CARBON TRUST

# Phase III summary report

## Floating Wind Joint Industry Project

# Acknowledgments

This summary report has been produced by the Carbon Trust, with specific sections informed by studies delivered by the following external technical contractors:

- Heavy Lift Offshore Maintenance: ABL (formerly LOC) and WavEc
- Tow to Port Maintenance: ABL (formerly LOC) and WavEc
- Mooring in Challenging Environments: Leask Marine, Wood Thilsted, Exeter Consulting and First Marine Energy

Study results are based on an impartial analysis of primary and secondary sources, including expert interviews.

The Carbon Trust would like to thank everyone who has contributed their time and expertise during the preparation and completion of these studies.


# Disclaimer

The key findings presented in this report represent general results and conclusions that are not specific to individual floating wind concepts. Caution should therefore be taken in generalising findings to specific technologies.

It should be noted that information and findings do not necessarily reflect the views of the supporting industry partners but are based on independent analysis undertaken by the Carbon Trust and respective external technical contractors.

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# Abbreviations

| | |
|---|---|
| **AHTS** | Anchor Handling Tug Supply (vessel) |
| **DP** | Dynamic Positioning |
| **FOW** | Floating Offshore Wind |
| **FOWT** | Floating Offshore Wind Turbine |
| **FWS** | Floating Wind Substructure |
| **HLV** | Heavy Lift Vessel |
| **LCOE** | Levelized Cost of Energy |
| **MPV** | Multi-Purpose Vessel |
| **OSV** | Offshore Service Vessel |
| **ROV** | Remotely Operated Vehicle |
| **SOV** | Service Operation Vessel |
| **TLP** | Tension-Leg Platform |
| **TRL** | Technology Readiness Level |
| **TTP** | Tow-to-port |
| **WTG** | Wind Turbine Generator |

# Executive summary

The floating offshore wind sector has remained active over the last year, with many countries turning their attention to floating wind and adding commercial scale projects to their offshore wind pipelines. Floating offshore wind is also thought to be an important area of renewable generation in the journey to net zero, according to key industry players such as the International Energy Agency[1]. Floating offshore wind (FOW) technologies enable more wind resources to be exploited by developing wind farms further from shore and in deeper waters. Current pilot project and demonstration arrays have shown the potential for similar, or even higher yields, from floating turbines compared to bottom-fixed projects; as they can be situated in locations with higher wind resources. FOW arrays are nearing commercial deployment but there are an inherent number of challenges to overcome with commercial scale farms. The Floating Wind Joint Industry Project (Floating Wind JIP) was set up in 2016 with the aim to find solutions to these common challenges.

This report provides an update of the recent Floating Wind JIP studies that focused on heavy lift operations, tow-to-port maintenance and moorings in challenging environments, as well as, updates on two recent competitions that will accelerate the progression of the floating offshore wind industry.

In terms of market growth, though there has been little active deployment over the last year, largely due to Covid-19 related delays, the industry has still been advancing technology, knowledge and funding opportunities. Global FOW deployment is expected to increase to up to 126MW by the end of 2021, with the completion of the largest site to date at Kincardine, Scotland. The pipeline for demonstration projects has expanded outside of Europe, with projects planned in Japan and in the US in the coming years, further demonstrating the commitment to the industry.

There are however still significant technical challenges to be overcome before achieving large-scale deployment of floating offshore wind, which will require innovation from supply chain and developers alike. Both operational projects, and projects under development, will be key to providing learnings to increase understanding of these assets and to de-risk future commercial-scale projects. Many of these technical challenges are common to multiple floating wind projects, making them suitable for industry-led collaborative research and development. The Floating Wind JIP Phase III projects addressed a number of these key challenges:

**Heavy Lift Maintenance**: The Heavy Lift Maintenance study showed promising early conclusions around the logistics of offshore maintenance at the wind farm. Although many of the existing heavy lift vessels are unable to lift to the required hub height for 10MW+ turbines, new technologies are currently being developed to overcome this challenge. These technologies include vessel mounted cranes and turbine mounted cranes, for which operating costs were found to be closely linked to the cost of turbine downtime and initial vessel hire. With a continually developing market, these new technologies open up the possibilities for maintenance on large scale commercial wind farms that may be situated further from ports.

[1] IEA (2021): Net Zero by 2050

**Tow-to-port**: This study explored the feasibility of tow-to-port as an alternative maintenance approach. Tow-to-port is the process of detaching turbines and towing them to port to undertake large scale corrective maintenance. One of the main challenges of this process is the safe detachment and storage of wet cables and mooring connections. It was determined that, at this stage, the technologies to help overcome these challenges are best suited for semi-sub substructures, as other substructure types were thought to have stability issues during towing and may require further innovation to be commercially viable. A number of novel technologies were assessed to assist with safe disconnection and connection of mooring lines, as well as, power cables and technologies that assisted with towing procedures. It is likely that for a commercial maintenance operation a number of these technologies would be required. The study also highlighted the importance of port specifications, with water depth proving key to carry out large scale corrective maintenance. With the growing pipeline of floating offshore wind projects, port specifications and logistics should be a key consideration within O&M.

**Moorings in Challenging Environments:** The increased popularity of floating offshore wind and large pipeline of projects means that different seabed characteristics will be encountered. The Moorings in Challenging Environments study assessed the methodology of mooring in more challenging environments, including shallow waters (<70m), deep waters (>1000m), seismic environments and challenging seabed conditions. New technologies were assessed that would assist with reducing loads in shallow environments, but for other scenarios combinations of already existing approaches were assessed, to analyse their effectiveness in certain environments. Though there are many suitable options for mooring using existing technologies and methods, the study suggested that there are further innovations that would help reduce costs within the industry, namely innovation around floating specific mooring equipment or techniques and standardisation across the industry.

**Technology Acceleration Competition:** Floating Wind JIP developers designed the Floating Wind Technology Acceleration Competition (FLW TAC). The £1 million competition was founded by the Scottish Government to assess and support technologies with the greatest potential to overcome four key industry challenges: floating component exchange, disconnection and reconnection of structures when they are towed to port; monitoring, inspection and manufacture of mooring lines, cables and foundation structures; and installation and maintenance of mooring lines and anchors.

# Introduction

## Introduction to the Floating Wind JIP

The Floating Wind Joint Industry Project (Floating Wind JIP) is a collaborative research and development (R&D) initiative between the Carbon Trust and 17 leading international offshore wind developers: bp, EDF Renouvables, EnBW, Equinor, Kyuden Mirai Energy, Ørsted, OW Offshore, Parkwind, RWE Renewables, ScottishPower Renewables, Shell, SSE Renewables, TEPCO, Tohoku Electric Power Company, Total Energies, Vattenfall, and Wpd.

Since its formation in 2016, the programme has delivered two stages, each consisting of studies to outline the critical needs for the sector to reach cost parity with other energy technologies. An initial review of policy needs, cost trends, and technology status for floating wind in Stage I resulted in the prioritisation of several key technical challenges which have been investigated in the ongoing Stage II. Key findings for previous phases of Stage II have already been published and can be found here: Phase I and Phase II.

This report presents the key findings from Phase III projects (see sections 2-4) along with overviews of two recent competitions delivered through the Floating Wind JIP. The Phase III projects, outlined in this report, were completed in 2020-21. An overview of the Phase IV projects that are in delivery 2021-22 can be found in section 6.

## Objectives and scope

The primary objective of the Floating Wind JIP is to overcome the challenges and investigate opportunities for the deployment of large-scale commercial floating offshore wind farms. The programme is technology-focused, with a particular emphasis on:

- **Large-scale deployment:** Floating offshore wind technology has been proven at prototype and pilot scale, through single or a small number of multi-MW units. However, commercial wind farms will bring new technological and logistical challenges due to the increased scale of turbines and units deployed.

- **De-risking technology challenges:** Limited commercial deployment of floating offshore wind to date means that several perceived risks exist. It is expected that many of these challenges can be overcome using existing solutions from other sectors, but there is a need for further investigation to establish the true level of risk presented and undertake research that can reduce risk throughout the project lifecycle.
- **Identifying innovative solutions:** Several technology challenges will require the development of novel and innovative solutions. Innovation will be central to delivering optimised and cost-effective solutions for the industry, which is expected to present considerable opportunities for suppliers, innovators, research bodies, and academia.
- **Cost reduction:** All activity within the programme is guided by the need to deliver cost reductions ensuring that floating wind becomes a competitive energy technology in all major global markets. Cost assessments are included within the scope of most projects in order to build a robust estimate of the cost projections and cost drivers for programme partners to use when developing future commercial projects.

***Image: Kinkardine (Cobra[2])***

[2] https://www.grupocobra.com/en/proyecto/kincardine-offshore-floating-wind-farm/

# Objectives of the Phase III Floating Wind JIP studies

Below is a summary of the projects in Stage II Phase III of the Floating Wind JIP. The full project summaries, including innovation and technology needs can be found in sections 2-6. An overview of the current research being undertaken can be found in section 7.

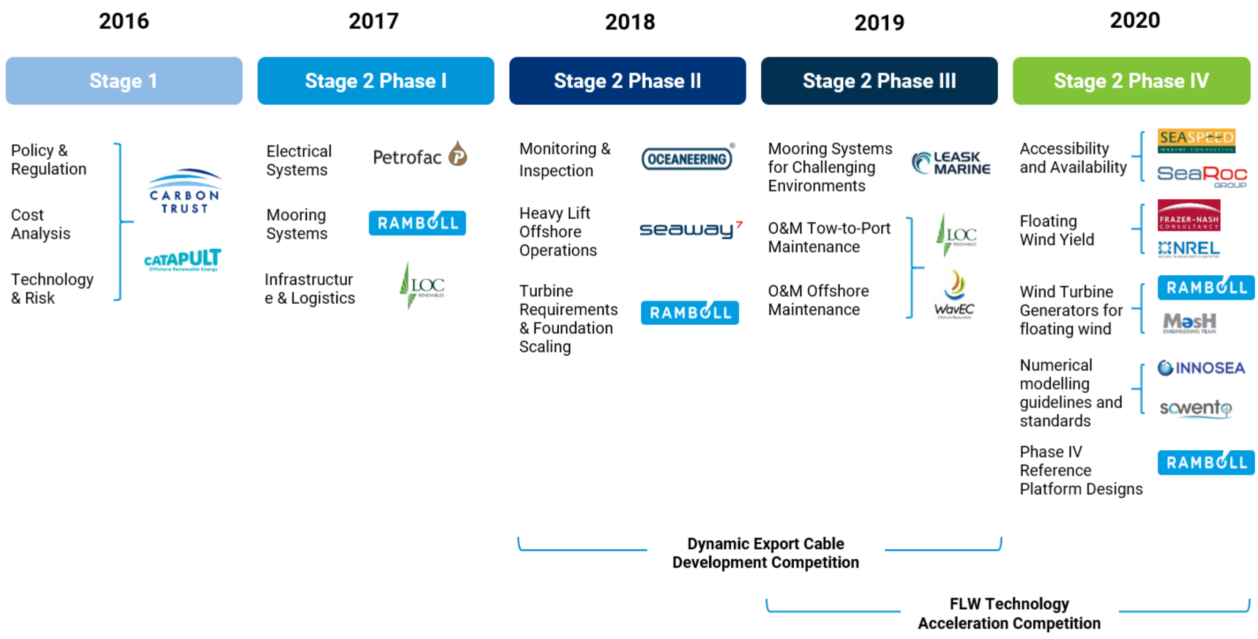



**Figure 1: Floating Wind JIP project overview**

## Heavy Lift Offshore Maintenance

The 'Heavy Lift Offshore Operations' study carried out in Phase II of the Floating Wind JIP found that heavy lift vessels focused particularly on lifting capacity, as it is required for the oil and gas industry, as opposed to lifting height, which is required for floating wind.

The objective of the Heavy Lift Maintenance (HLM) study was to examine the process of major component exchange when a floating wind substructure remains in-situ at the wind farm location. It is expected that jack-up vessels will not be viable due to water depth and that floating platforms will be required as an alternative. Furthermore, it is expected that component exchanges will have to be undertaken by floating crane vessels or alternative ‘temporary crane’ solutions that are able to utilise lower cost vessels. The increasing size of next generation turbines is creating demand for new, larger dynamic positioning (DP) installation vessels. However, given the expected high cost of using these large, heavy-lift DP vessels for maintenance work, there is considerable interest in understanding alternative solutions that can perform component exchange operations utilising smaller vessels.

The study assessed current state-of-the art methods for undertaking offshore heavy lift operations and assessed their technical feasibility and logistical practicality against a base case heavy lift vessel. High level cost estimates for these technologies were also produced.

