Installation of Floating Wind – Current Methods

Floating offshore wind turbines are being developed into a source of marine energy. This paper reviews the current status of the installation methods for floating offshore wind turbines (FOWT). Key areas of FOWT installation research are identified with details of current research gaps and recommendations for future work. The methods for construction and installation floating offshore wind turbines is at an early stage of development. The fabrication, inshore construction, tow out and installation of floating offshore wind turbines has a significant influence on project capital costs and development schedule. Fabrication of steel and concrete substructures take place in shipyards, and a fit out quay, where the tower, nacelle and blades, are installed, at a sheltered inshore location. The completed structure is then towed offshore for connection to moorings and dynamic export cables. It is expected that the fit out quay is reasonably close to the offshore wind farm, in order to minimise tow out time. Many challenges need to be addressed and much research is pending into the construction and installation of FOWT. Some of the challenges are specific to the type of floater but others apply generally and this paper will seek to address these opportunities. Floating wind in the Mediterranean platforms are described.

Introduction

The Question

The methods for construction and installation floating offshore wind turbines is at an early stage of development as only about 25 have been constructed. There are different ways of constructing and installing floating offshore wind turbines, which has been reflected in those built to date. This paper sets out to develop checklists against which floating wind installation methods can be compared

Methodology

Information has been assembled on existing and future floating offshore wind turbine (FOWT) projects, through a literature search. This includes FOWT research from magazines, on line press releases, reputable academic research institutions and national laboratories, [ABS, 2021]. The paper primarily focuses on those projects that are currently in operation or under construction. The selected projects include a worldwide review based on various FOWT designs and developers.

The fabrication, inshore construction, tow out and installation of floating offshore wind turbines has a significant influence on project capital costs and development schedule.

The method of analysis is by reviewing information on the design, fabrication of components, construction and installation of floating wind structures [Zhiyu, 2021]. Also different ports and shipyards have published brochures and presentations on their capabilities, and these are reviewed with regards to their suitability to construct and fit out floating wind turbines.

Sections

This paper reviews floating wind by location, section 2, and by type in section 3. This paper examines the various concerns about marine operations during installation phases of a floating wind farm. Floating wind proposals in the Mediterranean is considered. Costs for floating wind are discussed in section 4. Commercial scale floating wind farms are expected to become competitive with bottom fixed wind farms only at water depths between 60m and 80m.

To progress FOWT will need to see cost reduction, [McMorland, 2022], compared to fixed bottom wind turbines. Heavy maintenance costs also need to be reduced [Rinaldi, 2021]. This paper presents current state-of-the-art installation research with focus on FOWT construction and installation challenges.

Possible Location of Floating Offshore Wind

General

Floating wind will be developed on locations where the water depth is too large for Bottom Fixed Wind Turbines (BFW).

There are limitations on where a floating wind turbine can be moored, [Pendleton, 2021] because of:

- Tow distance is too far from potential fit out quays
- Lack of high bollard pull tugs for the tow out
- Fishing grounds
- Underwater wrecks
- Commercial shipping routes
- Subsea pipelines
- Telecommunications and power subsea cables
- Areas of low wind speeds
- Military training areas
- Places where they may interfere with onshore radar stations
- Dumping grounds for UXOs
- National marine sanctuaries
- Locations of bird migration routes
- Sea mammal feeding, breeding and transit areas

Bottom trawl fishing will not be possible in floating wind farms because most of the area will be covered by mooring lines, in particular if these are catenary mooring lines. Mid water fishing will also be unwelcome as it could interfere with the dynamic cables connecting the FOWT to the export cables

There may be lack of large tugs for tow out and mooring connection may restrict deployment of floating offshore wind turbines. At least 2 tugs are required for tow out form the fit out yard, whilst up to 4 tugs are required during the mooring connection, [Burgess-Salmon, 2021]. It is not just a question of installed power and bollard pull: what will enable anchor handlers to complete large floating wind projects quickly and efficiently is large deck space, and large on-board chain lockers. As the market moves into deeper waters, so larger chain lockers and the ability to carry as many mooring lines as possible will be very important, [Foxwell, 2021]. Thus new large tugs for floating wind, [Lewis, 2023], are required, principally for laying catenary and taut mooring systems.

