TITLE

Installation Innovation for floating offshore wind

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INSTALLATION INNOVATION FOR FLOATING OFFSHORE WIND

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ABSTRACT

Floating offshore wind turbines are an emerging technology with notable prototype and demonstration projects being installed in recent years. Future floating wind farms enable the access to significant new wind resources in expanses of water too deep for conventional, bottom-fixed farms. Spar, barge, TLP and semisubmersible types have been deployed as demonstration units. Pre commercial units have been installed off the coasts of Portugal and the East Coast of Scotland.

This paper discusses naval architecture requirements for the temporary conditions of construction, ocean transport and installation. The requirements of Marine Warranty Surveyor guidelines for temporary conditions and the Classification Society requirements during the temporary phase are also taken into account. It is expected that major offshore maintenance will be carried out on floating offshore wind turbines by towing them back to more sheltered port locations. This paper is a literature and guideline review with additional information on intact stability during the tow to the offshore location. Thus, marine operations play a pivotal role throughout all phases of a floating wind farm's life cycle. In particular, uncertainties associated with offshore installation work can extend construction schedules and increase the capital expenditure required for the project. This paper will be of interest to researchers and practitioners in the floating wind sector, considering innovative installation methods as a means to reduce overall project lifecycle cost.

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
HAZID	Hazard indentification
HTV	Heavy Transport Vessel
HVDC	High voltage direct current
LOA	Length overall
M	Metre
SPMT	Self propelled modular transporter
SSCV	Semi submersible crane vessel
T	Tonnes
UXO	Unexploded ordinance
WFO	World forum offshore wind
WTIV	Wind turbine installation vessel

1. INTRODUCTION

There are several floating offshore wind turbine (FOWT) types in various stages of design. Only two types are currently producing pre-commercial electrical power. Figure 1 depicts the four main types namely barge, semi-submersible and Tension Leg Platform(TLP). This paper considers the installation aspects from port to offshore location. These temporary phases of a floating offshore wind turbine face many engineering challenges. As turbine sizes and distances from shore increase, weather becomes more severe and more important due to longer transit periods, increasing the logistics challenges for prospective floating wind farm developers and operators.

Figure 1 Floating options (courtesy ciercoenergy)

Marine operations play a pivotal role throughout all phases of a wind farm's life cycle. Uncertainties associated with offshore installation can extend construction schedules and increase the capital expenditure required for a given project. Installation costs can account for approximately 30% of the overall project cost and it is anticipated that informed engineering decisions in this area present further cost saving potential, through innovation. The increasing remoteness and heightened weather conditions increases the complexity of the marine operations.

There are 6 floating offshore wind turbines in UK waters (with another 4 under construction). Bottom fixed offshore wind turbines currently depend on wind turbines installation vessels (WTIV), which are limited to about 60m water depth though some WTIV are being modified to 80m water depth. Floating wind turbines are not so constrained bt water depth because they are completed in port or in a sheltered harbour.

There are about 60 different concept designs for floating offshore wind, two of which have reached pre commercial status, namely the Hywind Spar and Principle Power semi submersible. A further eight have been deployed at sea as demonstrators.

Floating wind turbines have their turbine nacelles and blades installed in a port or sheltered harbour. It is the intention to carry out maintenance on barge and semi submersible types back in a port.

The structure of the paper is as follows, section 2 reviews the current status of floating wind options, section 3 describes the temporary phases during installation, section 4 outlines the applicable rules and guidelines whilst section 5 discusses potential innovations. Section 6 provides a brief discussion and conclusions are drawn in section 7.

2. CURRENT STATUS OF FLOATING WIND

2.1 Types of Floating wind

This section will briefly review the main floating wind concepts and describe their main characteristics regarding stability and towout.

2.1.1 Spar

Spars have been derived from spars used in Oil and Gas. For in place stability, they require solid ballast to be placed in the base, a marine operation carried out afloat, figure 2. They require a large water depth 70 to 100 for construction and tow out.