As the technologies ranging in TRL some uncertainty remained, although the speed of crane deployment was key to reducing costs under the modelled conditions. The study showed that although there are a range of factors that affect the technology selection, vessel mounted cranes currently appear to provide the most suitably available solution for HLM, while other technologies require further development.

## Tow to Port Maintenance

Offshore maintenance for floating wind farms is significantly more difficult than fixed bottom, due to the motions of the floating turbine and maintenance vessel. A potential solution to this problem is to tow the floating wind turbine structure back to port for major turbine maintenance operations (e.g. gearbox replacement). This is an attractive option if a suitable port is located nearby. The implementation of a tow-to-port maintenance strategy for major component maintenance operations also poses some intrinsic risks and technical challenges including; the requirement for innovative technologies that optimize the connection and disconnection of moorings and/or subsea power cables, the need to reduce specific vessel requirements, addressing the challenges related to substructure stability during tow and working on port limitations such as maintained water depth (and thus under keel clearance).

This study assessed innovative technologies that could enable tow-to-port maintenance and undertook feasibility studies and logistics assessments, for both single component exchange and multiple turbine exchanges, to produce rough cost estimates for these different maintenance strategies. It was found that a combination of these innovative technologies would yield the most optimum results, though evidently this depends on wind farm location, component type, turbine size and distance to port, among other factors. This study was performed in conjunction with the HLM study, though with such significant differences to the two approaches, limited direct comparisons could be drawn between the two studies and at this time, a case by case approach would be required for assessing the best technology/technologies to use.

## Mooring in Challenging Environments

Mooring systems are critical for the station-keeping of floating offshore wind turbines. Though there is considerable track record from the oil and gas sector, floating wind turbines will require tailored solutions to minimise cost and risk. One of the main challenges when considering a commercial scale FOW array is that there will be exponentially more mooring lines, compared to the oil and gas industry, to account for the numerous turbines that are part of the array, so there are new challenges to overcome. While there are believed to be some cost-effective solutions for more benign conditions, there is a requirement for solutions that operate with more challenging environmental conditions, including shallow and deep waters, seismic environments and challenging seabed conditions that are likely to be encountered in future commercial scale FOW farms.

This study assessed a range of state-of-the-art and innovative mooring system solutions for the defined challenging environments, and subsequently undertook a technical assessment of a range of scenarios compared to a base case mooring system. These included not only innovative technologies (e.g. to reduce snatch loads) but also novel approaches such as shared moorings and anchors.

## Technology Acceleration Competition

To stay at the forefront of floating offshore wind innovation, the Scottish Government decided to invest £1 million to support innovations that would overcome key technology challenges, in particular the significant technical challenges identified by the Floating Wind JIP:

- Exchanging large turbine components on moving floating foundation structures
- Disconnection and re-connection of foundation structures, when they are towed to and from ports for maintenance
- Monitoring and inspection of mooring lines, cables and foundation structures
- Manufacturing, installation and maintenance of mooring lines and anchors

The Carbon Trust, in collaboration with the offshore wind developers in the Floating Wind JIP, designed the Floating Wind Technology Acceleration Competition (FLW TAC) to identify, assess and support technologies with the greatest potential to support floating wind. Eight projects were awarded a share of the £1 million grant funding and including contributions from the project participants, the projects had a combined total value of £1.5 million.

As well as funding the development of their technical solutions, a key benefit of the competition has been the opportunity to engage directly with offshore wind developers in the Floating Wind JIP, to understand their technological needs and the evidence they require to make decisions on the innovations to include in future projects. However, it should be noted that the publication of this report does not mean that each or any of the developers in the Floating Wind JIP endorse the technologies supported through the competition, nor the companies behind them. Overall, FLW TAC has enabled these projects to further develop designs and, in some cases, manufacture and test prototype products. The projects started with a range of Technology Readiness Levels (TRL) and all made substantial progress over the course of their projects. At the end of FLW TAC, one technology is now a commercial product, while others have secured additional funding for larger scale demonstration or are actively pursuing opportunities for commercial scale demonstrations.

Please note that this report gives an overview of the competition and individual summary reports for each of the competition winners are available on our website, here.

# 1. Market overview

## 1.1 Market growth

The Carbon Trust has undertaken a floating wind market analysis which provides an overview of projects in operation and under development. This analysis is not part of the Floating Wind JIP project and aims to provide a context to the current and future market as a reference.

### 1.1.1 Floating wind deployment to date

As of publication, a total of 74.05MW of floating offshore wind power is installed in countries across Asia and Europe. This is estimated to increase to 127.87MW of deployed technology by January 2022 (Table 1, Figure 2). Current installed capacity remains similar to the installed capacity at the time of writing of the Floating Wind JIP Phase II Summary report (released July 2020). This is due to the impact of Covid-19 which has delayed operations both throughout the supply chain and onsite. These impacts have pushed most project timelines into mid-2021, and some into early 2022.

An Example of a FOW farm that has been heavily impacted by Covid-19 include the remaining five turbines (48MW) at Kincardine, which were due to be installed in November 2020, but are now due to be installed by August 2021. This is due to delays to the supply chain and construction schedule. Similarly, full commissioning of the Tetraspar Demonstration has been pushed back to mid-2021 due to impacts of the global pandemic.

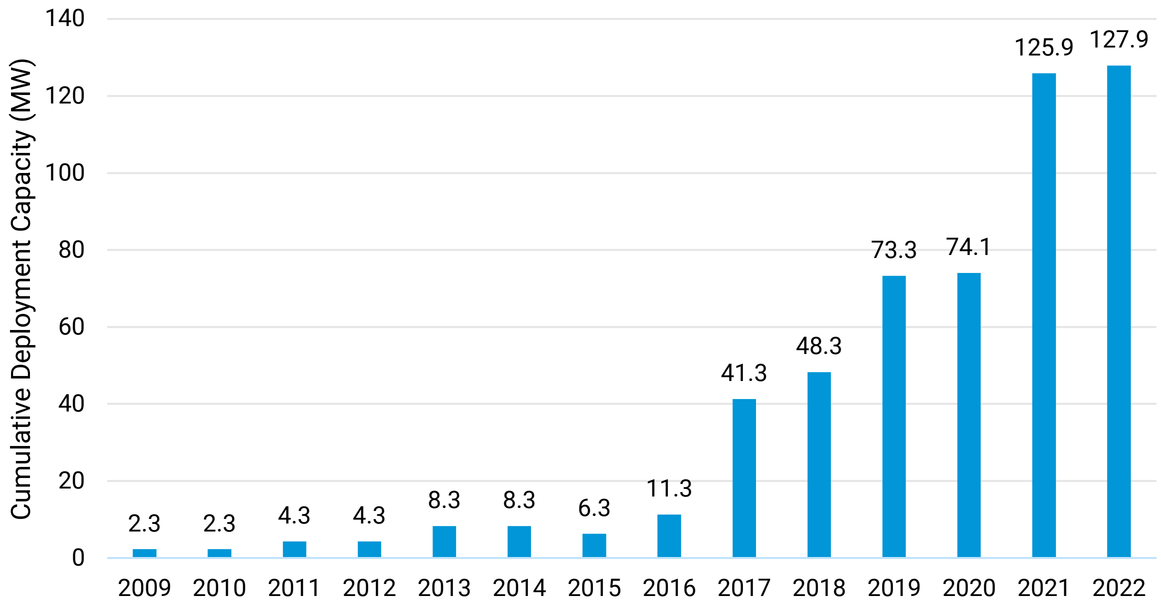



**Figure 2: Cumulative global development of floating offshore wind**

### Table 1: Decommissioned, fully commissioned and in-construction global floating wind projects

| Project | Country | First power | Project developer | Technology developer | Concept | Total capacity | Turbine rating | Turbine OEM |
|---|---|---|---|---|---|---|---|---|
| **Hywind I** | Norway | 2009 | Statoil | Statoil | Hywind | 2.3MW | 2.3MW | Siemens |
| **WindFloat Atlantic Phase 1* (Decommissioned)** | Portugal | 2011 | EDPR, Repsol, Chiyoda, Mitsubishi | Principle Power | WindFloat | 2MW | 2MW | Vestas |
| **Fukushima Forward-phase 1** | Japan | 2013 | Marubeni Corporation | Mitsui Engineering & Shipbuilding | Semi-Sub | 2MW | 2MW | Hitachi |
| **Kabashima** (Decommissioned)** | Japan | 2013 | Toda Corporation | Toda Corporation | Hybrid Spar | 2MW | 2MW | Hitachi |
| **Fukushima Forward-phase 2***** | Japan | 2015 | Marubeni Corporation | Mitsubishi Heavy Industries | V-Shape Semi-Sub | 7MW | 7MW | Mitsubi-shi |
| **Fukushima Forward-phase 3** | Japan | 2016 | Marubeni Corporation | Japan Marine United | Advanced Spar | 5MW | 5MW | Hitachi |
| **Sakiyama** | Japan | 2016 | Toda Corporation | Toda Corporation | Hybrid Spar | 2MW | 2MW | Subaru |
| **Hywind Pilot Plant** | UK | 2017 | Statoil | Statoil | Hywind | 30MW | 6MW | Siemens |
| **Floatgen** | France | 2018 | IDEOL | IDEOL | Damping Pool | 2MW | 2MW | Vestas |
| **IDEOL Kitakyushu Demo** | Japan | 2018 | IDEOL & Hitachi Zosen | IDEOL | Damping Pool (Steel) | 3MW | 3MW | Aerodyn |
| **Kincardine Phase 1** | UK | 2018 | Pilot Offshore, Cobra | Principle Power | WindFloat | 2MW | 2MW | MHI-Vestas |
| **WindFloat Atlantic 2** | Portugal | 2019 | EDPR, ENGIE, Repsol, PPI | Principle Power (PPI) | WindFloat | 25MW | 8.3MW | MHI-Vestas |
| **Ulsan Demo** | South Korea | 2020 | Unison, KETEP, Mastek Heavy Industries, SEHO Engineering, University of Ulsan | Mastec Heavy Industries | Semi-Sub | 0.75MW | 0.75MW | UNISON |
| **Tetraspar Demonstration ****** | Norway | 2021 | innogy SE, Shell, Steisdal OT | Steisdal Offshore Technologies | Tetraspar | 3.6MW | 3.6MW | Siemens |
| **PivotBuoy** | Spain | 2021 | X1Wind | X1Wind | PivotBuoy | 0.22MW | 0.22MW | Vestas |
| **Kincardine Phase 2****** | UK | 2021 | Pilot Offshore, Cobra | Principle Power | WindFloat | 48MW | 9.5MW | MHI-Vestas |
| **DemoSATH****** | Spain | 2022 | Saitec | Saitec | SATH | 2MW | 2MW | TBC |

* *WindFloat 1 decommissioned in 2016. The WindFloat 1 substructure redeployed in the Kincardine phase 1 project in Scotland.*
** *Kabashima 2MW turbine to be moved to location off Fukue Island.*
*** *Fukushima Forward- phase 2 7MW floater was decommissioned in September 2020.The 2MW and 5MW Fukushima Forward floaters are due to be decommissioned in 2021.*
**** *Tetraspar Demonstration: Scheduled to be fully commissioned in July 2021*
*PivotBuoy PLOCAN: Scheduled to be fully commissioned in July 2021*
*Kincardine Phase 2: One WindFloat device (2MW) was installed in 2018, and is producing power. The remaining 5 devices (48MW) are due to be fully commissioned in August 2021*
*DemoSATH: Scheduled to be fully commissioned in January 2022*

## 1.1.2 Upcoming pilot projects

There is a pipeline of upcoming projects that, as well as continuing to prove existing floating wind technologies, will work to pioneer new technologies and designs. These projects will also help to demonstrate supporting infrastructure and component technologies, such as mooring systems and dynamic export and inter-array cables. The results of these developments will be essential for securing a future for offshore wind across global markets.

As confidence in the technology is improving, bigger projects are becoming more commonplace. The majority of these developments will be located in Europe, but there are also projects located in the US and in Japan (Table 2). By the end of 2022 installed floating wind capacity is projected to reach 200-260MW.