United Kingdom

The Crown Estate Scotland, [Crown Estate, 2022], has started the ScotWind process and the INTOG intentions both of which would deliver floating wind off the coast of Scotland. There are plans for floating wind farms in the UK sector if the Celtic Sea. It is estimated that up to 70 GW of FOWT could be operational by 2040 [Crown Estates, 2022].

United States of America

The United States is carrying out research and planning floating offshore wind in particular off the West Coast, [Ramachandran, 2021]. There are various challenges to progressing floating wind, namely:

- Planning permits
- Procurement of equipment
- Construction supply chains
- Installation vessels
- Grid infrastructure

The transition from bottom fixed wind to floating wind is illustrated in figure 1. It show the following types of fixed wind (from left to the middle):

- Mono-pile, the most common form of BFW
- Jacket structure
- Tripod structure

The floating types shown are (from middle to the right):

- Semi submersible
- Tension leg platform(TLP)
- Spar

Figure 1. *BFW and FOWT, [courtesy Joshua Bauer, NREL 2022]*

Japan

Experimental floating offshore wind turbines have been deployed in Japanese waters, with most of them now removed.

South Korea

Because of its large shipyards South Korea is well placed to mass produce floating offshore wind turbines.

Norway

Large concrete Spars, which can be constructed and out-fitted in its fjords are being used in Norway for providing electrical power to existing oil and gas facilities to reduce their carbon footprint

Types of Floating Wind

General

The floating wind turbines are arranged in an array to optimize the capture of wind energy. Dynamic array cables connect each floating offshore wind turbine to a substation. From the substation the electrical power is transmitted at a higher voltage to the shore and hence to the grid system. The substation may be:

- A bottom fixed structure piled into the seabed
- A subsea unit
- A floating structure

Floating wind turbines will be moving further offshore into deeper waters where they can make use of higher wind speeds. This trend creates additional challenges in the design, construction and installation phases of a floating offshore wind farm. Several pilot and demonstration-scale floating wind farms are now operational in different parts of the world e.g.:

- Wind float Atlantic – Portugal (25 MW),
- Hywind – Scotland(30MW)),
- Wind float Kincardine –Scotland(47MW)
- Hywind – Tampen Norway (88MW when complete)

Investigations, [Castro-Santos, 2013], show that approximately 36% of the total floating project costs are incurred during the installation and dismantling activities. These studies have shown that the size of the floating wind farms has a large impact on installation costs and LCOE. \it is expected that LCOE will reduce as the floating wind farm size increases, because there will be mass production, [Rodriguez, 2014].

As part of the planning permission process ocean surveys are required. Assessment and prediction of met-ocean conditions are required for construction and installation of floating wind farms. In addition details of the seabed are required by geophysical and geotechnical surveys. In addition environment baseline surveys are required to investigate marine plants, birds, fish and sea mammals.

The installation procedures differ according to the type of the floater used. Generally, floating wind installation requires a greater number of vessels compared to bottom fixed wind, but the vessels are cheaper to hire and more easily available [Crowle, 2021]. Even though many floating wind concepts have been developed, only a few have been successfully deployed and commissioned in a commercial level. Anchor handling tug supply (AHTS) are also required in all these operational phases of a wind farm.

Anchoring

Types of moorings include:

- Catenary connected at each corner of the FOWT
- Vertical tendons
- Signal leg connected via swivel

Types of anchors, [30] are described in table 1.

Mooring lines consist of:

- Chain where the mooring line is touching the seabed
- Chain where the mooring line emerges from the FOWT
- For the mid-section of the mooring line it can be chain, wire rope or synthetic rope

Table 1. *Anchor types and installation vessel*

Anchor type	Requires crane vessel	Requires AHTS	Comment
Drag anchor	No	Yes	Not suitable for TLP
Suction pile	Yes	Yes	AHTS handles mooring lines
Drilled pile	Yes	Yes	AHTS handles mooring lines
Driven pile	Yes	Yes	AHTS handles mooring lines
Gravity anchor	Yes	Yes	Only suitable for hard rock seabed

Cables

There are the following cable types:

- Dynamic array cable (up to 66kv)
- Export cable alternating current(up to 250Kv) or direct current(up to 500kv)

The export cables are buried in the seabed, for their protection.

