance to piles driving
- Excessive pile driving
- Failing to float at proper draft
- Structural damage during installation
- Lines fouled on projecting fittings
- Drag of anchor
- Errors or omissions in design

To minimise accidents and errors requires training and use of simulators.

7.2. RELIABILITY

Substructure fabrication occurs in a shipyard, which does not need to be close to the offshore site. Conversely the fit-out yard for the lifting of the wind turbine components needs to be within about a short tow time of the offshore wind farm, as weather forecast are only reliable within about 3 days. In addition the blades, nacelles and tower need to be built at separate sites, each close to a load-out quay. Wet storage is needed close to the fit out yard for the substructure and for the completed structure.

The mooring equipment requires their own mobilisation port. The moorings (anchor and chain) needs to be installed and tensioned before the arrival of the completed floating wind structure.

The dynamic and export cables also need specialised factories next to a load-out quay. This is followed by ocean voyage and installation on dedicated cable laying vessels. The export cable needs burial in the seabed, and rock protection from potential damage from anchors or fishing trawls.

There are many technical and commercial problems facing the complete commercial development of floating offshore wind turbines, Blackfish (2020).

7.3. EXTREME EVENTS

Floating wind offshore turbines are subject to potential structural collapse due to the weather forces. In addition there also the possibility of compartment damage and partial flooding or even sinking during tow or operation.

Designers, suppliers of equipment, fabricators and the offshore installation companies are responsible to ensure that mechanical and structural do not occur. Mitigation measures need to be in place to ensure that minor failures do not propagate to complete collapse.

The construction company concerns with regards to extreme events include, Crowle & Thies (2022):

- Standards not complied with
- Poor quality control
- Tolerance on fit up exceeded
- Poor quality welds,
- Unapproved changes.
- Failure to meet all specifications,
- Lack of safety standards
- Temporary structure collapse

Reliability and risks detailed evaluation is essential to the selection of the preferred method for fabrication and offshore installation of floating offshore wind turbines.

Reliability and risk evaluation is related to the required contingency planning. Procedures thus need to be developed to prevent accidents. Mishaps in offshore installation phase require risks to be mitigated.

8. DISCUSSION AND CONCLUSIONS

8.1. DISCUSSION

Many countries are considering the use of floating wind, Floating Offshore Wind Centre of Excellence International Market Opportunities Summary Report (2022). Floating wind offers the possibility of installing turbines out of sight of land. In these deeper water the wind speed is stronger and more consistent, Castro-Santos & Diaz-Casas (2016). However, as the floating turbines are constructed inshore and will be very visible to people living close to the fit out port.

Spars of either concrete or steel construction has the advantage of low motions during the tow out. However, the Spar substructure requires deep water for vertical integration (fitting out) of the tower sections, nacelle, hub, and blades. Also deep water is required for the tow to the offshore wind farm.

The Hywind steel versions of the substructure were constructed in Spain. They were loaded out horizontally, using trailers onto to a heavy transport vessel (HTV). This was followed by dry ocean voyage on the HTV before being floated off in a Norwegian Fjord. The substructure was then upended, to the vertical, using sea water ballast before having sold ballast placed in the base to improve intact stability. A very large semi-submersible crane vessel was then used to fit the combined topside of tower, nacelle, and blades. Wet storage was in a deep water fjord.

The Hywind concrete version were built vertically in a dry dock After float-out the substructures were completed afloat using concrete slip forming. Solid ballast was added from a rock dumping vessel, with further sea water ballast pumped into the base to achieve the required draft. The Topsides of tower, nacelle and blades were installed using a very large land based crane, with the assistance of a spacer barge between the quay and the substructure.

The large steel Windfloat Semi-submersible substructures were fabricated in a shipyard in Spain. They were loaded out by trailer and then dry transported on a heavy transport vessel. The substructures were floated off in Rotterdam close to the vertical integration quay. Fit out, vertical integration, of tower sections, nacelle, hub, and blades took place with the substructure moored on a quay using a large onshore crane.

The ring barge by BW-Ideol has been deployed as a demonstration in steel and concrete versions. Outfit was done using large land based cranes being operated on the fit-out quay.

8.2. CONCLUSIONS

Several ports are needed for the fabrication and offshore installation of floating wind turbines:

- Shipyard for substructure fabrication
- Quays for nacelle, towers, and blades
- Marshalling port for anchors and chains
- Factory for the export power cables
- Vertical integration port for topside

Schedule and cost of construction can be reduced by:

- Planning components flow
- Storage on the fit out quay
- Details are to be Standardized
- Tight tolerances to be avoided
- Smooth labour force requirements
- Minimise weather down tine.

9. Terminology

TERM	DEFINITION
CAPEX	Capital expenditure
FOWT	Floating offshore wind turbine
GW	Giga watt
HTV	Heavy transport vessel
HVAC	High voltage alternating current
HVDC	High voltage direct current
LCOE	Life time cost of energy
Kv	kilovolt
M	metre
MW	Mega watt
MWS	Marine warranty surveyor
QA	Quality assurance
QC	Quality control
SPMT	Self propelled modular transporter
SSCV	Semi submersible crane vessel

CONFLICT OF INTERESTS

None.

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