**Table 2: Upcoming offshore wind projects**

| First power | Country | Project | Total capacity | Turbine rating | Project developer | Technology developer | Concept | Turbine supplier |
|---|---|---|---|---|---|---|---|---|
| 2022 | Japan | **Goto City** | 16.8 MW | 2-5 MW (HTW2.0-80) | Toda Corporation | Toda Corporation | Hybrid Spar | Hitachi |
| 2022 | Norway | **Hywind Tampen*** | 88 MW | 8 MW (SG 8.0-167 DD) | Equinor | Equinor | Hywind | Siemens-Gamesa |
| 2022 | Ireland | **AFLOWT** | 6 MW | 6 MW | DP Energy, Floating Power Plant | Floating Power Plant | Floating Power Plant | TBC |
| 2022 | Spain | **PLOCAN** | 8MW | 8MW | Floating Power Plant | Floating Power Plant | P37 Hybrid Floating Wind and Wave Energy Device | Floating Power Plant |
| 2023 | France | **Les éoliennes flottantes de Groix & Belle-Île** | 28.5 MW | 9.5 MW (V164) | Shell/Eolfi, China Guangdong Nuclear (CGN) | Naval Energies | Sea Reed | MHI-Vestas |
| 2023 | France | **Les Eoliennes Flottantes du Golfe du Lion** | 30 MW | 10 MW (V164) | Engie, EDPR, Caisse des Depots | Principle Power (PPI) | WindFloat | MHI-Vestas |
| 2023 | France | **EolMed (Gruissan) Pilot Farm** | 30 MW | 10 MW (V164) | Quadran | IDEOL | Damping Pool | MHI-Vestas |
| 2023 | France | **Provence Grand Large** | 25.2 MW | 8.4 MW (SWT-8.0-154) | EDF EN | SBM Offshore | TLP | Siemens-Gamesa |
| 2023 | USA (Maine) | **Aqua Ventus I** | 12 MW | 6 MW | University of Maine | University of Maine | VolturnUS | TBC |

**Power generated from the Hywind Tampen project will supply the Gullfaks and Anorre offshore oil fields in the North Sea*

# 1.2 Key market overview

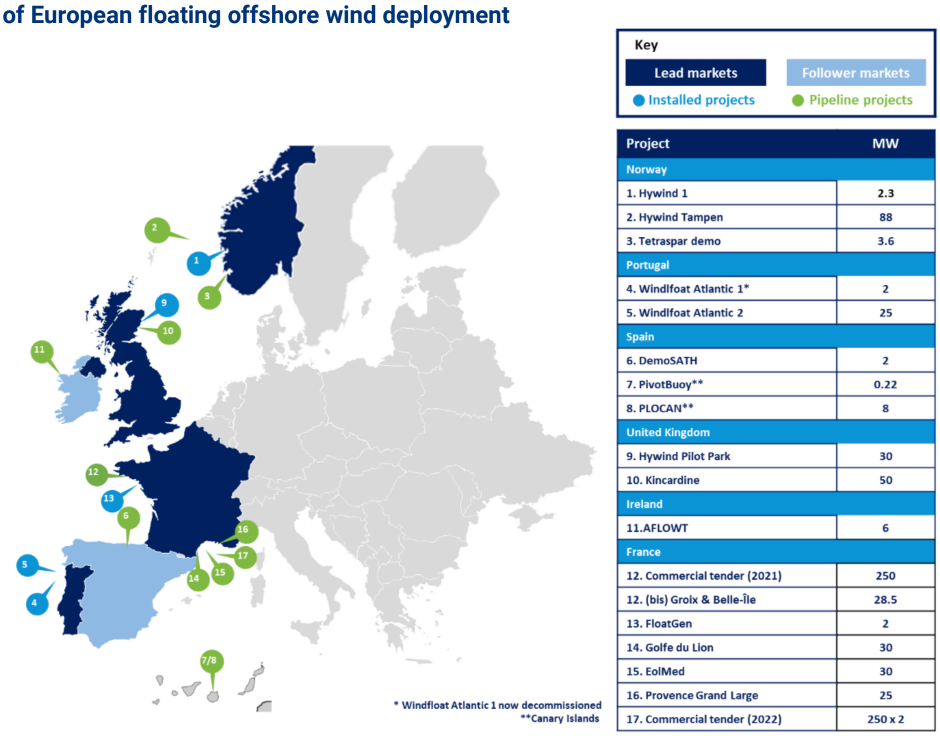
## 1.2.1 European market

As home to the world's first commercial floating offshore wind farm, Hywind and with the construction of the even larger-scale Kincardine underway, Scotland is a proven global leader in floating offshore wind. The Scottish Government has invested in its future as a leader in this industry by creating its own DeepWind cluster floating offshore wind subgroup. This cluster will support supply chain and project developers by increasing communication and shared learning while reducing transportation overheads. The southwest of the UK and areas of the coast of Wales also have sites suitable for floating wind technology, and projects are being planned for this area. The first of which is likely to be Erebus, a 96MW project which has been granted seabed rights off the Pembrokeshire coast. A recent announcement from the Crown Estate stated that they are planning to open additional leasing areas in the Celtic Sea, for early commercial-scale floating wind projects of circa 300MW.

The UK government has committed to the deployment of 1 GW of floating offshore wind by 2030. To achieve this, and to increase its floating offshore wind offering, the UK government is making investments including running a £17.5 million Floating Offshore Wind Demonstration Programme to support the demonstration of floating wind innovations at mid-TRL levels. The main challenge areas which have been identified are mooring and anchoring systems, dynamic cables and substructures or foundations.

France is also a very ambitious floating offshore wind market with plans for commercial tenders to be released annually. The country's Multiannual Energy Programme sets the regulatory framework that dictates 1GW of offshore wind, either fixed or floating, to be tendered per year. The first floating tender is a 250MW launch in 2021 in South Brittany off Belle-Ile and Ile de Groix. This will be joined by a 500MW extension in the region in 2024 following the award of two 250MW tenders on the Mediterranean coast in 2022.

**Figure 3: Map of European floating offshore wind deployment**




| Project | MW |
|---|---|
| **Norway** | |
| 1. Hywind 1 | 2.3 |
| 2. Hywind Tampen | 88 |
| 3. Tetraspar demo | 3.6 |
| **Portugal** | |
| 4. Windfloat Atlantic 1* | 2 |
| 5. Windfloat Atlantic 2 | 25 |
| **Spain** | |
| 6. DemoSATH | 2 |
| 7. PivotBuoy** | 0.22 |
| 8. PLOCAN** | 8 |
| **United Kingdom** | |
| 9. Hywind Pilot Park | 30 |
| 10. Kincardine | 50 |
| **Ireland** | |
| 11.AFLOWT | 6 |
| **France** | |
| 12. Commercial tender (2021) | 250 |
| 12. (bis) Groix & Belle-Île | 28.5 |
| 13. FloatGen | 2 |
| 14. Golfe du Lion | 30 |
| 15. EolMed | 30 |
| 16. Provence Grand Large | 25 |
| 17. Commercial tender (2022) | 250 x 2 |

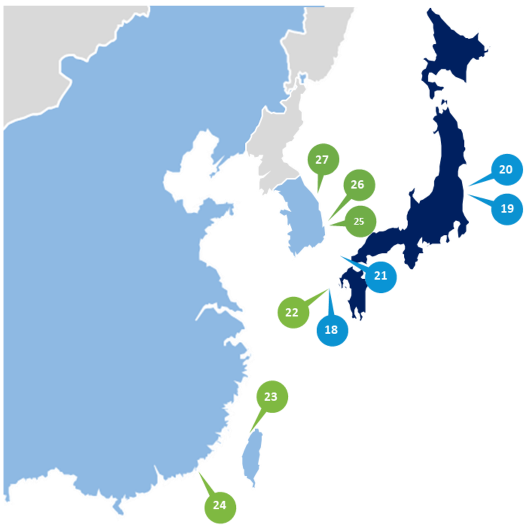
## 1.2.2 Asian market

Asia is likely to be the key market for floating offshore wind technology in the future due to the deep waters, high wind resource, long coastline and large energy demand from coastal cities. The region also has a track record in improving and reducing the cost of existing technologies to make them more commercially attractive. Such innovation will be key to the successful adoption of floating wind in this market and is beginning to be witnessed through the planning of a number of demonstration projects, specifically in Japan but also in China, South Korea and Taiwan.

Japan constructed the first floating offshore wind demonstrator in Asia in 2011 with the Fukushima FORWARD project. This was later followed by further floating turbine demonstrators in Goto Island and Kitakyushu. In 2018 the Japanese government passed legislation to allow for the development of offshore wind in deep water, including areas outside ports and harbours. This has opened the market to floating offshore wind technology securing its place as the leader of the Asian market. Although most designated offshore wind zones in Japan currently have been selected to favour fixed-bottom offshore wind projects, the first offshore wind auction held in Japan was for a small floating wind zone for projects with a minimum capacity of 16.8MW. This site off Goto Island, which opened to bidders in June 2020, was the first floating wind auction anywhere in the world.

With an overall vision for 12GW offshore wind power by 2030, South Korea has continued with its preparations for floating wind since the 750kW Shin-Gori Pilot. In May 2021, the 200MW Donghae 1 floating wind farm was approved by the Korean Development Institute following a feasibility study, giving the green light for South Korea's first floating wind farm (see 27 in the figure below). Continuing this momentum, President Moon Jae-in announced plans for a 6GW floating complex offshore from Ulsan, at the same site of the Donghae 1 gas field which is due to cease production in 2022. A 6GW floating wind farm would meet half of the country's 12GW by 2030 capacity target, indicating the high priority and importance of floating wind in the South Korean offshore wind market. There are other projects in the pipeline such as Equinor's proposal for an 800MW floating wind project, called Firefly, and ongoing work being done for the 1.5GW Project Gray Whale. Underpinning these advancements in South Korea's floating wind ambitions is a noticeable trend of Memorandum of Understandings (MoUs) and consortiums between various key Korean stakeholders, or Korean and international partners.

**Figure 4: Map of Asian floating offshore wind deployment**




Key

Lead markets | Follower markets

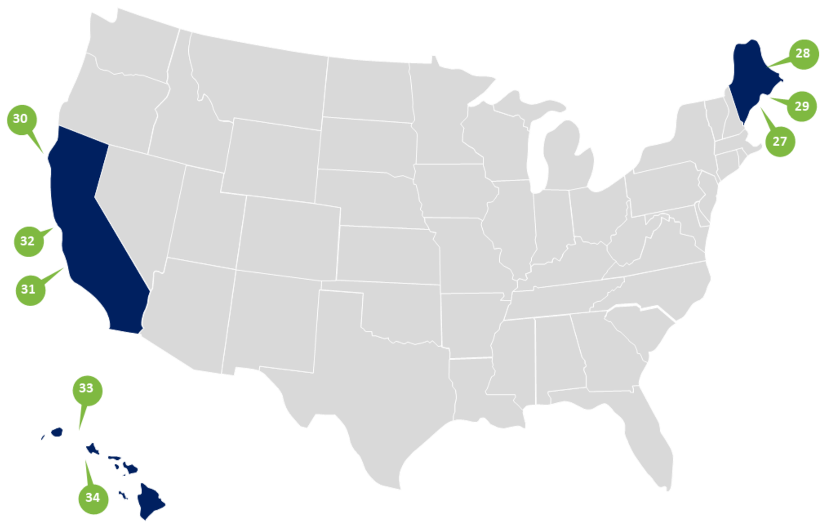
Installed projects | Pipeline projects

| Project | MW |
|---|---|
| **Japan** | |
| 18. Sakiyama | 2 |
| 19. Fukushima FORWARD: Phase 1 | 2 |
| 20. Fukushima FORWARD: Phase 2 and 3 | 12 |
| 21. IDEOL Kitakyshu demo | 3 |
| 22. Goto City | 22 |
| **Taiwan** | |
| 23. Eolfi Taiwan | 500-2000 |
| **China** | |
| 24. CGN Jieyang | 500-3000 |
| **South Korea** | |
| 25. Shin-Gori Pilot | 1 |
| 26. Ulsan Prototype | 5 |
| 27. Donghae Sites | 500-1500 |

## 1.2.3 US market

There are three main markets for floating offshore wind in the US; Maine, California and Hawaii. The closest to deployment is the demonstration of the VolturnUS platform in a project called Aqua Ventus II in Maine. Similar to fixed bottom projects, proposed commercial floating projects in the US have been held up due to consenting issues. However, the Biden Administration have vowed to accelerate the development and deployment of offshore wind. Recently, the Department of Interior and the Department of Defence reached an agreement to advance areas off California's northern and central coasts for offshore wind development, which will require floating turbine technology due to the relatively near-shore deep waters of the Pacific.

