Assessment of vessels required to serve floating offshore wind in the Celtic Sea.

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PREFACE

ORE Catapult is the UK's flagship technology innovation and research centre for offshore wind, wave and tidal energy. ORE Catapult is playing a leading role in the delivery of the offshore wind sector deal (partnership between UK Government and offshore wind industry), including the Offshore Wind Growth Partnership, focused on enhancing the competitiveness of UK supply chain companies for supplying into the domestic and export markets. ORE Catapult has developed and actively maintains technology roadmaps to co-ordinate R&D funding and activity across agreed industry priorities. This provides ORE Catapult with a unique broad and objective perspective on the UK and global offshore wind industry.

We are an independent, not-for-profit business that exists to accelerate the development of offshore wind, wave and tidal technologies. Our team of over 300 people has extensive technical and research capabilities, industry experience and track record.

Through our world-class testing and research programmes, we work for industry, academia and government to improve technology reliability and enhance knowledge, directly impacting upon the cost of offshore renewable energy. We organise our activities around key areas for future innovation and developing local Centres of Excellence that will support the transformation of our coastal communities. These areas include:

- Floating wind
- Marine energy
- Testing and demonstration
- Operations and maintenance

These Centres of Excellence champion innovation in robotics, autonomous systems, big data and artificial intelligence, balance of plant – especially foundations – and next-generation technologies.

To date, we have supported more than 800 SMEs, contributed to 328 active and completed research projects, and supported over 180 companies in their product development.

CONTENTS

NOMENCLATURE

FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
ORE	Offshore Renewable Energy
O&M	Operations and Maintenance
TLP	Tension Leg Platform
PoMH	Port of Milford Haven
SOV	Service Operation Vessel
CTV	Crew Transfer Vessel
AHV	Anchor Handling Vessel
AHTS	Anchor Handling Tug Supply
CLV	Cable Lay Vessel
OCV	Offshore Construction Vessel

1 INTRODUCTION TO HYPR: HYDROGEN PORT RE-FUELLING PROJECT

As Wales seeks to de-carbonise and meet future green energy targets, the Welsh Government have sought to explore possibilities in utilising hydrogen for various uses. The HyPR project seeks to explore the utilisation of hydrogen for use as a marine fuel for powering the Floating Offshore Wind (FOW) vessel fleet in the Celtic Sea in the short, medium and long term. The Offshore Renewable Energy (ORE) Catapult's involvement in the project looks to identify the vessel types and quantities required for servicing FOW in the Celtic Sea with a view to estimating the capacity of a hydrogen facility required at the Port of Milford Haven (PoMH) to service the FOW vessel fleet.

This report outlines work carried out in identifying the vessels required for FOW and in estimating the number of vessels that will be required for FOW development in the Celtic Sea.

2 INTRODUCTION TO THE CELTIC SEA

The UK government has identified floating offshore wind (FOW) as an important part of the path to Net Zero, as well as a significant opportunity for the UK economy. FOW is a technology that, while at an earlier stage of development than fixed-bottom, is seen by the Government as a crucial part of the UK's Net Zero target and its energy security strategy. In its Net Zero Strategy, the Government also notes the jobs and economic opportunities that could be unlocked by putting the UK at the forefront of this new technology.

ORE Catapult has identified the Celtic Sea as one of two favourable areas in the U.K. that is suitable for large scale FOW deployment. The new industry could utilise existing expertise and port infrastructure from ship building, and the existing marine industry in the Celtic Sea region with many key skillsets needed for FOW already available in the region.

The Crown Estate has set ambitious targets for development of FOW in the Celtic Sea of 4GW deployed by 2035 and a further 20GW out to 2050. This is a significant part of the UK requirement for at least 75GW of offshore wind energy by 2050. The Crown Estate's initial seabed leasing exercise which kicks off in 2023, aims to achieve 4GW deployment of FOW in the Celtic Sea region and is likely to take place between 2027 and 2035, with 1GW deployed per year in the later years. Thereafter the pace of deployment (1GW per year) continues until 20GW of floating wind has been deployed in the Celtic Sea out to 2050.

ORE Catapult's initial constraint mapping work identified over 100GW of potential energy in the Celtic Sea. Grid constraints in Wales, the South West, and beyond suggest that not all this energy could be brought ashore as electrical energy. Many stakeholders are therefore considering the merits of using FOW platforms to host electrolysers to generate hydrogen that could then be brought ashore to storage facilities to supply hydrogen for applications such as marine vessels, public transport, industrial users, and to mix into the onshore gas network.

Throughout the lifecycle of an offshore wind farm, there is a heavy dependency on the use of various vessels, from pre-construction survey vessels, to heavy lifting vessels during construction, to Operations and Maintenance (O&M) vessels during the operational phase of the wind farm. For example, based on vessel support assigned to far offshore fixed bottom wind farms in the North Sea, the requirement for Celtic Sea FOW O&M is likely to be at least one Service Operations Vessel per 1GW installed. ORE Catapult analysis of the decarbonisation trajectory of offshore vessels suggest that the transition away from fossil fuels to hybrid and then hydrogen will be a key feature of Celtic Sea operations and maintenance.

3 VESSEL REQUIREMENT OVERVIEW

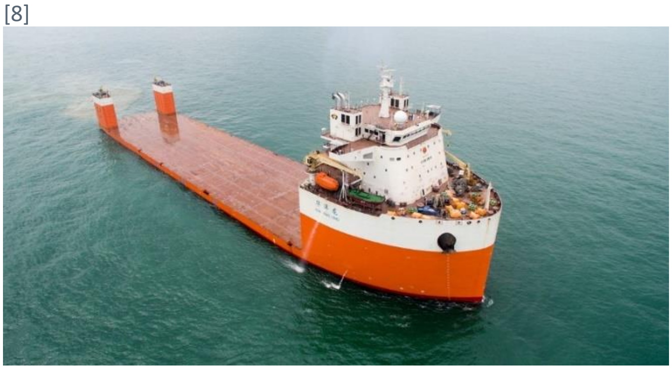
3.1 Common Vessel Types

A variety of different vessels are required for FOW, with the specific vessel requirements varying with the type of FOW substructure utilised and the construction approach taken (i.e. assembly at quayside or offshore). A list of the main vessel categories required to deploy, operate and maintain a typical FOW farm are shown in Table 1. It should be noted that the vessel types presented are categories of vessel and within each category, sub categories exist of varying vessel size, capacity and capability. For example, tug vessels of different sizes are required for a tow to site operation of an assembled FOWT. Typically a tug with a bollard pull capacity of greater than 200 tonnes is used to tow the assembly, with two other tugs with a bollard pull capacity of around 50 – 100 tonnes used to stabilise the structure during the same towing operation. These differing tug types will have differing fuel consumptions associated with them, and this variance will also occur with the other vessel types listed.