Intact stability of FOWT

It is important to have good weight control, [ISO, 2011] which covers:

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

The transitional conditions due to construction and transportation, in particular with regards to intact stability are as follows, [Collu, 2014]:

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

Marine warranty rules are provided by:

- ISO[ISO, 2011]

- DnV[DnV, 2020]

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

- ABS[ABS, 2020]
- Bureau Veritas[Bureau Veritas, 2019]
- Class NK[Class NK, 2012]
- DnV[DnV, 2020]

Spar Type

The spar-type substructures have large drafts which require the use of assembly in deep water, as can be found in several Norwegian Fjords. The installation phase also requires sheltered coastal waters (maximum significant wave heights are up to 0.5 m and wind speeds less than 10m/s, for some inshore lifting operations. This is a challenge, as sheltered waters with high depths are required near the construction sites, due to the high draft of the floaters.

The marine operations for a steel spar are:

- The pre installation of anchors and the mooring lines.
- Construct steel cylinder, horizontally, onshore
- Loadout steel cylinder onto a heavy transport vessel (HTV), using SPMT
- Ocean voyage of substructure on board the HTV
- Floatoff from heavy transport vessel
- Upend with seawater ballast
- Solid ballast (magnetite) added to the base using a rock installation vessel.
- Seawater ballast added to provide the required draft
- The tower assembly, with nacelle and blades, is mated with the substructure, [Jiang, 2021]
- A large semi submersible crane vessel (SSCV) lifts the tower from the shipyard
- After the mating, the complete wind turbines are towed to the offshore location on the wind farm.
- Connect the mooring lines and tension
- Connect the dynamic array cable

The marine operations for a concrete spar are:

- The pre installation of anchors and the mooring lines.
- Construct concrete partial cylinder, vertically in a dry dock
- Float partial cylinder to deep water
- Slip form remainder of the concrete cylinder in deep sheltered water
- Solid ballast (magnetite) added to the base using a rock installation vessel.
- A spacer barge separates the Spar from the quay

- The tower assembly is mated with the floater later using an onshore crane
- After the mating, the structures are towed to the location of the wind farm.
- Connect the mooring and tension
- Connect the dynamic array cable

For the in place condition periodic sub-sea inspections and maintenance will be performed using ROVs (Remotely operated underwater vehicle). Heavy maintenance of components such as the nacelle, can be exchanged using a dynamic-positioned offshore crane vessel, in combination with active heave compensation.

The spar buoy has inherently good intact stability during tow out [Anderson, 2016] and [Thiagarajan, 2014]. The deep draft of hull requires deep water for towing the spar from fit out to offshore. Figure 2, [Efthimiou, 2022] and [Equinor, 2022] shows a concrete spar during fit out. There is a further concrete spar in the background on wet storage moorings. Spars are moored using catenary moorings which are easy to pre-install at the offshore site using AHTS.

Figure 2. *Concrete Spar (courtesy Equinor)*

Semi Submersible

The installation operations are carried out with the help of harbour tugs and AHTSs (Anchor Handling Tug and Supply). Most AHTSs were constructed to serve the oil and gas industry, and they can be used for floating wind farm installation, where they are used for the installation of drag anchors, towing the FOWT offshore and finally to connect the pre installed moorings.

The marine operations for a steel semi submersible are:

- The pre installation of anchors and the mooring lines.
- Construct, vertically, onshore
- Loadout onto a heavy transport vessel (HTV), using SPMT
- Ocean voyage of substructure on board the HTV
- Floatoff from heavy transport vessel

- The tower and rotor assembly were mated with the floater later using an onshore crane
- After the mating, the structures are towed to the offshore location of the wind farm.
- Connect the mooring and tension
- Connect the dynamic array cable

Operation and 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 platform location). In case of large heavy maintenance or repair activities the platform can be towed to a sheltered location or port [Banister, 2017].

The Semi-Submersible substructure has a large advantage regarding Capital Expenditure (CAPEX). due to the the turbine installation and testing can be done and finalized in port, and hence removes a some of the offshore operations during the commissioning phase. The only operations needed at sea is hooking the structure up to pre-installed anchors and dynamic array cables. These anchors are often with catenary mooring lines, and thus become very long and expensive in deeper waters when a specific mooring compliance and station-keeping is required. The towing is also straight forward due to the inherent stability of the assembled system and the low draft. This also means that the total system can be towed to port for heavy maintenance.