**Figure 5: Map of US floating offshore wind deployment**




| Project | MW |
|---|---|
| **Maine** | |
| 27. Aqua Ventus I | 12 |
| 28. Aqua Ventus II | 450 |
| 29. Aqua Ventus III | 450 |
| **California** | |
| 30. Humbolt Coast | 150 |
| 31. Morro Bay | 700-1000 |
| 32. Diablo Canyon | 700-1000 |
| **Hawaii** | |
| 33. Oahu Northwest | 400 |
| 34. Oahu South | 400 |

# 2. Key findings: Heavy Lift Offshore Maintenance

## 2.1 Study overview

Operations and maintenance (O&M) is arguably one of the most discussed issues in bottom-fixed offshore wind farms, reflecting the challenges experienced by wind farm owners in reducing operational expenditure due to variable vessel charter costs and environmental constraints on accessibility. For floating wind farms, offshore maintenance is expected to be significantly more difficult due to the motions of the floating turbine and maintenance vessel. The high-level objective of the Heavy Lift Maintenance (HLM) and Tow-to-Port (TTP) study was to examine two alternative strategies for performing large component exchange on floating wind turbines, namely (i) performing operations from a floating platform within the wind farm array (HLM) and (ii) towing the turbines to shore for port-side maintenance (TTP).

For the exchange of large components within a floating offshore wind farm, it is expected that jack-up vessels will not be viable due to water depth and that component exchanges have to be undertaken by a floating crane vessel or alternative 'temporary crane' solutions that are able to utilise lower cost vessels. The increasing size of next generation turbines is creating demand for new, larger turbine installation vessels. However, given the expected high cost of using these large, heavy-lift dynamic positioning (DP) vessels for maintenance work, there is considerable interest in understanding alternative solutions that can perform component exchange operations utilising smaller vessels.

The HLM study examined general principles and requirements for large component exchange within a floating wind farm array. The objectives of the study were to:

- Conduct a literature review of current state-of-the-art methods for undertaking heavy lift operations, including the relevant standards, recommendation practices, guidelines etc.;
- Set initial parameters for the study and perform background research;
- Define a base case definition of wind farm maintenance requirements including blade and gearbox exchange;
- Examine a shortlist of HLM-enabling technologies in terms of their technical feasibility, logistical practicality and expected costs.

The HLM study and the TTP study described in Section 2 were both performed by London Offshore Consultants (now AqualisBraemar LOC Group) and WavEC, and as such were carried out with similar methodologies in order to allow a comparison between the different maintenance strategies (given in Section 3), to conclude if there is a preference for strategy and technology for different turbine sizes, substructure types and wind farm characteristics.

## 2.2 Key findings

**1 Many of the existing fleet of heavy lift vessels are unable to lift to the hub height of a 10MW offshore wind turbine.**

Over the lifetime of a wind turbine and particularly in the context of a large farm, it is not uncommon that large components such as rotor blades, generators, transformers or gearboxes need to be repaired or even replaced. Floating offshore maintenance poses challenges associated with the relative motions between the lift vessel and floating turbine, resulting in high demands on the dynamic positioning (DP) system and other motion-compensation systems plus weather-restricted operations.

Floating offshore maintenance has previously been performed within the oil and gas industry, but it is noted that many of the existing heavy lift vessels (HLVs) would be unable to lift to the hub height of a 10MW turbine (approximately 112m above sea level), although they would have adequate weight capacity. Contractors are already developing the next generation of wind turbine installation vessels that will be able to achieve lifts on offshore windfarms in the next few years. These HLVs would permit lifts of up to 1300t to heights of approximately 120m above sea level with a horizontal reach of 35m. Also in development are several innovative technologies, such as climbing cranes, which are expected to facilitate offshore maintenance without the use of HLVs, which may enable cost reductions.

In this study the semi-submersible crane vessel (SSCV) Thialf, was selected as a baseline technology against which a shortlist of innovative HLM technologies were compared. The Thialf is equipped with an advanced DP system, and two cranes capable of each performing a heavy lift of 900t to a height of 79.2m above work deck or 198t to a height of 129.5m.

**Figure 6: Heerema SSCV Thialf**

Most of the existing HLVs could have adequate lifting capacity at radius of 30-40m. There may be other lift options that could increase their viability, such as replacing the turbine rotor-nacelle assembly plus a tower section, rather than just the rotor or blade, which would lessen the requirement of HLV’s lift height and increase the availability of HLVs in the market.

For a typical floating offshore wind farm, it is expected that large component exchange will require at least 1-2 lifts annually, but the requirement for heavy lift component replacement might be significantly increased due to serial component failures, fatigue damage, extreme events etc. In particular, blade leading-edge erosion may lead to the requirement to replace a large number of blades within the design lifetime of 25-30 years. It is expected that there will be several options to facilitate major component replacement, including: temporary turbine-mounted cranes, vessel-mounted cranes, and traditional heavy lift vessels.

Nacelle cranes (either permanently or temporarily installed) will have smaller lifting capacities compared to external cranes and may require the components to be broken down into sub-components which incurs time, pre-lift preparation and the requirement for reassembly in the nacelle. Using external cranes, however, requires the use of a DP vessel which comes with its own challenges, including motion compensation systems, equipment transfer, safe handling zones, vessel availability and the possible need of assistance from an offshore service vessel (OSV) if the external crane vessel has limited deck space.

Advances in crane design that facilitate both heavier and higher lifts will benefit both fixed and floating wind, or even offer the potential for heavy lifting at height without the requirement of HLVs or larger deck area OSVs. Other technologies have their own advantages and challenges as shown in Table 3.

**Table 3: Advantages and disadvantages of a range of HLM options**

| Technology | Advantages | Disadvantages |
|---|---|---|
| Traditional Heavy Lift Vessels | • Compatible will all substructure types.<br>• No impact on WTG design. | • May not be able to achieve sufficient lift height with required capacity - could require multiple lifts.<br>• High charter costs, that are expected to increase with demand.<br>• Current vessels do not have capacity for next generation turbines.<br>• Crane hook motion-compensation systems not typically 'built-in'.<br>• Availability of vessels as installed capacity of FOW increases |
| Turbine-mounted temporary cranes | • Easy to transport, potentially by OSV.<br>• Lower charter rates than HLV.<br>• Could be stored at an onshore O&M base for emergency repair operations. | • Transfer of temporary crane between vessel and turbine is a complex, weather-constrained operation.<br>• Modifications to the turbine tower and/or nacelle are likely to be necessary to support the crane.<br>• Safety concerns if extensive crane assembly is required within or on top of a moving nacelle.<br>• May not be suitable for all types of substructure. |
| Vessel-mounted cranes | • Suitable for most substructure types.<br>• Limited turbine modifications required. | • Sophisticated motion-compensation systems required to minimise relative motion between the crane hook and turbine nacelle. |

**2** **Reduction of relative motion between the crane hook and turbine nacelle is a key technical challenge to HLM operations.**

In order to exchange a blade or drive train component from a floating wind turbine, the relative motion between the crane hook and turbine nacelle must be minimised to give displacement errors typically less than one metre. Remaining misalignments can then be accommodated by bumpers and guide systems.

Temporary turbine-mounted crane systems achieve acceptable relative motions by mounting the crane directly onto the floating turbine structure, either on the top section of the tower or the nacelle mainframe, such that the crane moves with the turbine. To prevent unacceptable motion of the components as they are being lifted (either due to substructure motion or wind loads which could lead to the lifted components striking the tower) additional restraints such as tag lines would be required.

Although turbine-mounted cranes solve the relative motion challenge, they are disadvantaged by the complex operation required to transfer the crane between the support vessel and turbine structure. They also require bespoke modifications to the turbine tower and/or nacelle to provide fixing points to the turbine structure.

Vessel-mounted crane solutions require complex motion-compensation systems to achieve the necessary reduction in relative motion between crane and turbine. These are likely to include multiple systems, such as a vessel DP system to reduce low frequency displacements of the vessel relative to the turbine substructure and 3D motion compensation systems built into the crane boom to address higher frequency horizontal and vertical translations of the crane hook relative to the turbine nacelle.

While the vessel-mounted crane technologies require more complex solutions to address relative motion, their advantages include much reduced set-up time and minimal modifications to the turbine structure.

Traditional heavy lift vessels provide inherently stable platforms due to their size and mass. However, in this application it is not sufficient for the HLV crane to have little movement in an absolute reference frame: the crane requires little motion *relative* to the floating turbine which may itself exhibit higher motions in an absolute reference frame than the HLV.

**3** **Vessel-mounted solutions are expected to operate with any type of substructure and tower, whereas turbine-mounted solutions may be better suited to specific substructures.**

The main differentiator in terms of the applicability to service different types of floating WTG foundations is the type of HLM technology. The vessel-mounted crane solutions are expected to be able to operate with any type of floating wind foundation. Initial concerns that the draught of the vessel may interfere with the turbine mooring system were satisfactorily addressed by the developers and operations appear feasible from a vessel held at a distance of approximately 10m from the foundation using their dynamic positioning system.

The vessel-mounted crane solutions can work completely independently of the nacelle and tower design, possibly only requiring the installation of optical targets onto the turbine structure as part of a position reference system.

The turbine-mounted crane solutions are less broad in terms of their applicability to different foundation types. One of the considered technologies requires the vessel to be positioned close to the tower during transfer of the crane system and so is better suited to substructures with small footprints such as spars. Another concept, on the other hand, requires a laydown area at the bottom of the tower from which components can be loaded/off-loaded by a vessel crane. Such a system would be better suited to a semi-sub or barge substructure on which a lay-down area can be more easily accommodated.

The turbine-mounted solutions are inherently connected to the tower structure, and as such, some form of modification to the tower or nacelle mainframe will be required.

**4** **The speed of crane deployment is key to reducing costs associated with component exchange campaigns.**

Within the HLM study, a range of enabling technologies were assessed in terms of their technical feasibility, logistical challenges and expected costs. A range of wind farm conditions and turbine requirements were considered, including:

- Distance to shore (50km & 100km);
- Size of turbine (10MW & 15MW);
- Component type (blade and gearbox);
- Met-ocean conditions (P25, P50 & P75 Hs for benign and exposed locations);
- Single component exchange and 50-unit campaign exchange.

An O&M logistics model was used to estimate the durations of O&M operations associated with each candidate HLM technology. The associated costs were then estimated as the sum of vessel charter costs and the cost of lost energy production. As many of the candidate technologies were in an early stage of development, it was not possible to estimate technology rental or purchase costs when these were distinct from the vessel costs, and so these technology costs were not included.

Modelling of campaign exchange operations revealed that temporary crane solutions requiring long durations for assembly and disassembly led to requirements for long vessel charter periods and therefore high costs.

Figure 7 compares predicted costs for a 50-unit component exchange campaign for a baseline HLV vessel and four HLM-enabling technologies (A-D). Temporary turbine-mounted crane technologies A and D required assembly and disassembly durations of up to 2.5 days per turbine, leading to significantly higher costs than a vessel-mounted crane (C). The multiple bars per technology (see key) show the conclusion to be relatively insensitive to weather conditions, turbine size, distance to shore and component type.

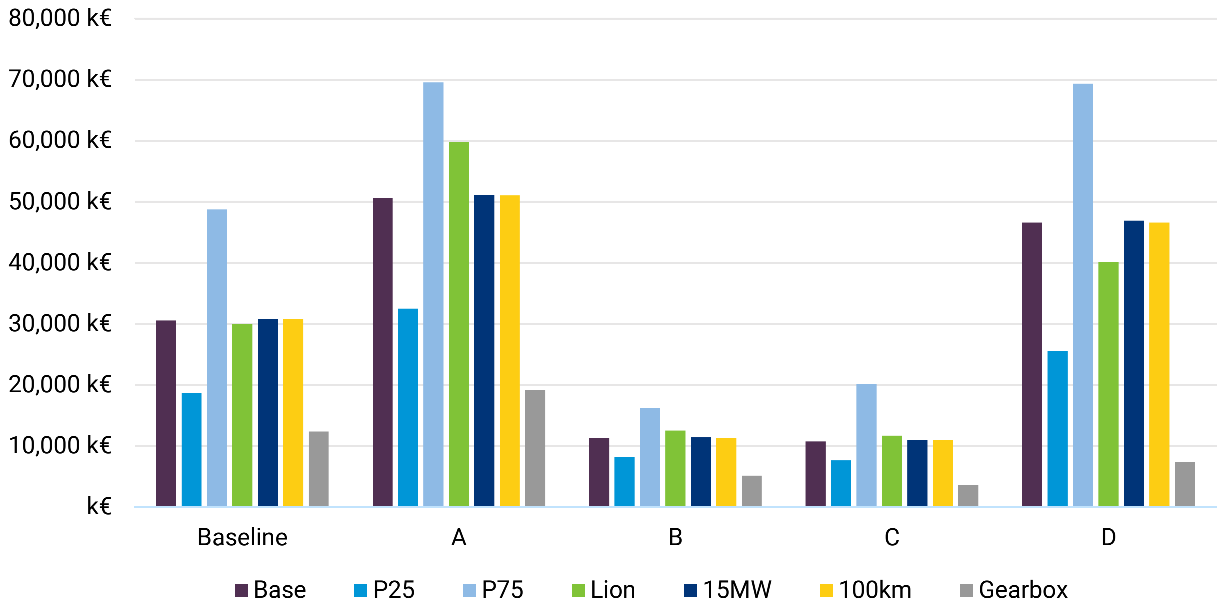



**Figure 7: HLM campaign exchange costs. Base refers to the 10MW blade set exchange at Hywind Scotland conditions, 50km to port with P50 conditions scenario.**

**5** **Vessel-mounted cranes currently appear to provide the most suitably available solution for HLM operations whilst other technologies still require further development.**

The technical reviews showed that the major advantage of the vessel-mounted crane solutions was found to be the deployment speed, given that no crane transfer or assembly is required. The main disadvantage, however, is the requirement for a motion-compensation system to remove relative motions between the crane hook and the turbine nacelle. The motion-compensation requirements in this case are less driven by heave compensation (which may be added relatively easily to the hook of conventional crane) and more driven by the need to compensate for horizontal motions resulting from pitch and roll of the vessel and turbine.