Table 1 Main vessel types required for FOWT deployment

Vessel	Typical Use	Indicative Picture
Survey Vessel	Geophysical, geotechnical, met-ocean, marine life surveys.	[1] 
Cable Lay Vessel (CLV)	Cable installation (array and export). Cable repair and removal.	[2] 

Anchor Handling Vessel (AHV), Anchor Handling Tug Vessel (AHTV)	Installation, repair, anchor and mooring hook up and removal.	[3] 
Anchor Handling Supply Vessel (AHSV)	Same operations as AHV. Larger capacity for chain, rope and anchors and multiple winches.	[4] 
Tug	Moving substructure or complete FOWT assembly to and around site. Tow of offshore storage and staging facilities.	[5] 

Offshore Construction Vessel (OCV)	Mooring line, anchor and cable installation, burial, repair and removal.	[6] 
Heavy Lift Cargo Vessel	Transport of heavy components. Offshore lifting and installation of turbine tower, nacelle and rotor. Offshore substation installation.	[7] 
Semi-submersible Vessel	Transport and handling of major components. Transport and installation of offshore substation.	[8] 
Service Operation Vessel (SOV)	O&M activities. Minor turbine repairs, transfer of crew to site, ROV surveys.	[9] 

3.2 FOW Substructures

3.2.1 Substructure Types

With the rapid development of FOW technologies over the past decade, floating substructure designs have been devised and developed, each taking different approaches to achieve the installations of FOW units at sea. With these different deployment philosophies, the vessel requirements for different designs can vary considerably from others. However, most FOW substructure designs fall into four general categories, with each broadly following similar construction methodologies and philosophies within their category. The four main substructure types are the semi-submersible, barge, spar-buoy and Tension Leg Platform (TLP). Each type, with its general construction approach, is discussed below.

Semi-Submersible

With semi-submersible substructures, typically three or four buoyant columns are connected using trusses and/or pontoons. Ballast is used to stabilise the structure and the wind turbine unit is placed on top of the structure, either above one of the buoyant columns or at the centre of the structure. Ballast can be provided in different forms, with some designs utilising concrete and others using steel. They are suitable for water depths greater than 40 metres and can be used with a wide range of mooring and anchoring configurations.

The fabrication of semi-submersible substructures takes place onshore, before the units are lifted into the water at the quayside. Following this, a variety of options exist as to how the remainder of the construction process takes place. If port depth allows, the turbine can be lifted onto the substructure at the quayside, before the entire assembly is towed out to sea, moored, ballasted and connected to its array cable. This approach is possible with semi-submersible and barge type substructures due to their inherent stability, allowing safe towing out to site without additional stability required from the towing vessel. This represents the lowest cost deployment option for the semi-submersible as no expensive heavy lift offshore vessels are required. However, if water depth at the port is not able to accommodate the substructure with the weight of the turbine added, the substructure is towed out to sea and construction takes place at sea using heavy lift or jack-up vessels.

Given the extensive use of semi-submersible platforms in the Oil and Gas industry, these substructures are considered relatively mature and have been adopted as a popular concept in the FOW industry. Figure 1 shows an example of a typical semi-submersible type platform with three buoyant columns.

Figure 1 Semi-submersible floating substructure [10]

Barge

With a single hull, barge substructures have a large surface area in contact with the water, providing stability with lower overall dimensions than those of an equivalent semi-submersible substructure. However, the large surface area of a barge can make these structures more susceptible to wave loading than other substructure types. Similarly to semi-submersibles, barges are suitable for water depths greater than 40 metres and follow a very similar construction approach, with fabrication taking place onshore and assembly being done in the port or out at sea. Ballasting is then carried out at the FOW site, if it has not already taken place at the port. As a result of these similarities, vessel requirements for barge type substructures are closely comparable to those for semi-submersibles.

A barge floating substructure design produced by BW Ideol is shown in Figure 2.

Figure 2 Barge floating substructure [11]

Spar Buoy

Spar substructures generally consist of a single long cylinder which is heavily ballasted at its lower end. The upper end protrudes above the water line and the turbine unit is mounted to the top of it. The low centre of gravity produced by the long structure with a heavy mass at its end produces a very stable structure. Due to their large draughts, spars require water depths typically above 100 metres. A range of anchoring and mooring configurations are suited to spar substructures.

With their deep draught, the assembly and ballasting of spar substructures must take place in deep waters. The structures are fabricated onshore before being placed into the water in a horizontal orientation at the port. In this orientation, they are towed out to deep waters before being ballasted and upended. The turbine unit is then lifted into place by a heavy lift vessel or jack-up vessel. The need for offshore construction in deep waters to deploy spar substructure FOWTs results in high vessel costs due to the high prices associated with hiring large heavy lift vessels. Figure 3 shows a typical spar floating substructure concept with the deep draught providing stability to the turbine shown.

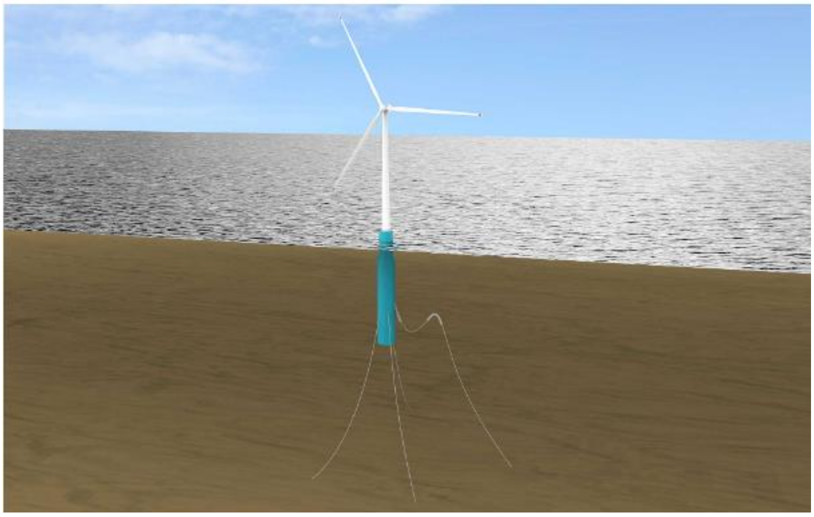


Figure 3 Spar floating substructure example [12]

Tension Leg Platform

Stability is achieved through different means with TLPs when compared to the other three substructure typologies. A buoyant platform is used, on which the turbine unit is mounted. The buoyancy of the platform is counteracted by taught tendons which run from the platform to a large anchoring installation on the seabed, leading to a platform that is held firmly in place through tendon tension. This type of substructure has the highest level of stability in rough sea conditions when compared to the other typologies and is typically suitable for water depths greater than 80 metres.

Similarly to semi-submersible and barge type substructures, TLPs are fabricated onshore and lifted into the water in the port. They can be assembled in port or at sea, with the construction approach taken depending on the stability of the substructure design prior to the taught lines being attached. Some designs offer a stable enough platform for the turbine to be lifted onto the substructure in the port, before being towed out to sea. However, some designs do not have high enough stability to achieve this portside assembly and must be secured to their taught mooring lines offshore before the turbine unit can be mounted onto the substructure. A classic TLP design concept is shown in Figure 4, with the substructure shown to be stationary in the water column, held in place by the taught tendons attached to the seabed anchor.

