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Floating Offshore Wind: A Review of Installation Vessel Requirements

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Abstract**—**Floating offshore wind farms may provide in the future large quantities of renewable energy. One of the challenges to their future development is the provision of installation vessels for the offshore installation of floating wind turbines. This paper examines the current fleet of vessels that can be used for inshore construction. Separate vessels are required for the ocean tow out and the offshore installation. Information will be provided on what new vessels might be required to improve the efficiency and reduce costs of installing floating wind turbines. Specialized cargo vessels are required for this initial mobilization. Anchor handling vessels are required to tow the floating wind turbine offshore and to install and connect the moorings. Subsea work vessels are required to install the dynamic cables whilst cable lay vessels are required for the export power cable. This paper reviews the existing and future installation vessel requirement for floating wind. Dedicated ports are required for vertical integration of the substructure and the tower, nacelle and blades.

Keywords**—**Floating wind, naval architecture, offshore installation vessels, ports for renewable energy.

I. INTRODUCTION

THIS document sets out the vessel requirements for the installation of floating offshore wind turbines.

Section II describes the wind turbines and the types of floating wind substructures that require use of installation vessels. Section III describes the many vessels required to install a floating wind turbine. The method of review of installation vessels are described in Section IV. The results of this review are providing in Section V. Discussions and conclusions are given in Section VI and VII respectively.

The method of analysis is to review how installation of existing floating wind turbines has been carried out and to understand the marine equipment that has been used. The selection of vessels and associated equipment for the installation phase is assessed. Possible future vessels required for the construction and installation are considered.

II. FLOATING WIND TURBINES

It is intended that Tension Leg Platforms (TLPs), semi-submersible and barge types are fully fitted out alongside a fit out quay prior to tow out offshore [1], [2]. Spar types are fitted out in sheltered deep water before being towed offshore for final installation. Some TLP installation options involve use of temporary buoyancy or large crane vessels with active heave compensation.

Turbine sizes are given in Table I [3]. This shows the size of the cranes required [4]-[7]. Consideration needs to be made of wind loads during blade installation [8]-[12]. In the fit out harbour, a sheltered location with minimum motions due to waves is required.

Table II describes the various vessel requirements for different anchor systems, [13]. Moorings may be:

- Centenary
- Taut
- Tension

Single point mooring systems use tension moorings.

TABLE I
OFFSHORE WIND TURBINES

Configuration	3 bladed upwind or downwind
Axis	Horizontal axis
Blade above sea level	30 m
Machine rating	3 to 15 MW
Rotor diameter	130 to 200 m
Gearbox	Single stage or direct drive
Height of nacelle	98 to 135 m

TABLE II
ANCHOR INSTALLATION

Anchor Type	Vessel for anchor installation	Vessel for mooring line lay down on seabed
Gravity-base anchor	Floating crane vessel with DP2	AHTS
Driven pile	Floating crane vessel with DP2	AHTS
Drilled pile	Floating crane vessel with DP2	AHTS
Drag-embedded anchor	AHTS	AHTS
Suction pile	Floating crane vessel with DP2	AHTS

Two barge type floating wind substructures have been built: one of concrete and one of steel. The complete floating wind turbine can be assembled in the fit out port, and set to its operating draft when moored alongside a fit out quay. The turbine can be installed from a land-based crane or a floating sheer leg crane. The turbine is on one side to maximise lift capacity of onshore cranes.

The barge floating offshore wind turbine (FOWT) advantages are at the fit-out quay, namely:

- Shallow draft so minimising dredging requirements
- The turbine is on one side so crane operations are optimised

The barge FOWT disadvantages during the ocean voyage to the offshore wind farm are:

- Small freeboard
- Higher motions in tow out

The semi submersibles in service have been constructed of

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steel. All of them have the turbine over one column, so that during fit out the capacity of the onshore crane could be maximised. Fig. 1 [14] shows such a steel option with ocean going tug for the tow out, accompanied by escort tugs used to steer the steel semi-submersible.

The semi-submersible FOWT advantages at the fir out quay and ocean voyage to the offshore wind farm are:

- Large 2nd moment of water plane area
- Shallow draft for fit out

On a semi-submersible FOWT, the turbine is preferably on one side or over a column, hence maximises use of onshore crane during fit out. The semi-submersible FOWT disadvantages are:

- High steel weight [15]
- Large plan dimensions

There are five steel spars in service, Fig. 2 [16], with anchor handling tug supply (AHTS) and escort tugs. Eleven concrete spars have also been installed. In addition, there is a spar with submerged ballast pendulum, see Fig. 3 [17].