Figure 2 Hywind Towout (courtesy Equinor)

2.1.2 Semi submersible

The semi submersible types are also derived from oil and gas technology, figure 3. For in place intact stability they depend on a large second moment of inertia water plane area, buoyancy and water ballast. They are fitted with large heave damping plates, under the columns, which means they take up a large area on land or dry dock or alongside an outfitting quay.

Figure 3 Semi submersible (courtesy Principle Power)

2.1.3 Ring barge

Ring barges, figure 4, are sized to dampen motions by sizing their moonpool. In place stability is derived from large buoyancy.

Figure 4 Concrete Ring Barge (courtesy Ideol)

2.1.4 TLP

The TLP is derived from oil and gas platforms, figure 5. In place stability is from taut vertical mooring lines or tethers. TLPs have low intact stability during tow to site.

Figure 5 TLP (courtesy Bluewater)

2.15 Suspended weight

The suspended weight option, figure 6, derives its in place stability once the weight has been deployed offshore. Tow out intact stability is low.

Figure 6 Suspended weight (courtesy Saipem)

2.2 Status

Floating wind has matured, enabling small-scale prototype projects and the world’s first pre-commercial arrays. Floating wind farms are the key to opening up new wind resources in expanses of water too deep for conventional, bottom-fixed wind farms.

This makes it an important area of research for the industry, Ref [1]. But as with many new technologies, one of the biggest obstacles standing in the way of full-scale floating wind commercialisation is cost. The turbines are of similar cost for both fixed and floating offshore wind structures. Installing anchors for floating offshore wind turbines is similar in time to installing the substructure for a bottom fixed wind turbine. However industrialized manufacturing of the floating platforms has not taken place so they are significantly more expensive than bottom-fixed offshore wind power. Floating wind still lags far behind bottom fixed wind in terms of commercial readiness due in part to lack of port facilities for construction and turbine outfitting. Compared to monopiles, substructures for floating wind turbines are, for now, considerably more expensive to manufacture and assemble. Steel substructures are many times heavier and more labour-intensive to put together than a simple jacket or tripod or monopile for a bottom fixed structure. However it is expected that in large water depths beyond say 80m that floating offshore wind turbines become a more realistic option.

Attaching the turbines to their substructures is one of the areas where floating wind has a clear cost advantage over bottom-fixed: turbines can be installed in a much more controlled environment, and without the use of expensive jack-up vessels. However, spar technologies require deep, sheltered waters and offshore cranes, resulting in a turbine installation process that is more costly than semi-submersibles and TLPs.

While more vessels are required for floating wind installation compared to bottom fixed substructures, these are considerably cheaper to charter than a jack-up vessel. An exception would be in the case of TLPs that, if not self-stable in towing, require bespoke installation vessels, which would incur significant expenditure.

Trial projects like the WindFloat project in Portugal and Scotland and Hywind in Scotland have yielded progress ref [2]. However, floating wind still has not reached the same status as bottom-fixed wind in terms of commercial readiness. Innovation is needed in port facilities and offshore installation to reduce the length of installation schedules and costs.

3.0 TEMPORARY PHASES

3.1 Phases

For a floating offshore wind turbine the temporary phases start with loadout from land onto a heavy transport vessel, or float-out from a dry dock, and conclude when the moorings and subsea cables have been connected. In addition the temporary phases include seabed surveys at the offshore site, along the tow route, the cable routes and at the ports used for construction.

The following temporary phases are required:

- Seabed Survey,
- Anchor and mooring foundation installation,
- Substructure construction
- Turbine construction
- Completed structure tow to offshore site
- Pre-lay Grapnel Run before cable laying
- Subsea Cable Installation
- Cable Burial

Seabed surveys include bathymetry, soil conditions, wreck appraisal and unexploded ordnance (UXO) identification. Some elements of the temporary phase include return to port for major maintenance or demolition.

3.2 Weight

It is vital that weight control is used throughout the project life to ensure that the floating offshore wind turbine floats at the required draft during the different temporary phases. Weight control should be performed by means of a well defined procedural system, such as that described in Ref [6]. Weight control procedures shall be in operation throughout construction and outfitting when afloat.