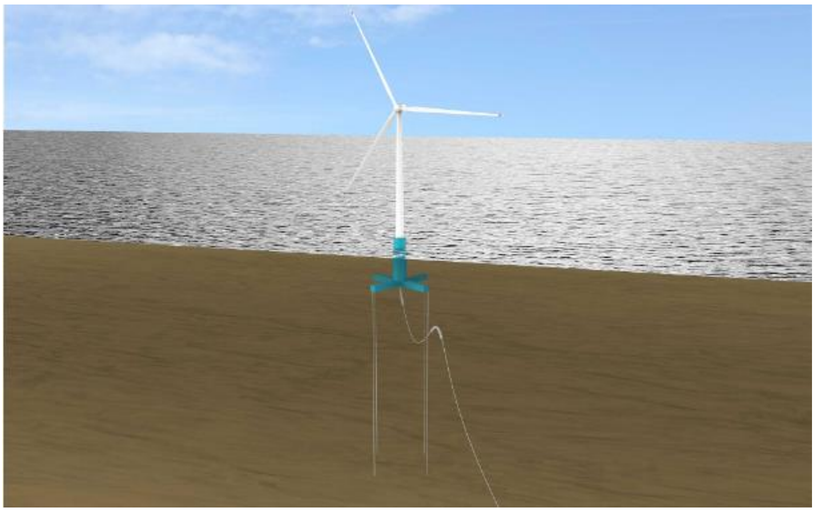


Figure 4 Tension Leg Platform substructure example [12]

3.2.2 Substructure Type Selection for the PoMH and the Celtic Sea

With the tendering process for the Project Development Areas in the Celtic Sea due to launch in mid-2023, no detailed site design information is available from developers at the time of this report. As such, uncertainty exists as to what substructure types, construction methods and vessel requirements will be used in the build out of these sites. See Section 3.3.3 for assumptions made on substructure typologies adopted in the Celtic Sea, feeding into the vessel demand predictions made.

The quayside and channel depths at the PoMH will likely influence the substructure types selected, with the port having depths of around 26 metres in its deeper West channel, reducing to 18 metres in its South facing estuary [13]. These operational depths will not be deep enough for some substructure types with deep draughts, imposing limitations on what substructure designs can access the port.

3.3 Vessel Time Estimation Methodology

3.3.1 Approach to Vessel Time Estimation

Various uncertainties exist in estimating the time required for each vessel during the development, construction and O&M phases of a wind farm. For example, the time required for towing and hook-up operations varies depending not only on the substructure typology used, but also the detailed design of the technology selected. Site characteristics and ocean conditions affect the time taken to complete surveys and lay cables. Construction approaches and the use of staging techniques can cause large differences in vessel transit mileages between different developers. Many other variables not discussed in this report also exist.

Several assumptions were made in the approach used in this report to estimate vessel time requirements as the many variables affecting the time and fuel used for each operation could not all be taken into account. As a result, the time estimates made are a best estimate for the purpose of port planning, however may not be exact and should be revisited as the development matures.

3.3.2 Method

To estimate the vessel demand across the Celtic Sea FOW market, the vessel time required for various vessel types across the key FOW farm pre-construction, construction and O&M activities was estimated per single FOWT unit. These estimates were made using a range of information which is available to OREC, from in-house accumulated knowledge to interactions with developers and vessel operators. The time estimates were then multiplied by predictions of the number of FOWT units to be deployed in 5 year periods up to 2050, producing an overall vessel time demand for 5 year periods up to 2050 for each vessel type. The details of these calculations and the assumptions made are discussed below.

OREC Market Projections

ORE Catapult regularly produce market projections for cumulative installed capacity of FOW for the UK. The projections produced for 2020 – 2040 were utilised in this analysis. OREC's market projections can be seen in Figure 5. Shown are three offshore wind deployment scenarios, estimating scenarios where a cumulative 75 GW, 100 GW and 150 GW of offshore wind capacity could be installed. Of each of these scenarios, ORE Catapult's Floating Offshore Wind Centre of Excellence report "Strategic Development of FOW Supply Chain and Infrastructure – Deployment Scenarios" approximates that 29 GW, 49 GW and 95 GW of the totals could be provided by cumulative FOW deployment [14].

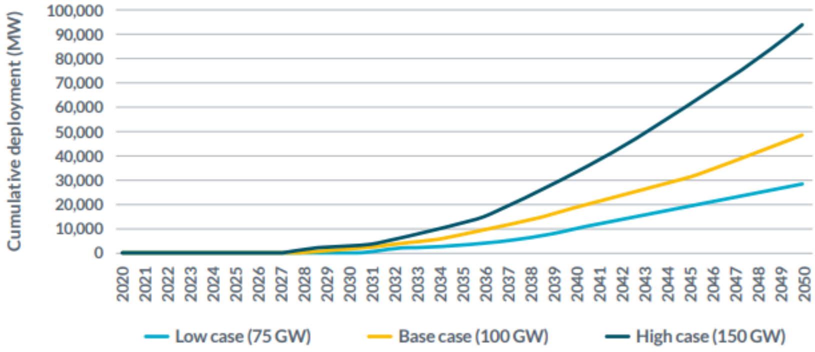


Figure 5 Cumulative Floating Offshore Wind Deployment in the UK between 2020-2050 [15]

Split into 5-year periods and tabulated, FOW deployment scenarios are shown in Figure 6, with the majority (85-90%) of deployment being estimated to take place between 2036 and 2050.

FOW Deployment Scenario (GW)	to 2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
29	78	396	2,415	7,208	9,500	9,403
49	78	1,896	5,490	10,980	13,212	17,343
95	78	2,396	9,590	20,980	28,252	33,704

Figure 6 FOW deployment to 2050 in 5-year periods [15]

The base case scenario of 49GW was used in estimating vessel requirements as it is currently considered the most probable trajectory for the FOW sector to follow. Of this 49GW of total deployment, around 7.5GW is estimated to be deployed in the UK before the end of 2035.

Offshore wind farm construction currently takes around 7-11 years, with 3-5 years dedicated to the development phase, followed by 1-3 years for pre-construction and 2-4 for construction [16]. With this considered, it is unlikely that the pre-construction phase for a site would be completed before

2025. Current estimates for the Celtic Sea, based on existing facility capacities, suggest that around 40 FOWT units could be installed between 2025 and 2030, equating to an installed capacity of around 700MW annually [14]. Following this, the Crown Estate aims to support the installation of further FOW capacity, adding up to a total of 4GW of capacity installed in the Celtic Sea by 2035.

Following 2035, the Celtic Sea has the economic potential to accommodate an additional 20GW of FOW capacity by 2045 [17]. If the Celtic Sea's 4GW of deployment by 2035 is taken as a proportion of the overall 7.5GW UK wide predicted deployment by 2035 and proportion is applied to the overall UK wide predicted deployment of 49GW by 2050, a proportional total of 26GW is calculated for FOW in the Celtic Sea. Thus, as a proportion of the overall FOW installed capacity in the UK by 2050, the goal of 24GW in the Celtic Sea by 2050 is proportionally broadly in line with the shorter term deployment prediction of 4GW by 2035. Therefore, in the analysis presented in this report, vessel requirements are calculated on the assumption that 4GW of FOW capacity will be installed by 2035, with a further 20GW being installed by 2050 in the Celtic Sea. The capacity installed in each 5 year window between 2025 and 2050 follows the same proportional deployment predictions as made by OREC for UK wide FOW deployment, as shown in Figure 6, with 85-90% of the overall capacity being installed between 2036 and 2050.

FOWT Unit Size

Analysis carried out by ORE Catapult indicates that the next UK FOW projects installed in 2027 and 2028 will likely utilise 14-15MW units, which is in line with current developer announcements and IEA's new 15MW reference turbine [18]. Going forward, turbine ratings for future ScotWind projects in the early 2030s are expected to increase to 17-20MW [14]. Taking into account these predictions, it was assumed that when estimating the number of FOWT units to be deployed, any units deployed up to 2030 would have ratings of 14-15MW, with units deployed from 2031 onwards having ratings of 17-20MW. Sizes larger than 20MW, although possible in future, were not considered as too little information is available to accurately predict when these may be utilised.