The Spar FOWT construction and installation advantages are as follows:

- Low centre of gravity, after ballasting,
- A small water plane,

The Spar FOWT has certain disadvantages during installation namely:

- Deep draft, requires deep sheltered water
- Needs solid ballast for intact stability
- Adds water ballast to optimize draft

Fig. 1 Semi-submersible tow [14]

Fig. 2 Steel spar tows [16]

Fig. 3 Submerged ballast spar [17]

Fig. 4 TLP sub-structures in harbour [17]

There are three TLPs currently in service i.e. Project Provence Grande Large, see Fig. 4 [18].

The TLP FOWT advantages are:

- Small area on the seabed
- Small steel weight

The TLP FOWT disadvantages are:

- Low intact stability during tow out requires buoyancy tanks
- Turbine is in the centre
- Installation on tethers is weather restricted
- Drag anchors are not possible
- It may need temporary buoyancy for tow out
- It may need crane vessel to assist offshore

III. CHOOSING VESSELS

The vessel selection design is about incorporating safe design principles in the design, construction and maintenance of workplaces. A number of countries include safe by design requirements in their health and safety legislation. This is to ensure that hazards and risks that may exist in the design are eliminated or controlled at the design stage, as far as reasonably practicable.

The vessel assurance audit provides initial information on the vessels under consideration. Marine operations are assessed in accordance with international standards [19], [20].

Major construction audits provide guidance on the major equipment items and the audit processes that should be followed. Regulatory requirements address a number of aspects including:

- Flag state and classification requirements.
- Minimum manning of vessel

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- Training and competencies.

The main regulatory regime for safe construction [21] uses the following rules:

- SOLAS load line (international conventions)
- Classification society rules
- Flag state rules
- MARPOL (marine pollution)
- MLC 2006 (Maritime Labour Convention)

The design of the FOWT is to be in accordance with classification rules [12]-[15]. The selection of a suitable vessel that is safe and appropriate for the range of intended activities needs to be an established process that takes into account the regulations that govern vessel build, maintenance and operation. The primary purpose of the International Maritime Organization (IMO) is to develop and maintain a comprehensive regulatory framework for shipping which includes safety, environmental issues, and legal concerns, as well as encouraging technical cooperation, maritime security and the efficiency of shipping.

Within territorial waters there are statutory legal requirements on vessel owners and other organisations in control of work to ensure both the health and safety of persons at work and the safety of the vessel. Project developers should therefore take all reasonably practicable steps to ensure that there are adequate management arrangements (vessel and shore based) to ensure the safety of the vessel and the health and safety of the crew, passengers and project workers on the vessel. Therefore, prior to vessel selection there should be a suitability audit or audits of those arrangements to determine if they are adequate.

For the safety of the vessel and crew, the responsible organisation will be the vessel owner, with statutory roles and responsibilities for the vessel Master. The operational safety management system for the vessel should comply with the International Safety Management (ISM) Code.

More dedicated vessels are essential for the future success of the offshore wind market [22]. A global supply chain can help the offshore wind market to flourish.

A detailed assessment [23] of the safety compliance requirements of installation vessel and its crew is as follows:

- National and international regulations
- Classification rules for vessel design,
- Rules for operation
- IMO approval of vessel design approval
- Technical people working on wind turbine
- Requirements for minimum safe manning
- Standards for vessel stability
- Requirement for registration and certification
- The safe use of crew transfer vessels
- Minimum crew berth regulations

As the industry has evolved, a range of vessels has been developed, adapted and utilised and with offshore wind farms moving into deeper waters, a new generation of vessels is coming into operation. The overall concept and holistic view in the selection of vessels, including how vessels work alongside one another, how they operate and dependencies and interdependencies within an emergency situation, is essential.