Turbine-mounted crane solutions benefit from the fact that, once installed, relative motions between the crane and turbine are removed, requiring no active motion compensation systems within the crane. A challenge of controlling the motion of the payload during the lift remains, which might be addressed using tag lines. The disadvantages of the turbine-mounted systems were found to be (i) the logistical challenge of transferring the crane between the service vessel and turbine, (ii) the need to assemble and disassemble the crane system on every turbine, and (iii) required turbine modifications such as strong points and tower shell reinforcement.

The outputs of the logistics assessment and costs assessments are summarised by the predicted single exchange costs in Figure 8. These costs comprise vessel charter costs and costs of lost energy production but exclude individual technology rental/purchase costs. The results suggest that for single component exchange, the least expensive solution is provided by a vessel-mounted crane (C), closely followed by one of the turbine-mounted crane technologies (B).

The baseline HLV is expected to be the most expensive solution for single component exchange, although it was found to be more competitive in the campaign exchange scenario (see Figure 7). The graph also shows that the ranking of the technologies for single component exchange costs is relatively insensitive to weather conditions, distance to port, turbine size and component type.

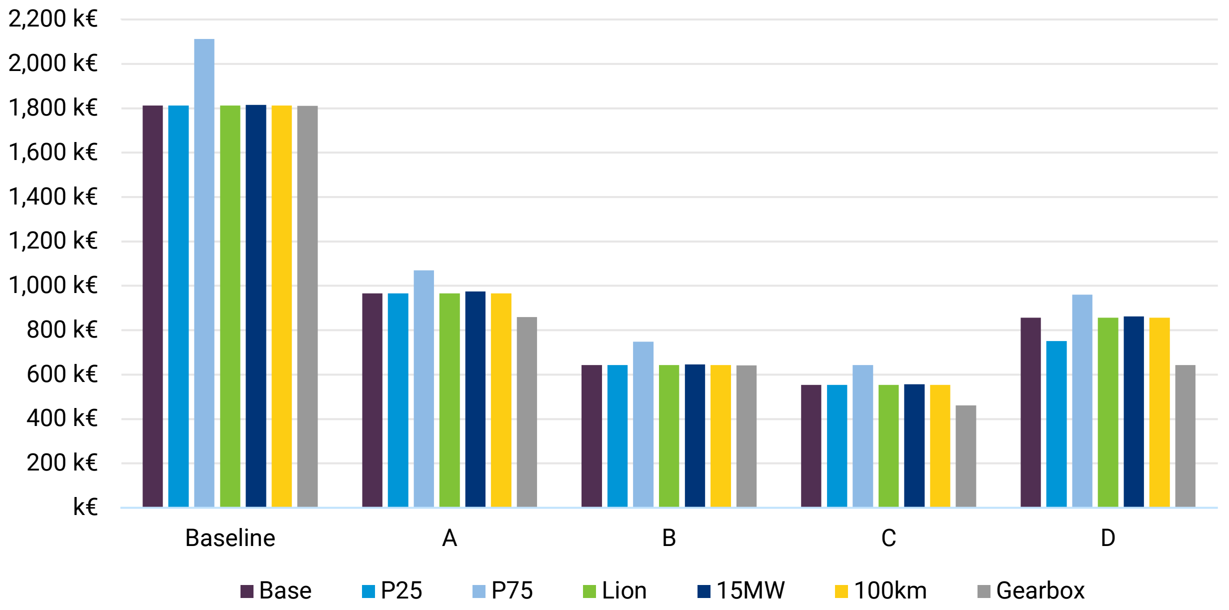



**Figure 8: HLM single component exchange costs. Base refers to the 10MW blade set exchange at Hywind Scotland conditions, 50km to port with P50 conditions scenario.**

## 2.3 Innovation/technology needs

**1 Alternative HLM technologies are at different stages of TRL and need further development.**

The different HLM technologies that were reviewed were found to span a wide range of development maturity. on this basis the following development needs were noted for each technology type.

Further development requirements for turbine-mounted cranes were found to include:

- Refinement of procedures to transfer cranes between the service vessel and floating turbine.
- Engagement with turbine OEMs in order to define acceptable fixing positions and possible tower reinforcement.
- Further development of lifting procedures, including considering whether a lay-down area is required at the tower base or whether components can be lifted directly to/from an attending vessel.
- Review of safety issues related to personnel working in/on a moving nacelle.

Further development needs of vessel-mounted cranes were found to include:

- Development of the motion-compensation systems to achieve (i) successful integration of DP and crane boom systems and (ii) acceptable crane hook motions relative to the moving nacelle of a floating wind turbine.
- Demonstration of the integrated vessel and motion-compensation systems.

**2 Development of tools and guides would aid accurate positioning of WTG components.**

It is apparent that even with development of HLM technologies, the industry could benefit from the development of special tools to aid the accurate positioning of components during an exchange operation.

There is a particular requirement for tools to enable safer ‘stabbing’ of the WTG blades during their exchange. These could be tools similar to the High Wind Boom Lock for horizontal blade exchange or a tower crawling crane which vertically stabs one blade at a time.

For exchange of components inside the nacelle, adapted bumpers and guides systems are expected and these should be considered in an early phase of the turbine design process.

# 3. Key findings: Tow to Port Maintenance

## 3.1 Study overview

Operation and Maintenance (O&M) is arguably one of the most discussed and analysed issues in fixed offshore wind farms, reflecting the difficulties experienced by wind farm owners in reducing operational expenditure due to large vessel hire costs and environmental constraints on accessibility. For floating wind farms, offshore maintenance is significantly more difficult due to the motions of the floating turbine and maintenance vessel. A potential solution to this problem is to tow the floating wind turbine structure back to port for major turbine maintenance operations (e.g. gearbox replacement). This is an attractive option if a suitable port is located nearby.

The implementation of a tow-to-port maintenance strategy for major component maintenance operations, which would otherwise require chartering large and expensive maintenance vessels (as outlined within the HLM study summary), isn't without its intrinsic risks and technical challenges. The recurrent requirement for towing the floating offshore wind substructures back and forth creates the need for innovative technologies that optimise the connection and disconnection of moorings and/or subsea power cables, reduce vessel requirements, reduce health and safety (HSE) risks, address the challenges related to substructure stability during tow, addressing at the same time port limitations such as under keel clearance.

The TTP study specified general principles and requirements for tow-to-port maintenance of floating wind farms. The objectives of the study were to:

- Investigate the procedures for disconnecting and reconnecting floating wind units in a large-scale wind farm.
- Evaluate key challenges and identify solutions to mitigate risks and costs.
- Identify and assess innovative technologies to enable tow-to-port maintenance.
- Undertake detailed feasibility studies and produce detailed method statements for tow-to-port maintenance operations based on the set of identified technologies.
- Undertake logistics assessments for large wind farm maintenance campaigns, with component exchanges on multiple turbines and including the effect of weather windows. This includes the replacement of 2 major components: a gearbox and a blade set for a 10MW and a 15MW turbine.
- Produce robust cost estimates for different maintenance strategies in different conditions.
- Evaluate technology development needs to optimise tow-to-port operations and engage with the market to identify additional innovative solutions.

This TTP study and the related Heavy Lift Maintenance (HLM) study were both performed by London Offshore Consultants (now AqualisBraemar LOC Group) and WavEC, and as such were carried out in conjunction, with similar methodologies to ultimately provide a comparison between different maintenance strategies which is given in Section 3, to conclude if there is a preference for strategy and technology for different turbine sizes, substructure types and wind farm characteristics. The high-level objective of these studies was to examine two alternative strategies for performing heavy maintenance on floating wind turbines, namely (i) performing operations from a floating platform within the wind farm array (HLM) and (ii) towing the turbines to shore for port-side maintenance (TTP).

**Figure 9: WindFloat Atlantic tow from port to site operation**

## 3.2 Key findings

**1 The more promising technologies evaluated benefited semi-sub structures whereas few addressed the specific challenges of TTP maintenance for TLP and spar substructures.**

The level of challenge concerning dynamic power cables connection/disconnection is likely to be fairly similar for the different types of floating wind substructure (FWS) and although intrinsically complex (depending on the technology option) the process is moderately well established. Mooring systems differ according to the type of substructure, thus requiring different connection and disconnection procedures, namely in respect to ensuring line or tendon tensioning. Overall, such procedures are relatively standard, facing moderate challenges, except for the case of the tension-leg platform (TLP), in which stability of the substructure needs to be ensured once the mooring system has been disconnected, particularly during the towing operation.

Semi-submersible substructures typically have comparably shallow draughts and float in a similar manner to ships. Hence, for this type of substructure, a wet tow is expected to be a relatively straight-forward operation. For installation, spar substructures are typically wet or dry-towed in the horizontal position to sheltered waters, where they are then upended, stabilised, and the WTG is mounted using heavy lift vessels. The whole assembled structure is then wet-towed in the vertical orientation to the wind farm site. The large draught of spar substructures creates major logistical challenges for port-side maintenance (assuming no WTG decoupling in the TTP scenario), with draught requirements not available in ports, limiting the TTP strategy to deep water sheltered waters.

Despite having many advantages, especially in very deep-water applications, TLPs are typically unstable when disconnected from the mooring tendons, requiring the development of innovative solutions. There are new technologies evolving, such as stabilisation frames to enable tow-to-port maintenance of TLP FOWT, which would be relatively quick to install. However, the technology is not currently conducive with larger scale turbines. Equally, although the technologies have been proven for smaller single turbines, the logistics of installing a support frame for each tow during the lifetime of the farm would be time consuming and may not be cost-effective.

Table 4 summarises the findings of the initial assessment of the TTP strategy.

**Table 4: Summary of potential impacts of limiting factors on each operation**

| Limiting factors on each operation | | Power cable connection/ disconnection | Mooring lines connection/ disconnection | Tow FWT from site to port/shelter | Port-side maintenance | Sheltered waters maintenance |
|---|---|---|---|---|---|---|
| FWS typology | Semi-sub | | | | | |
| | Spar | | | | | |
| | TLP | | | | | |
| Site characteristics | Sea State | | | | n/a | n/a |
| | Water depth | | | | n/a | n/a |
| | Distance to port/site | | | | n/a | n/a |
| Equipment requirements | ROVs | | | n/a | n/a | |
| | Other | | | | | |
| Port requirements | Maximum depth | n/a | n/a | | | n/a |
| | Crane capacity | n/a | n/a | n/a | | n/a |
| | Entrance Width | n/a | n/a | | | n/a |
| Vessel characteristic | Deck Space | | | | | |
| | Crane capacity | | | n/a | | |
| | DP | | | | n/a | |
| | Vessel availability | | | | | |
| Contribution to maintenance costs | | | | | | |

**Key:**

Very large potential implications on feasibility

Significant potential implications on feasibility

Limited implications on project feasibility

No anticipated implications on feasibility

The study assessed different technologies to enable tow-to-port operations, but after the initial assessment, enabling technologies were found less impactful for TLP and spar foundations, and as such the focus in the subsequent stages was mainly on the application to semi-sub substructures.

## 2 Port infrastructure and current onshore crane lifting height may be limiting factors for successful commercialised TTP maintenance.