Installation Capacity of Celtic Sea Areas

At the time of this report, the capacity of FOW to be installed at each Crown Estate leased site in the upcoming leasing round is unclear as the tendering process has not yet been initiated. Furthermore, no visibility exists for future leasing areas beyond the 4GW of capacity planned up to 2035. As a result, assumptions of the FOW capacity available for each Project Development Area (PDA) must be made to allow vessel fleet calculations to take place. As a simple approach, it was assumed that the installed capacity will be evenly spread by area available across all of the PDAs. The PDAs outlined by the crown estate are shown in Figure 7.

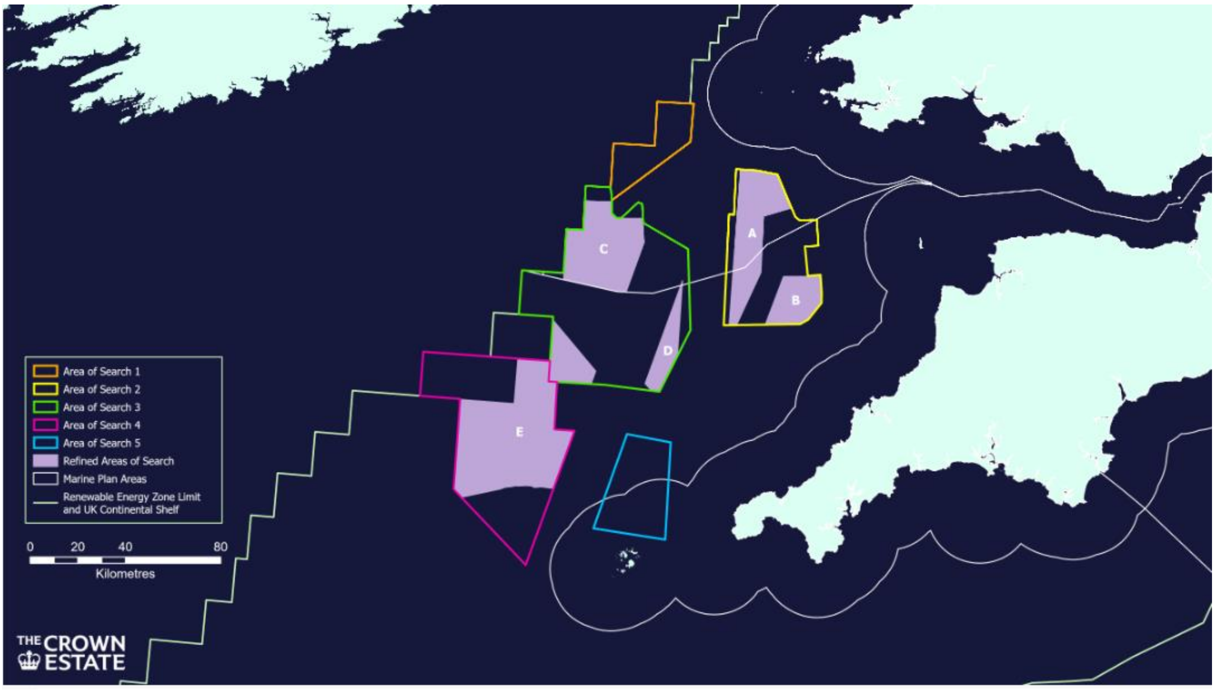


Figure 7 Crown Estate Celtic Sea Project Development Areas [19]

Shown in Table 2 are the sizes of the different PDAs, along with assumed total power capacities of each area. These capacities were calculated by taking the proportional geographical sizes of each area and multiplying them by the overall 24GW of capacity to produce proportional capacities for each area. The distance from each site to the PoMH is also shown.

Table 2 Area, distance to port and assumed total capacity for each Crown Estate Celtic Sea PDA

Refined Area of Search	Size of Area (km^2)	Assumed Total Capacity (GW)	Distance to PoMH (km)
A	810	4.2	55
B	371	1,9	85
C	953	4.9	120
D	281	1.5	110
E	2220	11.5	180

Capacity Installation Estimation

Using OREC's FOW deployment to 2050 in 5-year periods market projections, similar projections were made looking specifically at FOW deployment in 5-year periods for the Celtic Sea. Taking the Celtic Sea's proportion of 24GW of the overall UK wide 49GW of FOW deployment by 2050, the same proportions were applied to predicting deployment capacities in the 5-year periods between 2035 and 2050. Using the 4C Offshore estimates of partial and fully commissioned dates, it was assumed the no capacity would be deployed up to 2025, with 780MW of capacity being deployed between 2026 and 2031. With limited visibility of project deployment pipeline beyond this, a further 3220MW was estimated for deployment from 2031 to 2035 to meet the 4GW deployment target.

Predictions of FOW capacity to be installed in 5-year periods up to 2050 in the Celtic Sea using the described methodology are shown in Table 3.

Table 3 Celtic Sea predicted FOW capacity deployment in 5-year periods

Period	Up to 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 - 2050	Total (GW)
Capacity Installed in Period (MW)	0	780	3220	5034	6471	8495	**24**

Cumulative installed capacity estimates were also calculated and are shown in Table 4.

Table 4 Cumulative Celtic Sea predicted FOW capacity deployment in 5-year periods

Period	Up to 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 – 2050
Cumulative Capacity Installed (MW)	0	780	4000	9034	15505	24000

FOWT Unit Quantity Estimation

Using the FOWT unit size predictions discussed previously, calculations were performed to estimate the number of FOWT units to be installed to match the installed capacity estimates. Estimates for the number of units installed for each 5-year period up to 2050 in the Celtic Sea are presented in Table 5.

Table 5 Estimated number of FOWT units to be deployed in 5 year periods

Period	Up to 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 – 2050	Total
Number of FOWTs Installed in Period	0	58	239	272	350	459	1377

Table 6 presents the estimated total number of FOWT units to be installed per 5-year period for each PDA in the Celtic Sea. Numbers per area were calculated using the proportional area approach described previously.

Table 6 Estimated number of FOWT units to be deployed per PDA in 5 year periods

Refined Area of Search	Up to 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 – 2050	Total
A	0	10	42	48	61	80	241
B	0	5	19	22	28	37	110
C	0	12	49	56	72	94	283
D	0	4	14	16	21	28	84
E	0	28	114	130	168	220	660

Predictions of the cumulative number of FOWT units installed in the Celtic Sea are shown in Table 7. These numbers were used in calculating vessel demand during the O&M phase.

Table 7 Cumulative estimated number of FOWT units to be deployed in 5 year periods

Period	Up to 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 – 2050
Number of FOWTs Installed Cumulatively	0	58	296	568	918	1377

Table 8 presents the cumulative number of FOWT units to be installed per 5-year period for each PDA in the Celtic Sea.

Table 8 Cumulative estimated number of FOWT units to be deployed per PDA in 5 year periods

Refined Area of Search	Up to 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 – 2045	2046 – 2050
A	0	10	52	99	160	241
B	0	5	24	45	73	110
C	0	12	61	117	189	283
D	0	4	18	34	56	84
E	0	28	142	272	440	660

Estimation of Vessel Time for Each Operation

A matrix was constructed outlining the main vessel tasks involved in the pre-construction, construction and O&M of a FOW farm with the vessels required for each task and the estimated time required by each vessel per FOWT unit to accomplish each operation. The operation vs vessel time matrix produced is shown in Appendix 1 .