Figure 3, [Principal Power, 2022], shows a steel semi submersible which shows some of the technical challenges for floating wind during installation, namely:

- At least 3 harbour tugs required to steer the structure in confined waters
- Large area required for the construction
- Very wide channel needed to for the structure and harbour tugs
- Large ocean going tug to tow the structure offshore.
- Large anchor handling tugs (AHTS) used to connect moorings
- Turbine in one corner to maximise onshore crane capacity during fit out at a quay
- Large steel content

Figure 3. *Steel semisubmersible (Photo courtesy Principlepower)*

Barges

Barge type FOWT have installation and maintenance similar to that used for a semi submersible. They can be fabricated on land or in a dry dock. Figure 4 shows a barge type alongside a quay, [40].

Figure 4. *Concrete barge (courtesy BW-Ideol)*

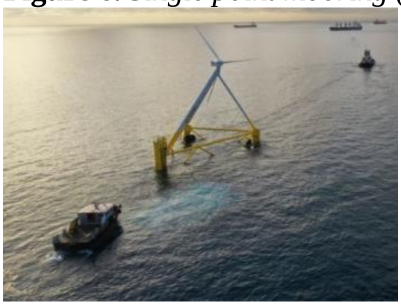
TLP

The installation of a TLP is a complex process, due to the tendon mooring system. The intact stability during tow out is an important consideration, [James, 2015] and may be very low or negative. Some TLP designs thus require use of temporary buoyancy during tow and installation. The tendons, which hold the platform in place, are installed with the floating wind turbine, which increases the installation schedule. The TLP is de-ballasted to a draft where the tendons attains the optimum tension. A specially adapted dynamically position crane vessel, with active heave compensation, is required for heavy maintenance.

The TLP consists mainly of an almost fully submerged buoyant structure. Due to the small draft and the fact the stability is obtained via the mooring system, these structures can be relatively small and light, see figure 5. For the TLP the inherently unstable system, during installation, will often require a bespoke crane vessel for assisting in installation.

A single point mooring system, also known as a pivot buoy is shown in figure 6,

Figure 6. *Single point mooring (courtesy X1 wind)*



Floating wind in the Mediterranean

The first floating offshore wind turbine was the Blue H, figure 7.

Figure 7. *Blue H TLP*

Provence Grande Large is based on TLPs, and will installed off the French coast. Figure 8 and 9 shows the substructure transition piece being fitted in the South of France construction yard. Its three wind turbines will each have a production capacity of around 8 megawatts.

Figure 8a. *TLPs under construction (Courtesy EDF)*

Figure 8b. *Provence Grande Large (courtesy SBM)*

Costing Methodology

Bringing Down LCOE

The development of large floating offshore wind farms is still in the planning stage. Based on the few floating wind turbines deployed to date is hard to estimate the CAPEX and LCOE. It is inevitable that where floating wind farms are used they are further offshore than bottom foxed windfarms, which means that substations and buried export cables are more expensive. However the steel used in construction of the substructure hull is of larger quantity and hence more costly than that used for a fixed structure. In addition there are further costs for delivery and installation of the mooring components. [Balanda, 2022], as the water depth increases.

Early prototypes that have been installed so far, have shown to be very expensive. However, early prototypes do not reflect the true costs that can be expected with large scale deployment. This will require designs to be optimized to reduce structural weight, but this may need novel component technologies. Improving installation techniques and adopting serial production processes, will have the largest effect on reducing per unit costs [Katsouris, 2016]. There is therefore significant potential for costs to come down to reach parity with bottom fixed offshore wind when deployed at large scale.

Thus when the cost of the dynamic array cable, deep water moorings and anchors is included, floating wind structures are expected to be more expensive than that of bottom fixed wind turbines.

Comparison of Floating Types

Delays during construction, ocean tow and offshore installation have a big effect on the outturn of CAPESX costs. There may be delays due to bad weather in the fit out yard if there is poor protection from wind and waves. Weather delays for different types of floating wind for the installation phase are shown in table 2. The cost of installation vessels consist of:

- Day rates for installation vessels
- Mobilisation time and cost
- Demobilisation time and cost
- Complexity of the offshore work
- Fuel usage, which increases with dynamic positioning

Table 2. *Weather downtime during installation*

FOWT Substructure	Intact stability during tow out	Weather limit during tow out	Wave height during installation	Weather downtime during installation
			Tp<10seconds	
SPAR	Good	Wind<15m/s	Hs<2.5m,	Low
Semi submersible	Good	Wind<15m/s	Hs<2.5m	Low
Barge	Acceptable	Wind<12.55m/s	Hs<2.0m	Medium
TLP	Very low	Wind<10m/s	Hs<1.5m	High

Floating offshore wind turbines can be assembled with the turbines by using onshore cranes on ports and transported by anchor handling tugs to the offshore wind farm.