Both towing operations and port access for large floating units will require ports with sufficient channel width, maintained water depth, and quayside length. Port-side maintenance of next generation wind turbines will require very large cranes to achieve enough lift height, reach, and capacity to undertake large component exchange (e.g. blade, gearbox). The combination of lift height, capacity and reach necessary for port side maintenance are only met by a limited number of cranes worldwide. Since very few onshore mobile cranes are able to operate at heights required by these operations (up to 150m-200m), an increase of market availability of such cranes might be required, as these are currently very costly (approximate cost €10k/day) and their limited availability could be a bottleneck for future maintenance.

Chartering jack-up vessels for port-side maintenance might be a possible alternative to using very large and costly onshore cranes, if seabed properties are adequate within the port for jack-up operations. In the elevated position, cranes onboard of jack-up vessels may more easily achieve the required lifting heights. However, in such cases, crane capacity and vessel availability may become challenging.

For large maintenance campaigns, improvements in efficiency and cost-reduction of maintenance activities may be achieved if the port is able to accommodate more than one structure at a time. This should be particularly evident if dry-docks are to be used given their significant daily costs (although this approach is unsuitable for spar substructures and their availability for 14 MW semi-sub or TLPs may be an issue). The availability and costs of cranes to achieve enough lift height, reach, and capacity to undertake large component exchange in 14 MW turbines is a challenge to be addressed.

The “tow to sheltered waters” option was assessed as a potential alternative to tow-to-port. For semi-subs, tow to sheltered waters may be a technically feasible, though potentially expensive, alternative to tow-to-port maintenance when a suitable port is too far away. The reported findings suggest that spar FOWTs will not benefit from a tow to sheltered waters strategy due to the lack of marine infrastructure in most geographical locations. The main constraints are related to the large substructure draft, for which there are no Heavy Lift Jack-up vessels available that satisfy both the water depths imposed by the draught of a spar substructure and the lifting capacity required.

## 3 Quay loadbearing capacity was found to be one of the most important port requirements.

During the port infrastructure logistics assessment, assessing 10 and 15 MW floating offshore wind turbines, one of the most important port capabilities was found to be the quay loadbearing capacity, i.e. having appropriate shore facilities for loading and unloading large wind turbine components with bearing capacities of at least 10 tonnes/m$^2$. Though potentially a bottleneck, the capabilities of existing port cranes was found to be less important as it is likely that temporary onshore cranes would have to be mobilised to achieve the required lift heights or, as an alternative, jack-up vessels would have to be used.

**4** **Tugs with dynamic positioning capabilities and SOVs with motion compensated gangway systems are recommended for better station keeping and safe transfer of cargo and personnel.**

TTP strategies are intended to mitigate the need for large heavy lift vessels, thus having a significant positive impact on overall maintenance costs. Availability of suitable vessels and marine contractors is nevertheless an important issue to ensure low-cost towing operations. Vessel selection is also vulnerable to sea states, as harsher sea states and severe wind conditions present a significant challenge to personnel boarding and the towing procedure, as do longer distances to port. Water depth, however, does not represent a challenge to the towing process itself except when the depth is insufficient for the substructure draught.

Towing procedures should be carried out using tugs of sufficient power and arranged in such a manner as to give adequate speed, control and holding power. Such vessels should have DP capability for better station keeping and manoeuvring capability to deal with emergency situations and restricted water tow. At least two towing vessels will be required to guarantee directional stability of the substructure being towed and to achieve a better towing speed.

A vessel fleet was proposed consisting of one Anchor Handling Tug Supply (AHTS), one ocean going tug for substructure towing and positioning, and one support vessel to carry out connection and disconnection activities. For the operations associated with most of the short-listed technologies, a Service Operation Vessel (SOV) was recommended as the support vessel due to the advantages of a motion compensated gangway system to safely transfer both cargo (e.g. temporary winches) and technicians onto the substructure. Finally, a list of equipment that can be expected to be used during a tow-to-port maintenance was defined, including temporary winches, work class Remotely Operated Vehicle (ROVs), motion compensated gangways and onshore cranes.

**5** **When analysing scenarios with a maximum distance to port of 100km, installation of a temporary cable joint to maintain array cable continuity was found to be more time consuming than FOWT absence from the site.**

The retrieval phase is a particularly challenging step of the entire tow-to-port maintenance process. Cables must be disconnected and safely wet-stored either on the seabed or temporary out-of-service arrangement. Although cable connectors may expedite the connection and disconnection process in particular, it is equally important to consider the associated rigging activities. For turbines connected in a daisy chain configuration, ensuring cable continuity is an arduous operation that requires disconnecting the cable (which at present will require cutting the cable if no connector is installed), removing lazy ‘s’ buoyancy elements, laying the cable on the seabed, disconnecting the moorings and wet-storing them, towing the substructure clear from site, retrieving the cable from the seabed, installing a cable joint, continuity testing, and finally, safely laying the cables back to the seabed. Such operation is long and expensive, and, throughout the entire process, the energy production is halted for the entire string of wind turbines installed upstream and downstream of the FOWT being serviced. This will likely result in significant revenue losses. It follows that electrical connection/disconnection technologies must address this challenge in a holistic manner.

The installation of a temporary cable joint was proposed as the standard approach to reduce array downtime for the baseline and for those shortlisted technologies which did not address the loss of electrical continuity of the array 'daisy chain' after disconnecting the FOWT. However, upon analysis of the durations it was found that installing the cable joint may not provide a cost-effective solution to reducing the revenue losses, given the assumed port-site distance and durations of port repairs. This is based on the assumption of temporary cable joint installation taking ~100 hours and the maximum distance to port analysed was 100km, whereas longer distances (above 300km) through harsher conditions may benefit from the installation of a temporary cable joint. Further analysis would be required to understand the parameters at which (or if) the installation of a cable joint becomes more favourable than omitting an entire string of operation.

The process for disconnection and reconnection of the mooring lines can cause many problems for the TTP procedure. Prior to disconnection, the mooring lines must be de-tensioned. This is typically achieved by positioning the substructure with the help of positioning tugs, and sometimes winches. If possible, the mooring lines must be laid on the seabed, away from the power cables in case they were also wet-stored on the seabed.

Dynamic power cable connection/disconnection operations will typically require a vessel with sufficient deck area and lifting capacity to handle the connector and/or cable weight, with vessel availability not expected to be an issue. Mooring lines connection/disconnection operations are also likely to be carried out using commonly available and relatively inexpensive vessels, such as SOVs which could be used without significant adaptation. In both cases (power cables and moorings connect/disconnect operations) dynamic positioning is a key issue to guarantee operational efficiency.

Site characteristics, such as sea state and water depth, have a strong influence on procedures for connecting and disconnecting dynamic power cables and mooring lines. Significant water depths may increase the duration of the dynamic power cable connection/disconnection procedures, especially if these require lifting elements from the seabed (e.g. cable connector or splice linking the dynamic to the static power cables or pull-in the cables from the seabed).

**6 Significant reductions in operation duration were found using an integrated solution for disconnection/reconnection of moorings and power cables.**

One major finding of the logistic assessment was that the most beneficial technologies were those which provide integrated solutions to the mooring and electrical cable disconnection/reconnection, as well as providing electrical continuity after disconnecting the FOWT. The potential advantages of implementing an integrated solution were clearly demonstrated in the simulations, but similar reductions in duration could also be achieved by using a combination of other technologies. The current available technologies reduce duration but are at different development stages. Further analysis might reveal potential benefits in combining other technologies.

### 7 Technologies that remove the need for laying down and retrieving cables also greatly reduced the duration of operation.

The potential benefits of simultaneously addressing the mooring and power cable connection challenges, even when using separate technologies, were demonstrated and quantified. Results suggested that removing the need for laying (and retrieving) the moorings and power cable on (and from) the seabed greatly speeds up the connection and disconnection process. Most importantly, it eliminates the requirement for removing (and reinstalling) the cable buoyancy modules which would require about 16 hours per connection and disconnection, significantly reducing the total operation durations. These design decisions were shown to translate into significant cost-reductions, which were further accentuated if electrical continuity of the array was ensured during the turbine's absence from site.

### 8 Most assessed technologies showed reduced costs and durations compared to the baseline, but implementing a combination of technologies would yield the best results.

Various technologies were compared against a baseline scenario, which provided a representation of how tow-to-port maintenance could be effectively achieved at present or in the very near future, using existing technologies. The entire tow-to-port maintenance strategies were broken down into three stages:

i. The retrieval, which requires the disconnection or the power cables, mooring cables and towing the FOWT to port,
ii. The maintenance activity per se, where the turbine is serviced,
iii. The redeployment, a reverse sequence of step i.

Prior to the retrieval phase, substructure inspections and preparations will also be required including ensuring the integrity of the mooring connections has not been compromised due to marine growth, which could require cleaning and the removal of biofouling using ROVs or divers. By approaching various floating wind project and technology developers, current practices could be determined and the baseline TTP procedure had the following modelled assumptions:

- The WTGs are connected in a daisy chain configuration;
- There is no electrical quick connector, but instead uses traditional HV separable connectors;
- Electrical continuity is ensured using a semi-permanent cable joint;
- After disconnection the cable is laid on the seabed;
- An ROV is required to support connection since the mooring line connectors are submerged;
- Tensioning of mooring lines requires vessels that specifically have sufficient bollard pull capabilities or winch capacity.

Once the retrieval phase can start the turbine will be remotely shut down and the subsea power cable can be disconnected by disconnecting cable conductors, capping and sealing the cable ends. The cable must then be protected and connected to a marker buoy for quicker retrieval and safely laid on the seabed until reconnection.

However, this wet-storing approach will most likely require the removal of the buoyancy elements of the cable since the lazy-S configuration would allow the cable to move around in the water column and particularly expose it to damage from anchor handling and vessel collisions. This introduces additional vessel requirements to handle the cable, and long durations of the connection and reconnection operations.

Analysis was carried out to assess the feasibility of using new and novel technologies to reduce costs (due to vessel hire) and durations of the baseline methodology outlined above. The technologies under assessment mostly addressed challenges related to the connection/disconnection of the power and mooring lines either by improving operations duration and safety or by reducing vessel and equipment requirements. Two technologies addressed power cable connection/disconnection procedures and out-of-service arrangements, four technologies addressed mooring connection/disconnection, one technology addressed shared mooring and power cables connection and disconnection and out-of-service arrangements, and one technology facilitated the towing operations of a TLP.

For the shortlisted technologies, different scenarios were simulated using WavEC's in-house logistic tool, in order to quantify the impacts of the met-ocean conditions (Hywind Scotland or Gulf de Lyon) and distance to port (50km or 100km) on the operational durations. The two component exchanges considered were a blade set exchange and gearbox exchange for a single component repair and in the context of a 50-turbine campaign.

**9** **The met-ocean conditions of the location, or month of component exchange, could have drastic implications on lost revenue due to downtime for a single component exchange,**

For the single cycle repair, the simulation results showed that implementing most technologies resulted in significant reductions in operation durations (including weather contingencies) relative to the baseline. In a single component exchange cycle the main conclusions were:

- selecting different months could have drastic implications on lost revenue due to downtime;
- the impact of type of component (blade or gearbox) had negligible effects on the total durations;
- the increase in distance to port from 50km to 100km resulted in small increases in total operation durations, mostly attributable to the increase in net transit/tow durations;
- selecting less energetic met-ocean conditions, such as Gulf of Lyon, dramatically reduced the expected waiting on weather.

It was found that all considered technologies have attractive benefits for floating wind projects. Results suggest that implementing the shortlisted technologies generally resulted in shorter operational durations, lower weather risks and ultimately in lower operational costs. Technologies that provided a solution to ensure electrical continuity of the array string after disconnecting the substructure have reduced the expected revenue losses due to downtime, and consequently the total costs.

The costs associated with a TTP maintenance strategy must be assessed as the sum of changes to CAPEX and OPEX costs. Depending on the technology option, dynamic power cables connection/disconnection procedures may imply relevant upfront costs of connectors for swifter operations, which can be avoided by opting for a cut and join solution, with potentially higher risks and uncertainties. ROV costs and/or HSE risks for divers must be considered. For moorings connect/disconnect, there is the need to resort to cost-effective connectors which are resistant to corrosion and biofouling, enabling connection with readily available tug and/or anchor handling vessels.