For the majority of the tasks outlined in the matrix, estimating vessel time per FOWT unit was the most appropriate metric. For some, however, such as export cable laying operations, a more appropriate metric would be vessel time per kilometre of cable laid. However, due to a lack of availability of information on the time required to carry out cable laying operations per kilometre of cable laid, it was decided that the vessel time required per FOWT unit metric would instead be used. The use of this metric will introduce some inaccuracy into the overall time estimations, however, it also simplifies the overall estimation process and will provide a broad estimate of vessel time required for these operations.

A number of other vessel and lifting equipment assets are involved in the construction of FOW farms, such as quayside heavy lift cranes, dumb barges and other non self-propelled vessels. However, with the focus of this study being on the fuel demand of FOW vessels, these other assets were not included in any calculations.

Calculation of Annual Vessel Time

For each 5-year period, the vessel hours per FOWT unit were multiplied by the predicted number of FOWT units to be deployed to produce estimates of overall vessel time required for each vessel for each of the 5-year periods. The calculated vessel hours for each phase are presented in Sections 4.2, 5.2 and 6.2.

In the pre-construction and construction phases, the installed number of FOWTs per 5-year period was used to calculate the vessel time required for each vessel. However, for the O&M phase the cumulative installed number of FOWTs was used to estimate the vessel time required as, with O&M being an ongoing activity, it is dependent on the number of turbines already deployed rather than the number under construction.

3.3.3 Assumptions

Quayside Assembly Philosophy

As discussed previously, different substructure types require differing approaches to the assembly of the FOWT units, with some favouring quayside assembly and other offshore assembly. However, with the current trend of OWTs increasing in size year on year, and developers favouring these larger units, the challenge of offshore assembly in deep waters will impose increasing practical restrictions. For Celtic Sea FOW sites, seabed depths are too great to allow jack-up barges to utilise the seabed for stability. Therefore, lifting operations must take place using HLVs and semi-submersible vessels. With the high costs associated with these vessels and the increasing challenge of lifting FOW units which are rapidly increasing in size and weight, dependency on these offshore lifting operations is likely to be avoided more and more. As such, in this report it has been assumed that Celtic Sea FOW developers will opt for assembly of the FOWT units onto the substructure in the port. The PoMH has sufficient depth to allow the assembly of most semi-submersible and barge type units at the quayside, with depths of around 26 metres in its deeper West Channel, reducing to around 18 metres in its South facing estuary [13].

FOW Innovations

The vessel requirement estimates presented in this report are based on currently employed wind farm construction methodologies. However, with the continual change in the FOW sector, due to the introduction of innovative new technologies and strategies, these construction methods may change in the medium to long term future. Innovations such as Sense Wind's Self-Erecting Nacelle and Service System could open up alternative approaches to FOWT assembly, allowing assembly at site rather than at the port, changing vessel and port requirements during the construction phase [20]. As a result, the vessel requirements presented in this report may also be subject to change and can only be relied on as a broad estimate in assessing hydrogen fuelling capacity required at the PoMH.

PoMH Capacity Utilisation

In the Celtic Sea region, an array of coastal infrastructure exists. The primary industrial focus of this infrastructure is in importing and exporting aggregates and minerals, with other infrastructure supporting the import of liquid natural gas. Significant sized infrastructure exists around the Port of Milford Haven, Port Talbot and Bristol Port. However, of these three ports, the PoMH is the largest in capacity and lies closest to the proposed FOW sites in the Celtic Sea. As such, it is assumed for this report that the PoMH will be the primary port utilised for Celtic Sea FOW development and will see the largest quantity and size of FOW associated vessel traffic. Estimations made in this report assume that the PoMH will utilise as much of its available capacity as is possible to support Celtic Sea FOW development activities, whilst continuing to utilise a proportion of its capacity for other industrial uses.

FOW Utilisation of Other Ports

In the build out of FOW in the Celtic Sea, it is likely that port infrastructure across the South Coast of Wales and the West Coast of England will be utilised to meet construction demands. This report presents estimations of the overall number of vessels required to achieve the construction of the planned FOW capacity in the Celtic Sea, however, these may not all use the PoMH. Estimations will be made in the Work Package 3 report as to the proportion of the overall FOW vessel traffic that will require fuelling at the PoMH.

FOW Vessel Fleet Availability

Many of the operations described in the following sections could be carried out using a range of different vessel types as many vessels have a range of capabilities. However, as this report focuses on producing broad estimates of vessel requirement for FOW vessels at the PoMH, the analysis carried out only considers the primary vessel type required for each operation along with a selected number secondary vessel options. Furthermore, in the vessel requirement calculations, it is assumed that all of the vessels required for FOW deployment in the Celtic Sea will be available to carry out the works. Considering the size of the existing and projected vessel fleet to meet the FOW vessel demand in the near and long term future was not considered due to the size of that task falling outside the scope and timescale of this report.

Vessel Number with Growing FOWT Ratings

The calculations performed assume that the number of vessels required for each operation during pre-construction, construction and O&M remain the same regardless of FOWT size. As sizes of FOWT units increase year on year, the number of vessels required to complete each operation may vary. However, there is a high level of uncertainty associated with predicting this change as the FOWT sizes described do not currently exist, so it is impossible to understand the details of offshore vessel operations involving these units. Therefore, for simplicity it was assumed that the number of vessels required for each operation will remain constant with increasing FOWT size.

4 VESSEL REQUIREMENTS IN PRE-CONSTRUCTION

4.1 Vessel Types Required

Prior to construction works taking place on a FOW site, a range of surveys need to be carried out to assess different characteristics of the intended site. These are done to understand key aspects of the site which in turn informs the selection of technologies for deployment and the planning of the site layout.

Types of survey carried out include:

- Geophysical surveys – examining seabed features, site bathymetry and identifying any man made features on the site, such as unexploded ordnance.
- Geotechnical surveys – assessing soil/rock strata and engineering properties of the seabed inform anchoring and fixing technologies selected for use. Carried out after geophysical surveys have been completed and identified preliminary foundation locations on site.
- Environmental, resource and met-ocean surveys – carried out to investigate various aspects of the site, such as sea life, wave conditions and tidal flow.

To facilitate these surveys, it is possible to utilise different vessel types. An overview of the preferred vessels for these operations is shown in Table 9, along with secondary vessel options that could be utilised in place of the primary option if it is unavailable.

Table 9 Vessel types required for pre-construction operations

Operation	Preferred Vessel Option	Secondary Vessel Options
Site surveys (geophysical, geotechnical, environmental, resource, met-ocean, marine life)	Survey Vessel	OCV, SOV

Further information on the vessels listed is presented in Section 3.1.

4.2 Pre-Construction Vessel Quantity Estimates

Using the methodology developed for estimating vessel demand for FOW deployment (as outlined in Section 3.3), the predicted number of vessels required to support the pre-construction phase of FOW deployment in the Celtic Sea was calculated.

Table 10 shows the results of these calculations, with the estimates of vessel years required for each required vessel type in pre-construction activities for the predicted number of FOWT units deployed in each 5-year period.