A detailed weight control procedure is required at the start of design. The weight report should consider and include:

- Net dry weight
- Gross dry weight
- Installation weights for loadout, dry tow, in port, wet tow, in place
- Gross installed weight

- Centres of gravity for all conditions
- Radii of gyration for temporary and permanent conditions

The substructure will be weighed before loadout to measure weight and the plan centre of gravity.

A trim and stability book is to be produced covering:

- Hydrostatics
- Ballast tank capacities and centres
- Allowable VCG curve
- Damage conditions

An inclining experiment may be carried out either on the substructure or completed structure at the outfit port. This will be used to determine the vertical centre of gravity.

3.3 Substructure construction

3.3.1 Spar

To date 6 steel Spars have been installed in Europe, though the demonstration project has now been decommissioned. The installation procedure, starting at the shipyard is as follows.

- construct substructure horizontally in a shipyard
- loadout with self propelled modular transporter (SPMT)
- submersible heavy transport vessel (HTV)
- ocean transport to a deep water site
- lay out temporary inshore mooring
- float off
- upend
- connect to inshore mooring
- add permanent solid ballast
- fit turbine
- tow offshore
- connect to prelaid mooring
- add permanent water ballast
- connect to pre laid power subsea cables

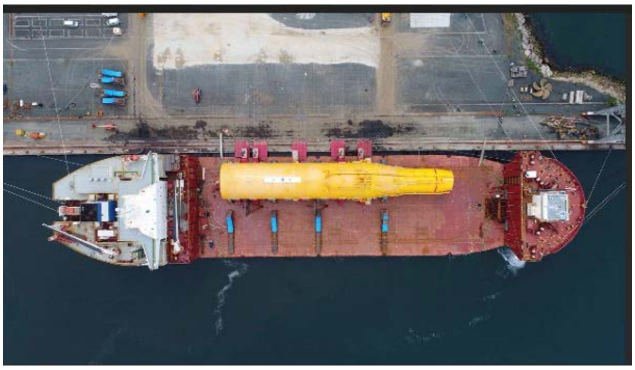

Figure 6 Loadout of Spar by SPMT (courtesy Navantia)

Innovation was required for the lifting frame design used by Saipem to lift and install the turbine, figure 7. The lifting frame had been developed from a moored floating sheer leg crane lift of a complete turbine onto a fixed structure.

The innovation required on Hywind by Saipem included se of their semi submersible crane vessel (SSCV):

- use of dynamic positioning
- lift onto a floating structure
- efficient damping system
- robust guiding method
- strong mating flange

Figure 7 Lift of turbine onto Spar (courtesy Saipem)

3.3.2 Semi built on land

To date three, pre commercial semi submersible FOWTs have been completed and another five are under construction. The construction procedure on land and subsequent installation can be summarised in the following sequence:

- construct substructure vertically on land
- loadout with self propelled modular transporter (SPMT)
- submersible heavy transport vessel (HTV)
- ocean transport, figure 8
- float off at the turbine assembly yard
- moor to quay
- fit turbine components
- pre commission
- tow offshore
- connect prelaid mooring
- permanent water ballast
- connect to pre laid cables

Figure 8 Substructure dry transport (courtesy Boskalis)

3.3.3 Semi built in a dry dock

To date three, semi submersible FOWT has been constructed in a drydock and installed in the following sequence:

- construct vertically in a dry dock, figure 9
- fit temporary buoyancy to minimise draft
- tow out of dry dock
- tow to the turbine assembly yard
- moor to quay
- remove temporary buoyancy
- fit turbine components
- pre commission
- tow offshore
- connect to pre laid mooring
- permanent water ballast
- connect to pre laid power cables

Figure 9 Semisub in drydock (courtesy Principle Power)

There are limitations on using dry docks because of the width of the structure, including the heave plates.