The outputs of the logistics assessment and costs assessments are summarised by the predicted single exchange costs in Figure 10. It is worth noting that these do not represent total costs of the TTP procedures, as technology-specific purchase or rental costs have not been considered. The presented costs represent the costs of the exchange due to lost energy production revenue, port costs and vessel charter costs. It is evident that although the baseline approach was found to be one of the solutions with the highest revenue loss due to downtime, other technologies increased the exchange durations to a point where the total exchange costs were more expensive than the baseline. The gearbox exchange was consistently found to be more expensive than the blade set exchange, due to longer service durations at the port, although the cost difference was negligible in terms of total exchange costs (<0.5%). It is clear from the multiple bars per technology shown in Figure 10 that the single exchange costs are relatively insensitive to weather conditions, distance to port, turbine size and component type.

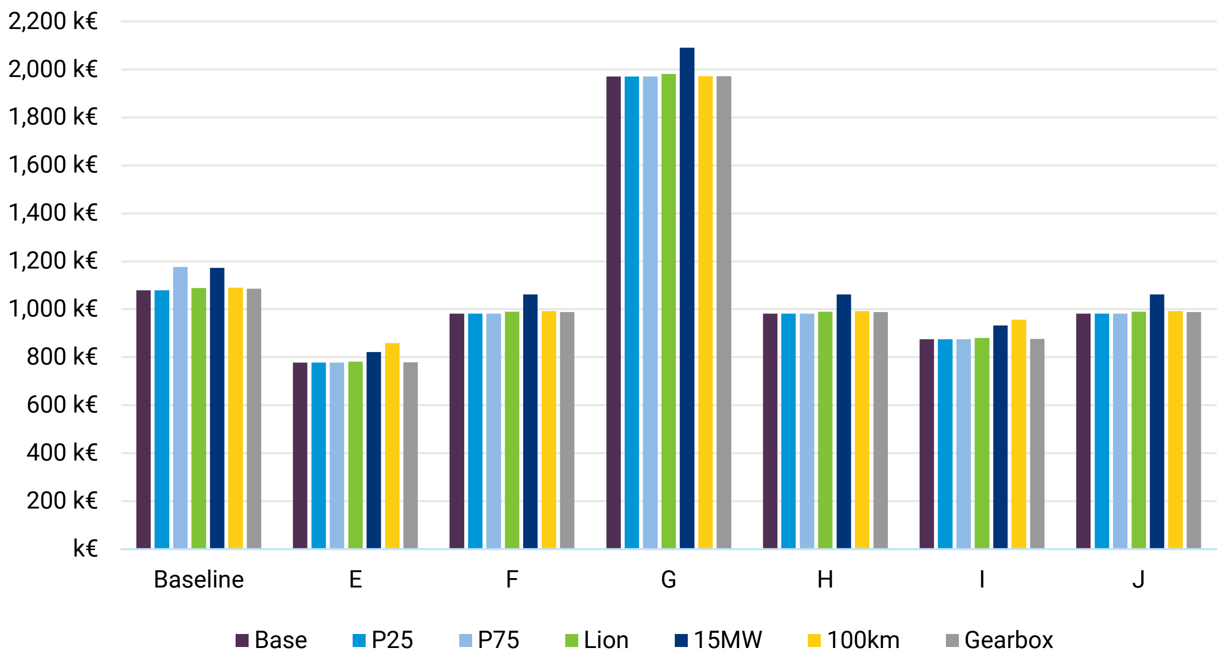



**Figure 10: TTP Single component exchange costs. Base refers to the 10MW blade set exchange at Hywind Scotland conditions, 50km to port with P50 WoW conditions scenario.**

**10** **Tow-to-port maintenance will generally require more than one fleet to complete a 50-turbine campaign within the March-October weather window, even with novel technologies.**

Finally, in respect of the campaign maintenance scenario, simulations were carried out to assess how many turbines could be serviced in each month using different technologies and to identify for which months the campaign intervention should ideally be scheduled.

When using a single fleet of vessels and carrying out the maintenance operations in a sequence, one turbine at port at a time, the servicing of 50 FOWT in the North Sea was, in most cases, expected to take more than a year. However, for less energetic weather climates such as in Gulf of Lion, most technologies allow servicing 50 FOWT in less than a year. It was also found that at more benign sites the selection of the starting month of the campaign intervention is less important. However, to reduce the expected campaign duration due to waiting on weather, it was found that campaign intervention should ideally take place during the March to October window, indicating that more than one fleet will be required for most technologies to ensure the 50-turbine campaign exchange is completed within a single season.

The total exchange costs showed a similar ranking to the single component exchange, although they proved to be more sensitive to weather conditions, distance to port, turbine size and component type than for the single exchange.

## 3.3 Innovation/technology needs

**1** Cable connection/disconnection procedures will need continuous development to adapt to the use of higher power turbines and higher power cables.

Dynamic power cables connection/disconnection procedures for next generation, higher rated capacity turbines will likely require the development of new connectors, with higher voltage and rated power, as the existing commercial solutions have been designed mostly for the O&G sector. Among other challenges, such connectors will need to demonstrate that they can perform reliably for long operational periods and ensure that cable condition monitoring can continue without disruption. The new turbines will require larger substructures and, consequently, more robust mooring designs. It is then expected that mooring connect/disconnect operations will be slightly more challenging. For the same reason, towing operations will require more robust equipment (e.g. higher strength towlines) and possibly higher power tugs, thus presenting, to some extent, a greater challenge.

**2** There is a requirement for vessel design to change to adapt to towing in harsh sea states.

TTP strategies are intended to mitigate the need for large heavy lift vessels, thereby reducing overall maintenance costs. Availability of suitable vessels and marine contractors is nevertheless an important issue to ensure low-cost towing operations. Towing is likely to influence the structural design requirements of the floating structures in that hull designs will need to be suitable for towing in harsh sea states to maximise operating windows.

**3** Supplementary availability of suitable cranes for port maintenance will be required to ensure maintenance activities do not impact on electricity generation.

Port-side maintenance of next generation wind turbines will require very large cranes to achieve enough lift height, reach, and capacity to undertake large component exchange (e.g. blade, gearbox). Currently, very few onshore cranes can be mobilised for use in port side maintenance, that have sufficient lift height and capacity. Greater availability of suitable cranes would assist the sector in the future and ensure maintenance activities would not become a bottleneck for wind farm operation.

**4** Further development of temporary cable joints could enable quicker installation durations, reducing overall maintenance durations at most site locations.

Although cable connectors may expedite the connection and disconnection process in particular, it is equally important to consider the associated rigging activities. For turbines connected in a daisy chain configuration, ensuring cable continuity is an arduous operation which is long and expensive, and, throughout the entire process, the energy production is halted for the entire string of wind turbines installed upstream and downstream of the FOWT being serviced. This will likely result in significant revenue losses.

Temporary cable joints could be used to reduce array downtime, however upon analysis it was found that the time taken to install the cable joint did not reduce overall maintenance duration if the TTP operation happened with traditional disconnect/connect techniques. This is based on current temporary join installation taking ~100 hours. At longer distances (above 300km) and harsher conditions, this option could be viable. Reducing the installation time could make this option viable and further reduce maintenance operation durations.

## 3.4 HLM and TTP comparison

To enable comparison of the TTP and HLM technologies, the same methodologies were used to assess the operational durations and costs of single component exchanges and campaign component exchanges. For each technology, costs were estimated as the sum of vessel charter costs, the cost of lost energy production and (for TTP technologies only) the cost of onshore crane hire. It should be noted that as many of the candidate HLM & TTP technologies were in an early stage of development, it was not possible to estimate technology rental or purchase costs when these were distinct from the vessel costs, and so these technology-specific costs were not included.

It is important to note that one of the recommendations for TTP maintenance was to use a combination of technologies, as each technology addressed a different challenge and some were not directly comparable. Equally, for an operating wind farm it will be highly likely that a combination of maintenance methodologies will be required, depending on the nature of the repair. For example, turbine-mounted crane HLM technologies may be better suited to an emergency repair as they can be easily stored near the site, whereas a combination of TTP technologies could be used for a campaign that does not have the same time pressures. This may also depend on weather conditions, distance to port and turbine size.

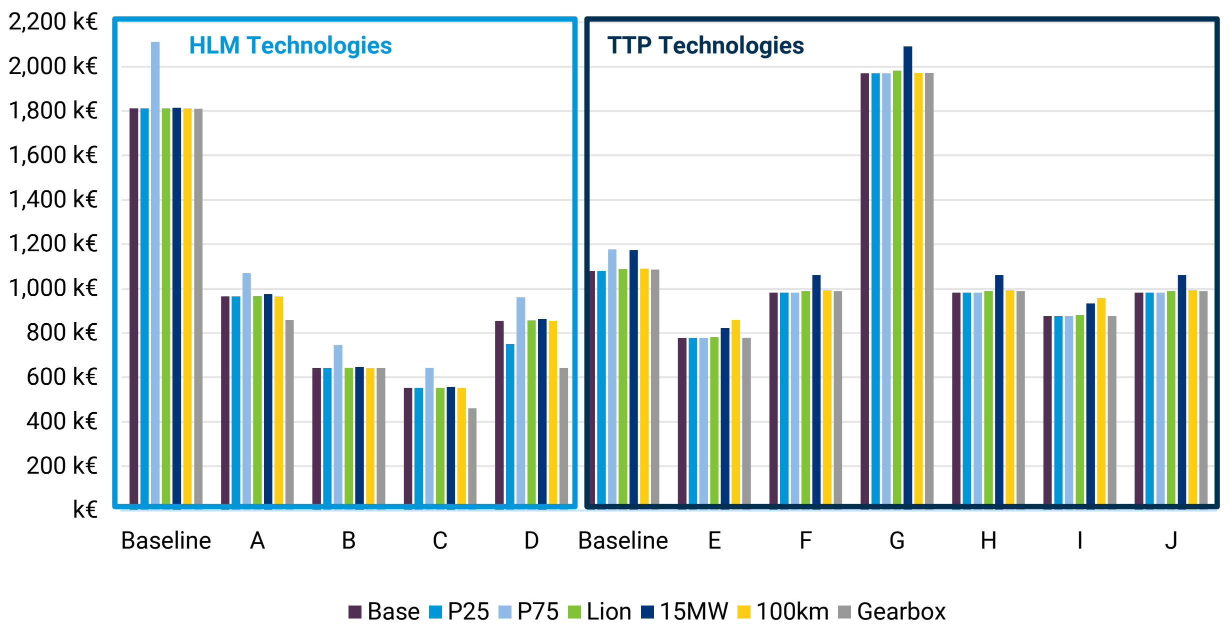



**Figure 11: Comparison of HLM and TTP single exchange costs. Base refers to the 10MW blade set exchange at Hywind Scotland conditions, 50km to port with P50 WoW conditions scenario.**

The results plotted in Figure 11 suggest that the lowest cost single component exchange operations can be achieved using HLM technologies. The ranking for both HLM and TTP technologies is seen to be relatively insensitive to site metocean conditions, distance to port, turbine size and component type.

The results plotted in Figure 12 suggest that the lowest predicted 50-turbine campaign exchange costs can also be achieved using HLM technologies. More variation can be seen in the HLM costs than the TTP costs as metocean conditions are varied, either by changing site (Hywind/Gulf de Lyon) or WoW percentile (P25/P50/P75). This is due to the more sea state limited operations being performed offshore for HLM maintenance rather than in port.