Table 10 Estimated vessel years required per vessel type used in pre-construction phase in 5 year periods

Period	Pre-Construction Phase Vessel Years Required for Estimated FOWT Unit Deployment Numbers		
	Survey Vessel	OCV <200t crane capacity	SOV
Up to 2025	0	0	0
2026 – 2030	1.03	0.32	0.32
2031 – 2035	4.25	1.31	1.31
2036 – 2040	4.85	1.49	1.49
2041 – 2045	6.23	1.92	1.92
2046 - 2050	8.18	2.52	2.52
Totals	**24.53**	**7.55**	**7.55**

For each 5-year vessel demand period, averages were taken over the 5 years to provide a rough estimate of vessel numbers required each year. The annual averages for each 5-year period are shown in Table 11. It should be noted that these averages were calculated using a rough approach. True values of vessel demand will vary year on year due to the differing demands of projects at different stages in their lifecycle. However, delving into that level of granularity was deemed outside the scope of this project. It may be beneficial in future, more detailed design work, to seek to predict annually varying vessel demand numbers to aid in the design of the hydrogen fuelling facility.

Table 11 Average annual estimated vessel years required per vessel type used in pre-construction phase in 5 year periods

Period	Pre-Construction Phase Average Vessel Years Required per 5-Year Period for Estimated FOWT Unit Deployment Numbers		
	Survey Vessel	OCV <200t crane capacity	SOV
Up to 2025	0	0	0
2026 – 2030	0.21	0.06	0.06
2031 – 2035	0.85	0.26	0.26
2036 – 2040	0.97	0.30	0.30
2041 – 2045	1.25	0.38	0.38
2046 - 2050	1.64	0.50	0.50

A consideration when reviewing the vessel demand estimate is the seasonality of vessel demand. In the pre-construction phase, weather and ocean conditions affect the accessibility of FOW sites, with accessibility at its lowest in the winter and highest in the summer. The fuel demand to service the FOW vessel fleet will vary across the year as a result of this seasonality in all project lifecycle phases. However, due to the complexity of estimating peak demand times and effects, only the average annual and 5-year vessel demand estimates are considered in this report.

This seasonality effect will impose greater constraints in the construction phase where calm sea conditions are essential for heaving lifting and towing operations.

5 VESSEL REQUIREMENTS IN CONSTRUCTION

5.1 Vessel Types Required

Following the survey work and design of the offshore site, the construction phase begins. This is the most offshore intensive phase of the project lifecycle and involves the installation of FOWTs along with all of the other necessary infrastructure, such as array cables and offshore substations. The construction phase begins with the shipping of all of the major items to the construction port and finishes when the fully commissioned FOW assets are handed over to the operational teams, who then go on to operate the wind farm. Many tasks take place in tandem throughout the construction phase. Figure 8 shows a high level summary of the activities involved in a representative FOW project construction phase, along with the locations at which each activity takes place. In comparison to the pre-construction and O&M phases, the construction phase is where the highest vessel utilisation, and therefore fuel demand, takes place.

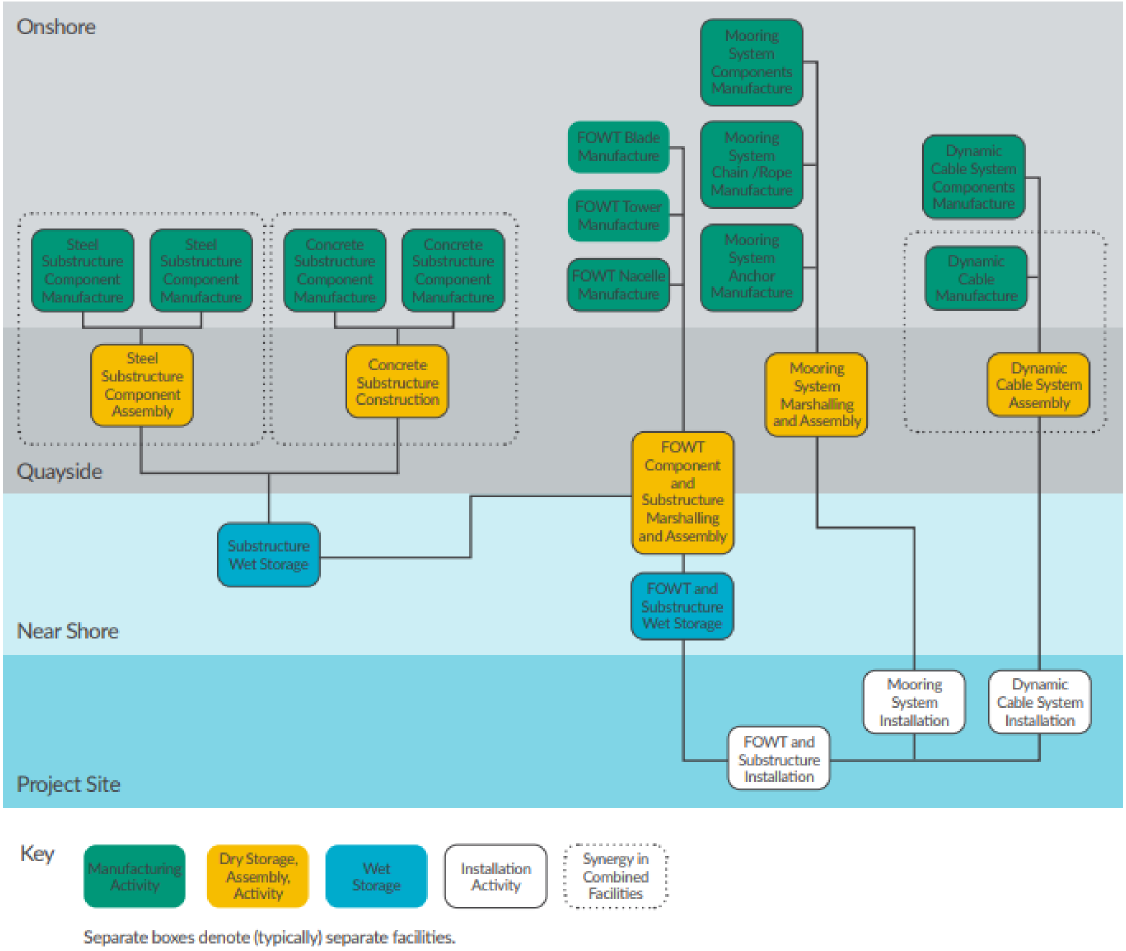


Figure 8 High level overview of construction activities for typical FOW farm [14]

A wide range of operations take place during the construction phase, each requiring different vessel types to complete. As discussed previously, however, it is possible to utilise different vessel types to complete the same operation, with some types being preferable over others. Table 12 lists the main operations that take place during the construction phase along with the preferred and secondary vessels selected to complete each operation.

Table 12 Vessel types required for construction operations

Operation	Preferred Vessel Option	Secondary Vessel Option
Seabed cable route surveys and preparations.	Survey Vessel	AHTS
Transport and handling of major components. Transport of major components to deployment port from fabrication location for assembly.	Heavy Lift Cargo Vessel, Semi-submersible vessel, Open Deck Carrier (ODC), Coaster	
Anchor and mooring line installation	OCV, AHTS	
Offshore substation installation	Semi-submersible vessel	Dumb barge, Heavy Lift Vessel
Cable installation and burial	CLV	
Towing of assembled structure	Tug	AHTS
Assembly of components offshore (onshore/inshore assembly favoured)	HLV	
Offshore hook up and commissioning. As-built surveys.	SOV	CLV, CTV

The vessel types presented represent categories of vessel type, however within each vessel type category, sub-categories exist of differing vessel sizes and capabilities. These sub categories of vessel are required in varying combinations during different construction operations. For example, when towing an assembled FOWT to site for mooring hook up, three tugs are typically be used. The towing tug is generally larger, requiring a bollard pull capacity of greater than 200 tonnes, with the trailing tugs only requiring around 50 – 100 tonnes of bollard pull capacity.