In addition, other purpose-built vessels are entering the market, some already utilised within the oil and gas industry and others built specifically for the installation of offshore wind farms. There are also new installation methods that are evolving, often previously used in the oil and gas sector such as 'float-over' installation for substations. With larger turbines and a range of substructure designs being used, this will encourage other types and new vessels to enter the industry. For example, installation vessels may increasingly remain on site and the components will be transported to site by transportation (feeder) barges. Costs of hiring vessels are an important element of determining the viability of the floating wind project [24]. Furthermore, with floating wind being typically further offshore, it will require significantly longer export cables that may necessitate larger purpose-built cable lay vessels capable of carrying a full length of cable and the range of lay equipment required.

Dynamic Positioning (DP) has evolved is fitted on many of the intended installation vessels. The definition of DP is:

- Integrated control systems
- Computer control of propulsion and thrusters
- Sensors for position reference
- Measure wind, waves, current and motions

DP enables installation vessels to complete the installation works much more efficiently with less weather downtime. Thus, the DP vessel can then quickly move to the next project.

The range of the vessels includes:

- Tugs
- Transport vessels
- Cargo barge
- Crane vessels
- Cable lay vessels
- Rock dump vessels
- Crew transfer vessels
- Guard vessels

IV. DYNAMIC POSITIONING CONSTRUCTION VESSELS

The following vessels are a selection of the major types currently in use for the construction phase of an offshore wind farm. Whilst the list is intended to be complete it focuses on the major types only and does not seek to reflect all the vessels available.

The use of DP systems for station keeping has become standard for newly built vessels, and an upgrade on older commercial vessels. Station keeping capability is required to maintain the vessel's position during offshore support operations. Station keeping performance is essential not only for safety (e.g. collision, diving operation) but also for operability; therefore, the DP system is considered as one of the most critical systems on board the vessel.

- DP Equipment Class 1 has no redundancy (DP-1): Loss of position may occur in the event of a single fault.
- Equipment Class 2 (DP-2) has single fault redundancy. No loss of position can occur from a single active system fault such as from, a thruster, switchboards, remote controlled valves or generator. A single failure may occur after failure

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of a static component such as a cable, pipeline or manual valve.

- Equipment Class 3 (DP-3): If there are two equipment failures there should be no resultant system failure. There should be no loss of position.

Whilst DP vessels can be used in shallower water their efficiency becomes more significant in water depths in excess of 30 m. Note that DP vessels with deep thrusters below the keel and then close to the seabed may damage the seabed.

There are some advantages to having non-DP vessels, as vessels operating DP will have disadvantages [25], including:

- High initial costs of construction,
- Large fuel usage
- High maintenance costs

V. OFFSHORE TRANSPORT OPTIONS

FOWT towing at sea will be subcontracted service, carried out by specialized companies. A Marine Warranty Surveyor (MWS), working on behalf of the owner's insurer, will be contracted for marine survey work, prior to the departure to check and approve work procedures and towing survey. The configuration for harbour tow is a rigid convoy (tugs in contact with the FOWT). For the ocean tow, there is one large tug towing with another in attendance acting as a back-up if the main tug fails. The FOWT is unmanned during the towing.

It can be expected that for all floating wind types the tow out vessel requirements are:

- Large anchor handling tug supply
- 3 harbour tugs inshore
- 2 escort tugs for the tow route

For a TLP without temporary buoyancy, the following ocean transport option would be suitable:

- Offshore crane vessel with DP
- Crane hook active heave compensated
- 2 escort tugs to assist offshore

Heavy transport vessels are required for the dry tow of the substructure and RNA and tower, from their separate construction shipyards, to the fit-out quay.

Spacer barges are utilised in the floating offshore industry for keeping the substructure away from the quay during fit out namely e.g. for semi submersibles at the fit quay, see Fig. 5 [26], and for Spars during floating construction, see Fig. 6 [27]. These barges range in size and facilities from a 'dumb' barge to more sophisticated barges that can be ballasted and moored and are able to carry a range of deadweight cargo or equipment.

Deck cargo barges, Fig. 7 [28], are utilised extensively in the floating offshore industry for a range of activities, including:

- Transportation of sub units for the substructure
- Transport of anchors from the factory

Ocean going tugs are used to tow the deck cargo barge.

Submersible barges are used for load-out and float-off of substructure, see Fig. 8.

Self-propelled heavy transport vessels (HTV), Fig. 9, which are submersible, are used for load-out, ocean transport and float-off of substructures, which need to go on a long voyage.