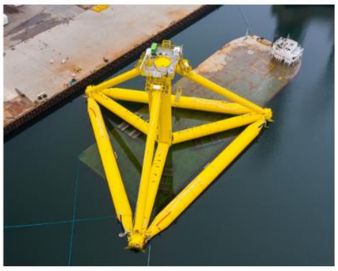
Economies of Scale and Design Selection

As far as the fabrication costs are concerned, the FOWT is more expensive compared to the bottom fixed wind turbines, [Ury, 2021]. There are also additional costs for the fabrication and installation of the mooring systems and dynamic array cables.

Substructures represent a significant part of floating wind capital costs CAPEX, and thus their mass production would significantly reduce costs. However, in addition to economies of scale the industry would also need to narrow down the wide range of designs and configurations that exist today. Floating wind technology is far from mature, and far-offshore environments need to be widely understood for the technology to grow beyond the interest today to commercial deployment.

Floating wind is expensive compared to other forms of power generation. This means currently subsidies will be required before coast are required mass production can reduce costs. The number of floating wind turbines installed or deployment is a major, if not the main, cost reduction driver. The FOWT shown in figure 9, [Stiesdal, 2022], shows a substructure whose intact stability is derived from an underwater ballast tank.

Figure 9. *Tetra Spar designed for mass production (courtesy Stiesdal*)



Deployment – not time – will reduce floating wind CAPEX

There is insufficient track record for project developers and financial institutions to be willing to take the risk in developing and investing in floating wind projects because they are high cost. The number of turbines installed or deployment is a major, if not the main, cost reduction driver for offshore wind. The effect of deployment on LCOE is shown in a figure 10. The key cost drivers specific for floating wind are:

- Fabrication, manufacturability and serial production of floating platform, [Kadenv, 2022].
- Floating substructures have a higher cost compared to offshore bottom fixed structures [Diaz, 2022].
- Offshore bottom fixed structures are more expensive than onshore wind wurbines
- Logistics, both onshore and offshore, [Adachi, 2022], on multiple projects

- Need for consolidation to a small number of platforms types
- Design optimization to reduce fabrication, installation and operational costs
- Heavy maintenance, undertaking the replacement offshore or towing the units for repair in a port.
- Make best use of existing ports [Ore Catepult, 2020]

Figure 10. *LCOE versus deployment*

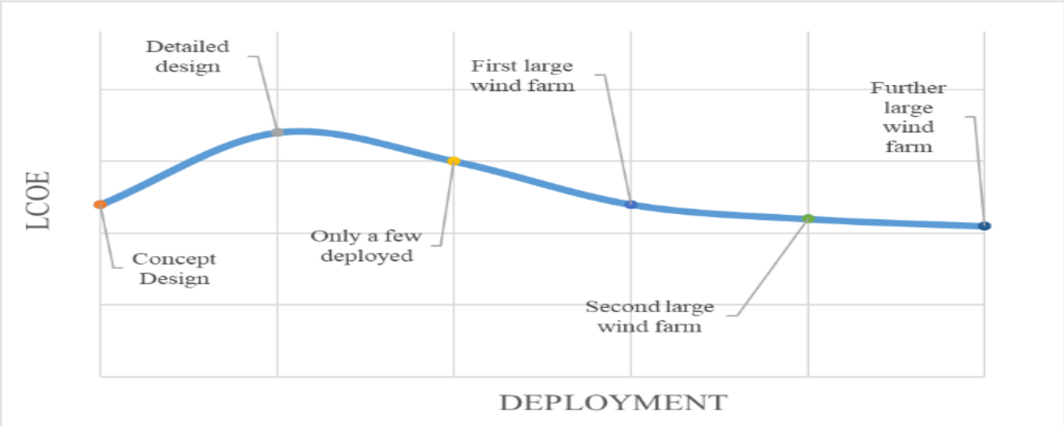


Table 3 compares different FOWT types costing requirements against those of mono-pile bottom BFW.