5.2 Construction Vessel Quantity Estimates

The predicted number of vessel years required for each vessel type to support the construction phase of FOW deployment in the Celtic Sea are shown in Table 13.

Table 14 also shows average annual vessel demand figures each 5-year period, calculated using the method previously discussed.

Table 13 Estimated vessel years required per vessel type used in construction phase in 5 year periods

Period	Construction Phase Vessel Years Required for Estimated FOWT Unit Deployment Numbers												
	Survey Vessel	Semi-submersible	Heavy Lift Cargo Vessel	ODC	Coaster	CLV	OCV <200t crane capacity	OCV 200-400t crane capacity	OCV >400t crane capacity	AHTS bollard pull <200t	AHTS bollard pull >200t	Tug	SOV
Up to 2025	0	0	0	0	0	0	0	0	0	0	0	0	0
2026 – 2030	1.03	0.55	1.50	0.95	0.95	1.11	1.03	1.19	0.55	1.90	1.66	0.71	0.55
2031 – 2035	4.25	2.29	6.21	3.92	3.92	4.57	4.25	4.90	2.29	7.84	6.86	2.94	2.29
2036 – 2040	4.85	2.61	7.08	4.47	4.47	5.22	4.85	5.59	2.61	8.95	7.83	3.35	2.61
2041 – 2045	6.23	3.35	9.10	5.75	5.75	6.71	6.23	7.19	3.35	11.50	10.06	4.31	3.35
2046 - 2050	8.18	4.40	11.95	7.55	7.55	8.81	8.18	9.44	4.40	15.10	13.21	5.66	4.40
Totals	**24.53**	**13.21**	**35.85**	**22.64**	**22.64**	**26.42**	**24.53**	**28.30**	**13.21**	**45.28**	**39.62**	**16.98**	**13.21**

Table 14 Average annual estimated vessel years required per vessel type used in construction phase in 5 year periods

Period	Construction Phase Average Vessel Years Required per 5-Year Period for Estimated FOWT Unit Deployment Numbers											
	Survey Vessel	Semi-submersible	Heavy Lift Cargo Vessel	ODC	Coaster	CLV	OCV <200t crane capacity	OCV 200-400t crane capacity	OCV >400t crane capacity	AHTS bollard pull <200t	AHTS bollard pull >200t	Tug	SOV
Up to 2025	0	0	0	0	0	0	0	0	0	0	0	0	0
2026 – 2030	0.21	0.11	0.30	0.19	0.19	0.22	0.21	0.24	0.11	0.38	0.33	0.14	0.11
2031 – 2035	0.85	0.46	1.24	0.78	0.78	0.91	0.85	0.98	0.46	1.57	1.37	0.59	0.46
2036 – 2040	0.97	0.52	1.42	0.89	0.89	1.04	0.97	1.12	0.52	1.79	1.57	0.67	0.52
2041 – 2045	1.25	0.67	1.82	1.15	1.15	1.34	1.25	1.44	0.67	2.30	2.01	0.86	0.67
2046 - 2050	1.64	0.88	2.39	1.51	1.51	1.76	1.64	1.89	0.88	3.02	2.64	1.13	0.88

During the construction phase of a FOW farm, vessel operations are generally at their most sensitive to weather and sea conditions as calm conditions are often essential for heavy lifting and towing operations. As a result of this sensitivity, the seasonality of vessel demand is at its highest during the construction phase, with a particularly high demand for larger vessels in the calmer summer months and a lull in demand over the winter where sea conditions are generally worse. The variance in vessel demand across years where construction operations are particularly numerous will have a significant effect on the fuel requirements to service the FOW vessel fleet across the year.

6 VESSEL REQUIREMENTS FOR OPERATIONS AND MAINTENANCE

6.1 Vessel Types Required

The main O&M activities for FOW are shown in Table 15, with vessel options for carrying out these activities listed.

Table 15 Vessel types required for O&M operations

Operation	Preferred Vessel Option	Secondary Vessel Option
Mooring and subsea cable inspections using ROV. Substructure hull inspection. Seabed, topside inspections.	SOV, Survey Vessel	OCV
Substructure, blade, nacelle light repair operations. Cable re-burial interventions.	OCV	AHTS, SOV
Offshore major interventions (tow to shore, mooring replacement, cable replacement). Light mooring and cable repairs.	AHTS	
Tow to port for major repairs	Tug	AHTS, SOV
Inshore major repairs after tow to port	Non self-propelled jack-up vessel	HLV

6.2 O&M Vessel Quantity Estimates

Unlike with the pre-construction and construction phases, where the turbine numbers to install each year are used to calculate the vessel demand, with the O&M phase, the previously installed capacity is used to estimate the vessel demand for each period. Using this methodology, which is outlined in Section 3.3.2, estimates of vessel years required to carry out the O&M activities for the predicted number of FOWT units in place for each 5-year period were calculated, as shown in Table 16. The average number of each vessel type required for each year within the 5-year periods is also shown in Table 17.

Table 16 Estimated vessel years required per vessel type used in O&M phase in 5 year periods

Period	**O&M Phase Vessel Years Required for Estimated FOWT Unit Deployment Numbers**						
	Survey Vessel	OCV <200t crane capacity	AHTS bollard pull <200t	AHTS bollard pull >200t	Tug	SOV	CTV (from mother SOV)
Up to 2025	0	0	0	0	0	0	0
2026 – 2030	0.08	0.32	0.16	0.32	0.16	1.27	0.40
2031 – 2035	0.41	1.62	0.81	1.62	0.81	6.49	2.03
2036 – 2040	0.78	3.11	1.56	3.11	1.56	12.46	3.89
2041 – 2045	1.26	5.03	2.52	5.03	2.52	20.13	6.29
2046 - 2050	1.89	7.55	3.77	7.55	3.77	30.19	9.43
Totals	**4.41**	**17.63**	**8.82**	**17.63**	**8.82**	**70.40**	**22.04**

Table 17 Average annual estimated vessel years required per vessel type used in O&M phase in 5 year periods

Period	O&M Phase Average Vessel Years Required per 5-Year Period for Estimated FOWT Unit Deployment Numbers						
	Survey Vessel	OCV <200t crane capacity	AHTS bollard pull <200t	AHTS bollard pull >200t	Tug	SOV	CTV (from mother SOV)
Up to 2025	0	0	0	0	0	0	0
2026 – 2030	0.02	0.06	0.03	0.06	0.03	0.25	0.08
2031 – 2035	0.08	0.32	0.16	0.32	0.16	1.30	0.41
2036 – 2040	0.16	0.62	0.31	0.62	0.31	2.49	0.78
2041 – 2045	0.25	1.01	0.50	1.01	0.50	4.03	1.26
2046 - 2050	0.38	1.51	0.75	1.51	0.75	6.04	1.89

7 VESSEL REQUIREMENT QUANTITIES/OVERVIEW

Combining the vessel demand estimates from all three phases produced an overall estimate of the vessels required for each 5-year period. These estimates are shown in Table 18. Estimates are also shown in Table 19 of the annual average vessel for each 5-year period.