Fig. 5 Spacer barge for semi-submersible [26]


Fig. 6 Spacer barges for Spar [16]


Fig. 7 Deck cargo barge alongside SSCV [28]


Fig. 8 Submersible barges [26]

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Fig. 9 Heavy transport vessel float off [16]

Fig. 10 Harbour tug [29]

Fig. 11 Escort tug [29]

Fig. 12 Ocean going tug [29]

Harbour towing, in sheltered waters, is used for manoeuvring of a ship to or from a berth, Fig. 10. Harbour tugs are usually hired locally.

Escort towing, Fig. 11, is a precautionary measure to use tug while navigating in restricted waters to protect the FOWT and harbour or damage to other vessel, if engine or steering failure occurs.

Large tugs, Fig. 12 [29] have been developed for salvage work and can have up to 250 tonnes bollard pull. Ocean going tugs may be hired from any location.

Anchor Handling Tug Supply (AHTS) vessels, Fig. 13 [30] are mainly built to handle anchors for offshore rigs, tow them to location, and use them to secure the rigs in place. Some large AHTS have bollard pull of about 300 tonnes.

AHTS, vessels are designed for towing and offshore anchor handling. To fulfil these functions, AHTS have large engines and hence high bollard pull, plus winches that can handle the ropes and chains. AHTS can quickly release anchors, which are operated remotely from the navigation bridge.

For the sub structures which use centenary moorings, (not TLPs) a large anchor handling tug supply (AHTS) vessel is required to pre lay drag anchors for centenary mooring. The AHTS also assists crane vessels for the pre installation of suction piles, driven piles and drilled piles, where soil conditions show they are required. For a TLP, tendon moorings are installed after their arrival at the offshore location and AHTS are required to assist in connecting the tethers.

Even if AHTS-vessels [31] are built for anchor-handling and towing, they can also do the following:

- ROV (remotely operated vehicle) operations,
- Rescue and safety of people and vessels
- Supply between port and offshore wind farm

Fig. 13 AHTS 250t bollard pull [33]

There are new generation purpose-built wind turbine installation vessels (WTIV) specifically designed for the requirements of fixed offshore wind farm projects, Fig. 14 [32]. They will typically be self-propelled and able to operate on DP whilst moving to location and when relocating between work sites. They will then 'jack up' to provide the required stable work platform. It is very unlikely that a WTIV would be used offshore with a FOWT as their current water depth limit is about 60 m, with a few new ones being built to operate in 80 m water depth, thus floating wind sites are beyond the capability of

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WTIVs. However, WTIVs may have a role to play in carrying out work in a fit out quay for FOWT, where it is not possible to deploy a large onshore crane.

Fig. 14 Wind turbine installation vessels [32]

Fig. 15 Sheer leg cranes [29]

Fig. 16 Monohull Heavy lift crane vessel [28]

Fig. 17 SSCV [33]

Fig. 18 Dive support vessel [29]

Heavy lift crane vessel types are large with different characteristics:

- Sheer legs, for sheltered locations, Fig. 15
- Mono-hulls 4,000 t and DP2, Fig. 16.
- SSCV with DP, Fig. 17

DP diving support vessel are specialised vessels that offer a wide range of capabilities including a built-in diving system that offers both air, surface supplied diving operations, through to bell deployed fully integrated saturation systems, Fig. 18. Working alongside are typically remote operated vehicles (ROV) and work remote operated vehicles (WROV). Both the diving bells and ROV are often deployed through a central moon pool. DP support vessels are large, typically around 100 m in length with a beam of 20 m, with a project crane capacity of approximately 120 t. They are normally fitted with an integrated saturation diving system, together with an air diving capability and possibly both ROVs and WROVs. These vessels are relatively high cost but can offer a versatile stand-alone option for construction projects with sufficient deck space to accommodate cable laying, stabilisation and heavy lifting capabilities to carry out a variety of tasks in addition to subsea requirements.

There are small anchored vessels that have been in common use in shallower waters. They are capable of carrying out surface supplied air diving operations to a depth of 50 m. These small dive support vessels are typically 30-50 m in length with a beam of 6-12 m. Diver deployment is usually over the side or stern of the vessel. They generally have limited lifting capability with a crane capacity of up to approximately 30t.