3.3.4 Barge in a dry dock

To date one, concrete barge FOWT has been constructed in a drydock and installed in the following sequence:

- build on a pontoon barge
- move into dry dock
- separate substructure from pontoon barge
- tow out of dry dock
- tow to the turbine assembly yard
- moor to quay
- fit turbine components
- pre commission
- tow offshore
- connect pre laid mooring
- permanent water ballast
- connect to pre laid cables

3.3.5 TLP built on land

No TLP FOWT are currently operating. The small Blue H demo has been decommissioned. Construction is as follows:

- construct vertically on land
- loadout by SPMT onto a submersible HTV
- ocean transport to the turbine assembly yard
- float off
- moor to quay
- fit turbine components
- fit temporary buoyancy
- pre commission
- tow offshore
- connect and tension vertical mooring
- remove water ballast
- remove temporary buoyancy
- connect to pre laid cables

Figure 10 0.08MW TLP (courtesy Blue H)

3.4 Tow to site

All the FOWTS types are towed from the outfit yard to the offshore locations using an anchor handling tug (AHT). A further AHT accompanies the tow.

A dedicated installation vessel with work class remotely operated vehicle (ROVs) is used to connect the pre laid mooring lines to the FOWT. Tensioning of the mooring lines is done by a winch on one of the AHT.

A specialised cable installation vessel is required to connect the subsea power cables

3.5 Anchor installation options

The main types of anchor under consideration are listed in table 1. Drag anchors and small suction piles can be installed with a anchor handling tug. Large suction piles and driven piles require medium sized crane vessels for installation plus anchor handling tugs for pre laying the mooring lines on the seabed.

Table 1 Anchoring options

	Barge	Semi-Submersible	Spar	TLP
Drag anchors	Suitable	Suitable	Suitable	Not suitable
Suction piles	Suitable	Suitable	Suitable	Suitable
Drive piles	Not preferred because of noise from pile driving and its effect on ocean mammals			Suitable

Chain mooring lines are connected to the anchor and pre laid on the seabed, prior to the arrival of the floating wind turbine.

3.6 Duration

The estimates of installation durations below, table 2, assume the same offshore location, assuming tow distance of about 290 nautical miles from the outfit port to the offshore site speed of 3 knots. These estimates are based on similar oil and gas structures taking account of different shapes and sizes.

Table 2 Typical installation durations

Item	**Barge**	**Semi**	**Spar**	**TLP**
	Days	**Days**	**Days**	**Days**
Anchor installation	12	6	6	18
Substructure loadout onto a Heavy Transport Vessel	2	2	2	2
Dry tow to outfit port	5	5	5	5
Float off from Heavy Transport Vessel to a sheltered harbour.	2	2	4	2
Outfit turbine tower, nacelle and blades in a sheltered harbour	10	10	10	10
Tow to site	4	4	4	4
Connect moorings	12	6	6	18
Connect power cables	5	5	5	5
Total	**52**	**40**	**42**	**64**

4.0. RULES AND GUIDELINES

4.1 Classification

The following classification societies have developed design requirements for floating offshore wind turbines:

- ABS ref [9].
- Bureau Veritas ref [10].
- DNV ref [11].
- Class NK ref [12].

They provide guidance on all temporary phases, including load-out, transportation, installation, maintenance and repair.

The focus of the classification societies lies on the design and construction of the permanent works, as well as their integrity for all temporary phases.

The installation procedures documented in the installation manual are to be provided to the society for information. Installation procedures are to be submitted to an appropriate third party for review, to ensure compatibility with the site conditions and the FOWT design. The installation manual may include:

- personnel qualifications and skills
- interface points and any required technical specifications for civil and electrical construction works
- specialized tooling and required lifting fixtures or equipment
- limiting environmental conditions
- quality control check points, measurements and inspections, required by the design
- installation loads and load conditions
- description of safety instructions and planned environmental protection measures
- quality recording and record keeping processes

Installation tolerances are to be specified in the installation procedures, and duly taken into account in the design calculations.