Table 18 Combined estimated vessel years required per vessel type used in 5 year periods

Period	Total Vessel Years Required for Estimated FOWT Unit Deployment Numbers													
	Survey Vessel	Semi-submersible	Heavy Lift Cargo Vessel	ODC	Coaster	CLV	OCV <200t crane capacity	OCV 200-400t crane capacity	OCV >400t crane capacity	AHTS bollard pull <200t	AHTS bollard pull >200t	Tug	SOV	CTV (from mother SOV)
Up to 2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2026 – 2030	2.14	0.55	1.50	0.95	0.95	1.11	1.66	1.19	0.55	2.06	1.98	0.87	2.14	0.40
2031 – 2035	8.90	2.29	6.21	3.92	3.92	4.57	7.18	4.90	2.29	8.65	8.49	3.75	10.09	2.03
2036 – 2040	10.47	2.61	7.08	4.47	4.47	5.22	9.45	5.59	2.61	10.50	10.94	4.91	16.56	3.89
2041 – 2045	13.72	3.35	9.10	5.75	5.75	6.71	13.18	7.19	3.35	14.02	15.09	6.83	25.40	6.29
2046 - 2050	18.24	4.40	11.95	7.55	7.55	8.81	18.24	9.44	4.40	18.87	20.76	9.43	37.11	9.43
Totals	**53.47**	**13.21**	**35.85**	**22.64**	**22.64**	**26.42**	**49.71**	**28.30**	**13.21**	**54.10**	**57.26**	**25.80**	**91.29**	**22.04**

Table 19 Average annual combined estimated vessel years required per vessel type used in 5 year periods

Period	Total Average Vessel Years Required per 5-Year Period for Estimated FOWT Unit Deployment Numbers												
	Survey Vessel	Semi-submersible	Heavy Lift Cargo Vessel	ODC	Coaster	CLV	OCV <200t crane capacity	OCV 200-400t crane capacity	OCV >400t crane capacity	AHTS bollard pull <200t	AHTS bollard pull >200t	Tug	SOV	CTV (from mother SOV)
Up to 2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2026 – 2030	0.43	0.11	0.30	0.19	0.19	0.22	0.33	0.24	0.11	0.41	0.40	0.17	0.43	0.08
2031 – 2035	1.78	0.46	1.24	0.78	0.78	0.91	1.44	0.98	0.46	1.73	1.70	0.75	2.02	0.41
2036 – 2040	2.09	0.52	1.42	0.89	0.89	1.04	1.89	1.12	0.52	2.10	2.19	0.98	3.31	0.78
2041 – 2045	2.74	0.67	1.82	1.15	1.15	1.34	2.64	1.44	0.67	2.80	3.02	1.37	5.08	1.26
2046 - 2050	3.65	0.88	2.39	1.51	1.51	1.76	3.65	1.89	0.88	3.77	4.15	1.89	7.42	1.89

From the vessel year projections, it is clear that there will be a rapidly increasing demand for FOW vessels going forward to 2050, with a particularly high demand from 2036 onwards. With this rapid increase in vessel numbers, an important consideration to make is the capacity of the PoMH to meet this demand for vessel space and fuel demand. If the port seeks to capitalise on the large numbers of vessels in operation for FOW deployment in the Celtic Sea, it must consider its capability to meet their demand for space and fuel. Furthermore, with the preferred construction methodology focussing on maximising construction and assembly works at the quayside, the PoMH should consider its capacity to service and meet those demands.

The overall vessel demand calculations presented in this report will feed into further calculations carried out in Work Package 3, which will estimate the fuel supply required to service the predicted FOW vessel fleet.

8 CONCLUSION

A wide variety of vessels will be required in future for FOW deployment in the Celtic Sea, each carrying out different operation to facilitate pre-construction, construction and O&M activities. FOW vessel numbers will increase as deployment of FOWTs in the Celtic Sea gradually increases in the early to mid 2030s, before ramping up rapidly from the mid to late 2030s onwards. Estimations were made by approximating the vessel time required per FOWT unit and calculating the number of vessel days and years required to deploy the projected amount of FOW capacity in the Celtic Sea. A number of assumptions were made in calculating the vessel time required, including the quayside construction methodology adopted. The resulting estimates have a level of uncertainty associated with them due to the assumptions made, however, they provide a rough estimate of vessel numbers which can feed into further project work.

It is likely that the vessel demand seen by the PoMH, both in providing vessel fuel and in providing space for FOWT construction activities, will be a result of the capacity which is made available for FOW deployment at the port. Work Package 3 of the HyPR project will look to calculate the fuel and hydrogen demand required by the vessel fleet size estimated in this report, which will then feed into the design of a facility in the PoMH for hydrogen production.

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APPENDIX 1 VESSEL DEMAND CALCULATOR

Days per turbine unit/days per km	Phase	Operation	*Vessel Specification* Task	Survey Vessel	Semi-submersible Carrier/Barge	Heavy Lift Cargo Vessel	Open Deck Carrier (ODC)	Coaster Vessel	CLV	OCV with <200 ton crane capacity	OCV with 200 - 400 ton crane capacity	OCV with >400 ton crane capacity	AHTS with bollard pull capacity <200 ton	AHTS with bollard pull capacity >200 ton	Tug	SOV	CTV (from mother SOV)
/km	Pre-construction	Surveys	Geophysical/geotechnical surveys for export cable	3						1						1	
/Turbine unit			Geophysical/geotechnical surveys for array cables	1.5						0.5						0.5	
/Turbine unit			Geophysical/geotechnical surveys for anchors and moorings	2						0.5						0.5	
/km	Construction	Surveys	Pre-cable lay survey	6.5									3.5				
/Turbine unit		Transport of Major Components	Wind turbine unit (nacelle, tower, blades)			4	3										
/Turbine unit			Substructure		3.5	2	1.5										
/km			Cables					1									
/Turbine unit			Mooring lines			1.5		2.5							0.5		
/Turbine unit			Anchors			2	0.5	2.5									
/km			Offshore substation				1										
/Turbine unit		Assembly	FOWT assembly at quayside														
/Turbine unit		Transport and installation	Drag anchor							0.5	0.5	0.5	1	1			
/Turbine unit			Piled anchor							0.5	1.5	1					
/Turbine unit			Suction Anchor							0.5	0.5	1					
/Turbine unit			Mooring lines								2.5	0.5	1	2.5			
/km			Array cables						1		0.5	0.5					
/km			Export cable						2.5								
/km			Cable burial (array and export)						2	2							
/Turbine unit			Mooring line hook up							1	1		1	3		1	
/Turbine unit			General towing operations for hook up process										3	3.5	4		
/Turbine unit			Cable pull in						1.5	2	1		2.5	0.5		2.5	
/Turbine unit	O&M	Inspections & Light Maintenance	Subsea (moorings, hull, cables)							0.5						2	1
/Turbine unit			Topside (wind turbine generator, rotor,							1						2	1.5
/Turbine unit			ROV subsea inspections (moorings, cables, hull)	0.5												1	
/Turbine unit		Major Interventions	Moorings & cables											0.5			
/Turbine unit			Nacelle components													1	
/Turbine unit			Hull													0.5	
/Turbine unit			Rotor (blades)													1	
/Turbine unit			Tow to port							0.5			1	1.5	1	0.5	

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