Particular consideration should be given to the following limitations:

- Limiting weather conditions
- Safety limit air diving to 30 m depth

- Productivity air diving limited amount of time

Air diving is not envisaged at the offshore location. However, at the fit out, quay air diving may be used with air lines (not scuba diving) to check the seabed where the FOWT substructure is to be moored.

Construction support vessel, Fig. 19, is similar to a Dive support vessel. However, it does not necessarily require the same level of DP redundancy. They will often provide a different range of services, including supply vessel function and medical support facilities. There is a wide range of support services these vessels can provide, which could include:

- Safety standby vessels
- Supply vessels/crew change
- Construction support
- Anchor handling tug supply (AHTS)

Fig. 19 Construction support vessel [29]

Fig. 20 Service operation vessel [29]

Service operation vessels, Fig. 20, are needed in the final stages of commissioning and light offshore maintenance, [33]-[39].

The early offshore wind farms were close to shore and in a more sheltered 'near shore' environment and consequently simple barges were utilised with carousels and cable lay equipment installed as required.

As the floating wind farms have moved further offshore and the cable routes for the export cables have become more exposed, more sophisticated vessels are required, Fig. 21. The export cable lengths may be in excess of 100 km and larger purpose-built cable lay vessels are required with integrated carousels to be able to carry these much longer lengths of cable safely. The new generation of cable lay vessels is multi-purpose; they are able to lay, trench and survey the cable from an integrated system; with a DP-2 system, these vessels are able to lay heavy and long export cables.

Fig. 21 Cable lay vessel [29]

Fig. 22 Rock dumping vessel [29]

Fig. 23 Trencher ROV [29]

Rock dump vessels are used to deliver solid ballast for Spars, Fig. 22. Rock dump vessels are increasingly used within the offshore renewable industry for a range of activities, including cable protection, with the accuracy that a rock dump can now be deployed, this is an efficient option. They operate typically on DP2 and they are able to accurately dump up to 3,000 tons/hour through a flexible fall pipe system.

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The export cable needs to be buried, using a trencher ROV, see Fig. 23 and possibly rock dumping. Initial survey and post installation survey may include an observation ROV, see Fig. 24. It is expected that work class ROVs are required during mooring connection and dynamic cable deployment, see Fig. 25.

Fig. 24 Observation class ROV [29]

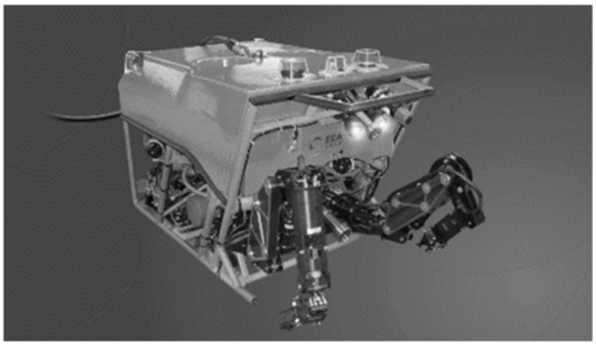

Fig. 25 Work class ROV [29]

Fig. 26 Autonomous drones [40]

Fig. 26 shows an underwater drone, i.e. Autonomous Underwater Vehicle (AUV), [40], which can operate in water depths of up 1,300 metres. They also provide survey data over big areas. Fig. 27 shows typical AUVs as used in deep water surveys for potential locations for floating offshore wind turbines.

Aerial autonomous robots on a floating offshore wind platform for inspection and monitoring operations. Specifically, using autonomous vehicles can offer visual inspections and assessments of the structure.

General cargo ships [41] are used to deliver components to the fit out yard:

- Towers, Fig. 27
- Hubs, Fig. 28
- Blades, Fig. 29

Fig. 27 Cargo ship with tower units [41]

Fig. 28 Geared heavy transport vessel [41]

Fig. 29 Heavy transport vessels with blades [41]

VI. FUTURE VESSELS

For offshore crane vessels to be able to carry out construction work on TLP type FOWTs or offshore maintenance work active heave compensation units will be required on the crane hooks [42]. Research is ongoing to assess the capability of floating crane vessels to install the tower, generator hub and blades offshore [43].

The base case assumption for floating wind projects is for large anchor handlers and subsea construction vessels to be deployed to pre-install mooring systems, to tow the structures and to hook-up the floating turbines. To reflect the unique challenges of floating wind, a new generation of vessel designs is emerging. The economics of such a vessel are challenging as material and construction.