The installation survey includes, but is not limited to, the following operations:

- installation of anchors
- deployment of mooring lines
- test loading of anchor and lines
- connection to floating platform and tensioning
- post-installation inspection of the system

4.2 Marine warranty surveyor

The marine warranty provides certificates to proceed for:

- loadout
- substructure transport
- float off
- tow to offshore site
- mooring and subsea cable connection

The approval certificates input is:

- weather forecast for the intended marine operations
- use of best industry practices
- suitable personnel
- design for temporary works
- construction of temporary structures
- marine vessel status
- installation equipment suitability
- risk analyses
- contingency procedures

Design calculations include:

- weight control
- ballasting
- intact stability
- damage stability
- motions
- global strength
- local strength
- rigging sizes

Further details are given in ref [7] and ref [8].

5.0 INSTALLATION INNOVATIONS

Installation starts with the loadout of the floating offshore wind turbine substructure onto a heavy transport vessel or the floatout from a drydock and finishes with the mooring line and subsea cable connection. The industrialisation of floating wind requires specialised construction yards and inshore floating cranes or large land based cranes.

Floating technology ref [5] is used to deploy offshore wind in sea areas that have high wind speeds but are too deep to be cost effective for bottom fixed foundation installation. There is innovation potential in this area to support the commercialisation and future deployment in new deep water, high wind speed resources. There is a significant expected growth in the floating offshore wind market, in the UK, wider Europe, and internationally. Innovations in this sector will include dynamic high voltage cable systems, moorings for challenging seabed conditions as well as for very deep and shallow water, foundations and new installation, maintenance and fabrication innovations.

As floating turbines get larger and are being situated in deeper, rougher waters, reliable and cost-effective moorings are becoming essential for deployment increases to occur.

The development of new, cheaper to produce and install substructures, as well as validation of existing designs, are essential to lower the cost of floating wind. The layout of construction ports and outfit ports need to avoid constraints on layout space and carne capacity.

The development of commercial scale projects of approximately 500MW or greater is required to demonstrate the feasibility of floating wind as a competitive energy source.

Innovations in wind turbine floating substructure design as well those that decrease the costs of manufacture and installations will be the main drivers of deep-water wind farm deployment. Significant innovation opportunities exist for substructure, installation, logistics as well as offshore operations.

The fabrication of a large quantity of floating structures must be given particular attention. Floating structures could be built in modules with each module being built in specialized areas and by specialized suppliers. That would allow a ‘serial-like’ fabrication process to be put in place achieving optimum quality.

In terms of final assembly due to the nature of the floating solutions, there does not seem to be a suitable alternative to assembly at port. Thus, large investments need to be made in order to increase the port area, or drydock sizes, and dredging at the fit out quay.

Urgent innovation is also needed for offshore maintenance, ref [3]:

- Heavy lift maintenance operations from floating vessels offshore.
- 3D motion compensation systems from floating crane vessels when working close to floating wind turbine.

The tow to port maintenance innovation work should seek to:

- Investigate the procedures for disconnecting and reconnecting floating wind units in a large scale wind farm
- Evaluate key challenges and identify solutions to mitigate risks and costs
- Carry out intact and damage stability analysis
- For TLPs investigate how temporary buoyancy can be re-connected

6.0 DISCUSSION AND CONCLUSIONS

The stability triangle is useful to classify and locate the different floating technologies regarding their main stability mechanism, namely ballast, buoyancy and mooring. The triangle drawn in ref [13] considers in place conditions. Following the explanations above, we modify the stability triangle for tow out condition, see figure 10. Stability is measured by metacentric height (GM) and range of intact stability.

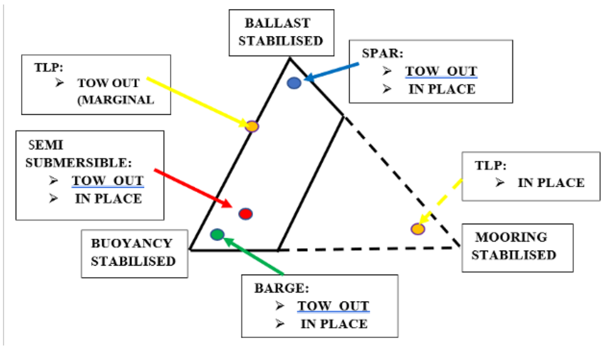

Figure 11 Tow out stability restrictions

The TLP has challenges during tow out and installation. But the TLP has some benefits as well, very small foot print, low structure weight, and less heave / surge motions of the turbine. Research on TLP installation is needed and may result in a requirement for new installation vessels.