Table 3. *Relative construction and installation cost drivers for FOWT*

Item	Mono-pile	Spar	Barge	Semi submersible	TLP
Port quay strength	low	very high	very high	very high	very high
Port water depth	low	very high	low	medium	medium
Temporary buoyancy	none	none	low	low	high
Solid ballast, inshore	none	very high	none	none	none
Onshore cranes	medium	very high	high	high	high
Cargo ships	medium	medium	medium	medium	medium
Heavy transport vessels	none	medium	medium	medium	medium
Wind turbine installation vessels	very high	none	none	none	none
Harbour tugs	low	high	high	high	high
Anchor handling tug supply	low	high	high	high	high
DP crane vessel installation	high	none	none	none	very high
DP crane vessel heavy maintenance	high	very high	medium	medium	very high

Results

Developers, regulators, insurers, and financers need significant advances to upscale floating offshore wind capacity to meet the expectations in reducing project risk and minimising installation time, [Houlder, 2022]. As well as powering electricity grids, floating wind will help decarbonise offshore oil and gas production and play a critical role in green hydrogen production. Choosing the best substructure technology is critical to delivering the best levelised cost of energy (LCOE) for floating offshore wind projects, which includes an assessment of available port infrastructure and supply chains as well as water depth and operational weather conditions.

Understanding the installation methodology and major maintenance operations is also critical to determining which substructure type is best for the wind farm. Initial development strategies suggest that it is cheaper to tow barge and semi submersible floating turbines to shore where crane operations are simpler and there is ready access to onshore services and personnel. One of the main challenges for the tow to port option is the safe detachment and wet storage of cables and mooring connections, [Carbon Trust, 2021], on the seabed. Conversely, for in-situ maintenance, there are challenges with the limitations of heavy lift crane vessels as many of the existing vessels are unable to lift to the required hub height with the required reach for larger turbines.

Future development requires an integrated design interface between anchors, mooring system and substructure which will reduce the installation schedule. Investment required to develop the port infrastructure required to fabricate the substructures is significant and there thus needs to be confidence there will be sufficient volume of projects to cover that investment. That approach lends itself to consistency and repeatability in fabrication.

Discussion

As the floating industry matures, research is needed to frame innovative methods and technologies to reduce the CAPEX and Operational costs and thus lifetime cost of energy (LCOE). Floating offshore wind turbines provide opportunities for batch construction and deployment, in order to have full commercialization of floating wind farms. Semi-submersibles are observed to be the most cost-efficient design from an installation point of view, but broader research is needed to consider all the factors applicable to the whole life-cycle of the wind farms. Several challenges are yet to be addressed to reduce the costs concerning spar-type platforms and TLPs.

Conclusions

There is much research to be done for the easy and cost-effective installation of TLPs. It is important to introduce and implement innovative and cost-effective methods and technologies in this domain. Marine operations, due to the involvement of human life, environment and marine life, are of paramount importance. They are most dependent on met-ocean conditions, so accurate prediction is important. In situ measurements should be encouraged for getting accurate weather data throughout the life-cycle of the wind farm.

Marine operations can be improved in two different ways i.e., either by developing better metocean prediction models, for example, analytical models augmented by in situ measurements, or improving the operability of vessels in harsh seas by implementing innovative technologies and methods. Specialised vessels are expensive, but by reducing costs in other areas they can lead to reductions in the overall LCOE. Generally operations and maintenance have stricter weather restrictions compared to installation operations (e.g.: towing).

Abbreviations

Abbreviation	Meaning
AHTS	Anchor handling tug supply
BFW	Bottom founded wind turbine
CAPEX	Capital expenditure
FOWT	Floating offshore wind turbine
GM	Metacentric height
INTOG	Innovation and targeted oil and gas
Kv	kilovolt
LCOE	Levelised cost of energy
M	Metre
m/s	Metres per second
MW	megawatt
O & G	Oil and gas
O & M	Operations and maintenance
OPEX	Operational Expenditure
ROV	Remotely operated (underwater) vehicles
SPMT	Self propelled modular transporter (trailers)
SSCV	Semi submersible crane vessel
TLP	Tension leg platform
T	Tonnes (metric)
Tp	Peak wave period
WTIV	Wind turbine installation vessel

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