VII. RESULTS

The installation vessels have different weather restrictions for their operations, transit and waiting on weather conditions. This is shown in tables:

- Table III: Ocean transport to the fit out quay
- Table IV: Activity at the fit out quay
- Table V: Completed structure tow offshore
- Table VI: Offshore crane vessel
- Table VII: Offshore installation

The significant wave height (Hs) values are the maximum significant wave height. The peak wave period (Tp) values are the maximum allowable associated wave period. The wind speed is the maximum 1 minute return value at 10m above sea level. Typical operational restrictions are based on:

- Personnel transfer
- Motion limits on equipment
- Use of cranes where applicable

Designs are emerging for a new generation of vessel dedicated for floating wind mooring pre-lay and dynamic cable hook-up. Common features of these new generation anchor handlers are:

- High bollard pull.
- Large active heave compensated subsea cranes.
- Multiple large winch drums
- Large chain lockers
- Big stern decks to carry large anchors
- Work Class ROVs and a moon-pool
- Under deck space for equipment storage
- Flexibility to support tensioning options.
- Fitting of an anchor handling frame.
- Low or zero emissions operations

TABLE III
OCEAN VOYAGE TO FIT OUT QUAY

Vessel	Draft m	Hs Wave height m	Tp Wave period sec	Wind speed m/s
Unrestricted Operation				
HTV	8 to 12	7	12	30
Cargo ship	7 to 9	5	10	25
Harbour Tug	5 to 6	1.5	9	10

TABLE IV
ACTIVITY AT THE FIT OUT QUAY

Activity	Hs Wave height m	Tp Wave period sec	Wind speed m/s
Lift tower	0.75	8	10
Lift nacelle/hub	0.50	8	8
Lift a blade`	0.40	7	7

TABLE V
COMPLETED STRUCTURE TOW OFFSHORE

Vessel	Draft m	Hs Wave height m	Tp Wave period sec	Wind Speed m/s
Weather Restricted Operation				
Semi	10 to 15	2.75	10	15.0
Spar	70 to 90	3.00	10	15.0
Barge	8 to 12	2.25	9	10.0
TLP	9 to 13	1.50	9	10.0

TABLE VI
OFFSHORE CRANE VESSEL

Vessel	Use	Hs Wave height m	Tp Wave period sec	Wind speed m
Weather Restricted Operation				
SSCV	Crane	2.0	12	12.5
Mono-hull	Crane	1.8	10	10.0
Sheer leg	Crane	0.8	7	10.0

TABLE VII
OFFSHORE INSTALLATION

Vessel	Use	Hs Wave height m	Tp Wave period sec	Wind speed m/s
Weather Restricted Operation				
Survey vessels		2.0	11	12.5
ROV		2.0	11	12.5
Air Drone				10.0
Cable layer	Export cable	2.0	11	12.5
Cable layer	Dynamic cable	1.7	10	10.0
SOV	crew transfer	2.0	10	12.5

VIII. DISCUSSION

Engineering document review of installation and approval related to a wide range of temporary phase marine operations and land transportation. These include:

- Offshore location analysis
- Approval including cable installation
- Approval including mooring installation.
- Load-out method review
- Transportation analysis
- Offshore Installation review
- Cable lay procedure review

Commercial floating wind farms are a relatively immature technology today, but will begin installation at scale by 2030.

Vessel characteristics familiar to the offshore industry are also be required to support floating wind development. Demand for large anchor handlers and subsea construction vessels will grow. Vessel shortages are likely in the longer-term.

There are a few large anchor handlers active today that meet the minimum requirement for floating wind farms. However, despite being suitable for floating wind, the majority of the current fleet lack one or more of the technical characteristics required to satisfy all technical needs.

The market conditions are in place for interest in new building activity. However, commercial challenges remain for both traditional vessels as well as for new generation floating wind installation anchor handlers.

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ABBREVIATIONS

The following abbreviations are used:

AHTS	Anchor Handling Tug Supply
FOWT	Floating Offshore Wind Turbine
GW	Gigawatt
HTV	Heavy transport vessel
MW	Megawatt
SPMT	Self-propelled modular transporter
SSCV	Semi-submersible crane vessel
TLP	Tension leg platform

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