Spars need deep water inshore for upending of the substructure and fit out of the turbines. Inshore moorings need to be laid for the Spars. Assuming parallel working then multiple inshore moorings are required. Thus, Spars need be constructed in locations where deep water is available close to the shore, such as Norwegian fjords.

Regarding semi submersibles from an inshore construction point of view their constructability varies with the location of wind turbine, figure 12. Some semi submersibles have the turbine over a corner so that the operating radius of the onshore crane is as small as possible. Other semi submersible options have the turbine in the centre, but have no underwater bracing between columns and in this case, the onshore crane can work from the corner of a fit out quay.

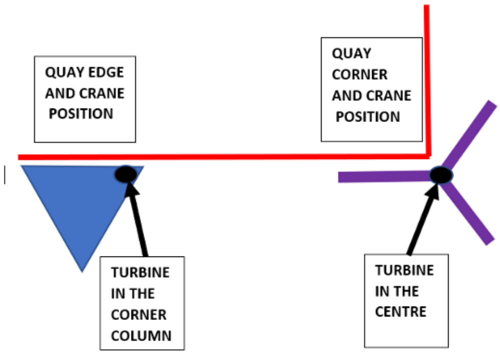

Figure 12 Semi submersibles at fit out quay

7.0 CONCLUSION

In general, a greater number of conventional vessels are required for floating wind installation compared to fixed offshore wind turbines. An exception is the installation of TLPs that, if not self-stable in towing, require bespoke installation vessels or large temporary buoyancy tanks, which would incur significant expenditure.

There is still considerable development needed to reach a stage of mass production for floating offshore wind turbines. Innovation in installation will assist in bringing forward large floating offshore wind farms.

8.0 ACKNOWLEDGEMENTS

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10.0 AUTHORS BIOGRAPHY

Alan Crowle is a naval architect studying for a masters by research degree at the University of Exeter, into the installation floating offshore wind turbines. He has a BSc (1974) from University of Newcastle-upon-Tyne and MSc (2020) from the University of Plymouth.. He has over 50 years marine experience in design, construction and offshore installatio of marine structuresn. His work includes steel jackets, semisubmersibles, FPSOs, large offshore and onshore modules, near-shore pipelines and LNG facilities. He has design experience in the installation of bottom fixed offshore wind turbines and fixed High Voltage Direct Current offshore platforms. He is a fellow of the Royal Institution of Naval Architects, the Institute of Marine Engineering, Science and Technology and the Society of Consulting Marine Engineers and Ship Surveyors. The focus of the research is into the installation of floating wind turbines including loadout, dry transport and wet tow through to offshore mooring and cable connection.

Prof Philipp R. Thies is an Associate Professor in Renewable Energy in the College of Engineering, Mathematics and Physical Sciences (CEMPS) at the University of Exeter. His research interest lies in the reliability engineering of renewable energy technologies with a focus on offshore energy. In current projects, he is Principal Investigator on a Joint Industry Project (Carbon Trust) for Floating Offshore Wind to demonstrate Intelligent Mooring Systems. He leads Exeter's contribution to the €45million EU Interreg initiative 'Tidal Stream Industry Energiser Project (TIGER)' and is PI on the Innovate UK funded project "Autonomous Robotic Intervention System For Extreme Maritime Environments (ARISE2)", led by L3 Harris. Prof Thies is a Co-Director of the EPSRC Supergen ORE Hub [EP/S000747/1] and Co-Investigator in the EPSRC/NERC Centre for Doctoral Training in Offshore Renewable Energy (IDCORE) [EP/S023933/1], training the next generation of offshore engineers.