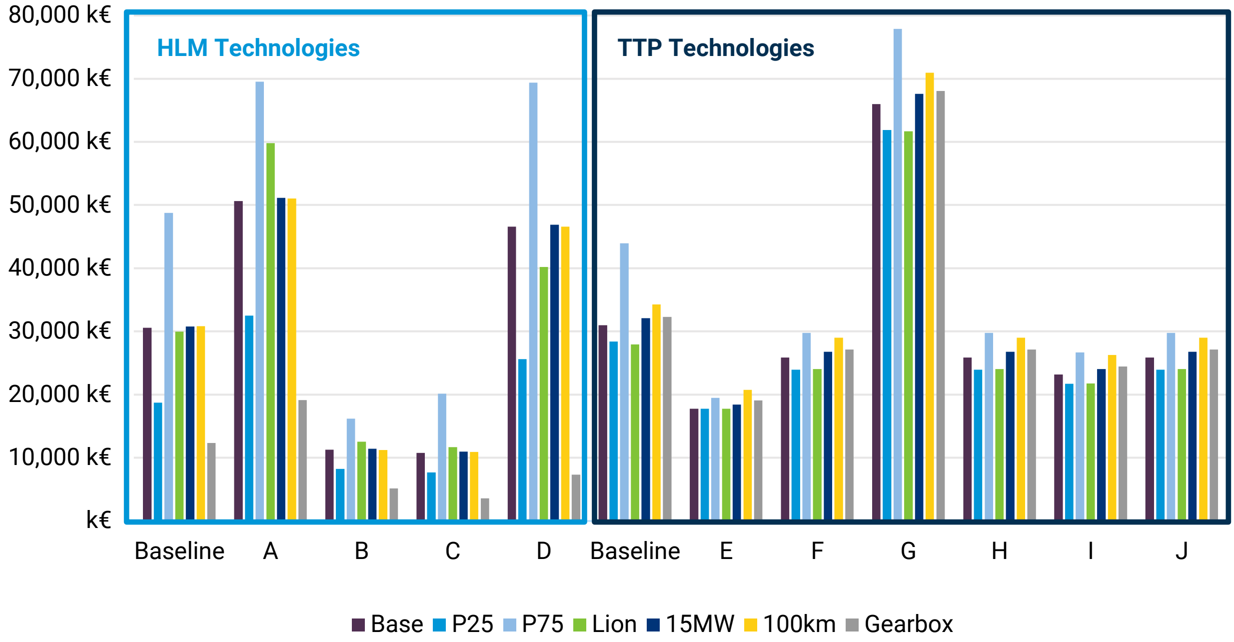



**Figure 12: Comparison of HLM & TTP campaign exchange costs. Base refers to the 10MW blade set exchange at Hywind Scotland conditions, 50km to port with P50 WoW conditions scenario.**

When drawing overall conclusions from these comparisons, the following points should be noted:

1. Vessels costs for both HLM and TTP technologies are based on best estimates and are assumed not to vary during the year. In practice, vessel costs can vary considerably due to market conditions or may remain stable if a long-term charter contract is in place.

2. Since undertaking of these reviews, many of the technologies have been developed further. At an appropriate point the logistics and costs should be reanalysed to show the effects of design changes on predicted costs.

3. Combinations of TTP technologies, or other technologies not assessed, which together provide a “quick-connect” functionality for moorings and power cables may perform as well as the quick-connect technology that was assessed positively in the TTP study.

4. Consideration of upfront technology cost and other logistical aspects, not just the exchange costs outlined in the sections above, is required when comparing or selecting technologies. This could include the challenge of vessel to turbine transfers and potential requirements for turbine modifications when using turbine-mounted HLM technologies.

# 4. Key findings: Mooring Systems in Challenging Environments

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## 4.1 Study overview

Mooring systems are critical for floating offshore wind turbines station-keeping. Despite the considerable track record and experience of the oil and gas sector in deploying mooring lines in a range of environments, floating wind turbines will require tailored solutions to suit their design and minimise cost and risk. Table 5 provides a high level summary of the characteristics of good mooring system design, grouped into those which are essential, general (should be met, but where requirements conflict safety takes priority) and additional desirable outcomes.

**Table 5: Summary of mooring system requirements**

| Essential | General | Additional |
|---|---|---|
| • Keep loads within safety factors<br>• Minimise mooring line slack, snatch or compressive forces<br>• Maintain station keeping in all environmental conditions<br>• Maximise integrity<br>• Non-detrimental effect on turbine performance and improve performance if possible<br>• Allow for safe installation and hook up of substructure hull<br>*Substructure dependent:*<br>• Yaw restraint may depend on orientation and loading<br>• Allow device recovery to shore | • Reduce/eliminate out of plane loads<br>• Avoid mooring line and power cable clashing<br>• Avoid resonance<br>• Allow adjustment of lines and future intervention<br>• Consider extended periods of wet-storage prior to hook-up<br>• Sufficient redundancy to minimise HSE risks during failure event<br>• Consider design of disconnect/ reconnect in case of repair | • Reduce cost of installation and hook up<br>• Reduce load test requirements of anchors to avoid congestion<br>• Minimise mooring equipment<br>• Minimise vertical load from moorings |

Cost-effective mooring solutions for floating wind are easier to design for more benign environments such as a mild sea-state, with 100-500m water depth and penetrable seabed. However, certain environmental conditions pose a greater technical challenge.

Both very shallow water depths (50-100m) and very deep water depths (800-1000m) are a challenge; the former due to wave properties in shallow water and the need to allow tolerances for storm events which could significantly alter water depth, and the latter due to the additional weight and cost of extremely long mooring lines. In addition, challenging seabed conditions including very hard, very soft or complex soils, or risk of liquefaction during seismic events also pose technical issues for anchors and can increase costs.


**Figure 13: Typical floating offshore wind substructures and mooring configurations (from left to right: semi-submersible, tension leg platform (TLP), spar and barge platforms)**

This study investigated state of the art and innovative mooring and anchoring solutions for a range of challenging environmental conditions. The study methodology comprised:

- An evaluation of current state-of-the-art and innovative mooring system solutions for challenging environments
- Development of detailed technical design specifications for a range of site conditions
- Applying the most promising innovations and design philosophies identifies in the initial technology evaluation to the technical specifications created in the previous step, to develop realistic design scenarios, with robust cost estimates for each scenario, including design, preparation, procurement, installation, and maintenance. These cost estimates fed into a cost analysis comparing the levelised cost of energy (LCOE) of different mooring configurations.
- An evaluation of technology development requirements to commercialise innovative mooring and anchoring solutions

## Defining challenging environments for floating wind mooring systems

For this study, the suitability of mooring system technologies and approaches were assessed in two challenging environments:

- Shallow water site: 70m water depth consistent with north-western North Sea; and
- Deep water site: 1000m depth, consistent with the west coast of the USA.

With corresponding met-ocean conditions for each geographical location.

Three types of soil condition were considered for the assessment of anchoring systems:

- Loose to very dense sand (Gulf of Maine, North Sea, Taiwan)
- Soft to firm clay (Caspian Sea, Irish Sea, Norwegian Continental Shelf)
- Firm to hard clay/weak rock (North Sea, Japan, French Coastline, USA West Coast)

Selected extreme operating and survival load cases of a 15MW turbine were modelled in each location to evaluate the performance of the different technologies/configurations of mooring and anchoring systems in challenging environments.

## 4.2 Key findings

The key findings from this project are split into four main sections:

1. General findings related to technology availability and knowledge sharing with other industries
2. The potential for different mooring line components to suit challenging mooring system environments
3. Findings relating to ten different mooring technologies and design philosophies which were modelled and analysed under specific challenging site conditions
4. Insights from the cost analysis of different mooring system configurations in both very shallow and very deep waters

### General findings

**1 Existing technologies can be easily transferred from the O&G industry, but there are no current technological 'show stoppers' for challenging floating offshore wind environments.**

Across industry it is accepted that knowledge sharing from the Oil & Gas industry is vital to ensure the floating wind industry doesn't repeat the mistakes of the past. Industry engagement ascertained that many companies are hoping to sell existing technology or services that are deemed transferrable from the O&G industry into floating offshore wind, but some of the larger companies appeared more likely to 'wait and see' how the industry develops. This may be to see if there is sufficient demand, before launching an expensive R&D and product development process. Industry engagement also confirmed there are no immediate technological 'show stoppers' for mooring systems in challenging environments, though there are some promising concepts that currently appear to be at low TRL status.

One of the key challenges for developing cost-effective mooring systems is the need for whole system design (platform, turbine and mooring system) to collectively minimise CAPEX, installation duration, integrity, risk and overall LCOE.

## Mooring line components

**2** **Within mooring system components, materials have the highest development potential, and anchor development will be driven by the possibility to share anchors.**

Based on experience from the project delivery team, as well as industry feedback, the potential for certain mooring system components to be further developed to suit deployment in the challenging site conditions outlined in section 4.1 was assessed (see Table 6). Table 6 shows a summary of the components reviewed which have medium-high, high or very high development potential (i.e. there is an opportunity to improve their applicability to challenging environments).

Whilst this analysis was focused on individual component level development opportunities to suit challenging environments, it is also important to consider the overall supply chain of mooring systems, to maximise longevity and minimise the environmental footprint of materials. There are considerable opportunities to improve the sustainability of materials through reducing energy and material inputs (e.g. in steel production) and developing opportunities for reuse and recycling of synthetic materials.

**Table 6: Mooring components with high development potential**

| Category | Component | Development potential |
|---|---|---|
| Mooring line materials | Fibre rope (elastic) | Very high |
| | Elastomeric components | Very high |
| | Fibre rope (non-elastic) | High |
| Mooring connectors | Fibre rope terminations | High |
| Ancillary components | Load Limiters | Very high |
| | Mid-line buoyancy | High |
| | Clump weights | Medium-high |
| | Excursion limiters | Medium-high |
| Connection systems | Subsea connection and tensioning | Medium-high |
| Anchors | Pile anchors (drilled) | Very high |
| | Pile anchors | Medium-high |
| | Suction anchors | Medium-high |
| | Screw pile anchors | Medium-high |

## Technological assessment

The performance of nine technologies and design philosophies were evaluated compared to a base case mooring for both the deep and shallow water environment:

1. Non-redundant (single leg) vs redundant (double leg)
2. Shared anchor points
3. Shared moorings
4. Shared export cable and mooring line
5. Impact and different requirements for anchor types under the effects of soil liquefaction
6. Axial Load reducing mechanisms
7. Performance improving components – clump weights and buoyancy
8. Hook-up / removal tensioning tools
9. Quick disconnect tools to aid O&M (recovery of substructure)

**Scenario 1: Non-Redundant (Single Legs) vs Redundant (Double leg)**

There is a desire within the floating wind industry to reduce mooring lines within the water column to:

a. Reduce environmental impact and consenting risk – fewer mooring lines reduces any impact on marine wildlife or the marine environment.

b. Reduce capital and installation cost. There is a perception that fewer mooring lines will reduce upfront CAPEX as well as whole life costs.

Ultimately, when considering the requirement for redundancy, the key technical issue is whether the total mooring force is absorbed through one large line or two smaller ones. However, this study concluded that the choice between 1 or 2 lines at each connection point on the floating platform (there are typically three connection points per platform), is not driven by performance, but based on supply chain constraints, whole life costs and an assessment of risk of mooring line failure and the implications of this from technical, HSE and financial perspectives.

One of the key decision-making factors mentioned by several parties, is whether the lack of redundancy of a mooring system is acceptable to insurers and supported by regulatory guidance from agencies such as the UK HSE and the MCA (Maritime and Coastguard Agency).

**3** **The desire to minimise mooring costs with single lines could lead to high consequences including failure of inter-array cables, restriction of power production, entanglement of moorings and power cables, collisions and damage of cables due to anchor drag.**

The desire to minimise installation costs by mooring with single lines (non-redundant technique) would appear attractive initially, however technically it becomes challenging as the loads can be so large the size of components become difficult to procure and require more expensive vessels to install. In addition, the consequences of failure on the wind farm operation are greater and can increase HSE risk as well as have a major impact on the OPEX costs and hence LCOE. There consequences include:

- Failure of inter-array cable(s)
- Interruption or restriction of power production through the inter-array cable branch.
- Low likelihood of being able to reconnect immediately – failure would require emergency release from remaining lines, tow to port for repair, and repair/replacement of the mooring lines in field.
- Entanglement of moorings and power cables.
- FOWT colliding with another or blade clashing (this risk is higher in deep water due to longer mooring line length)
- FOWT hitting an ocean-going vessel
- High risk of injury or damage to personnel and vessels trying to repair the mooring system
- Hull breach of FOWT, either as a result of top connector failure, or secondary consequence from impact.
- Hitting substation (for FOWT's within proximity)
- Anchor drag through inter-array or export cable

Mooring integrity is a pressing issue for floating offshore wind farms due to the potentially very high cost of a mooring system failure. Despite this, non-redundant systems have almost become the norm, a fact which has caused designers, equipment suppliers, surveyors and insurance companies to express concern about the use of this design in a commercial setting. It is likely that non-redundant systems will be phased out due to them causing a high-risk of damage to adjacent FOWT's and inter-array cables.

4 **Improving the reliability of mooring lines at common failure points is important to reduce potential 'system failure' of FOWT moorings and lower HSE risks.**

Common failure points of mooring lines include:

- Connection points between the mooring line and the substructure (fairleads, gypsies)
- Touch down points (TDP) where the mooring touches the seabed
- Where discontinuities exist (e.g. shackles and connector swivels)

The equipment used at these locations is not novel, however improvements are generally being made to increase reliability, albeit with diminishing rate of improvement as several technologies are mature with limited innovation opportunities. The introduction of a new technology at these points can increase the risk of failure and hence extreme caution must be exercised if they are to be a permanent component. Extensive testing will be required in addition to phased testing and qualification before new technologies are deployed on commercial projects..

**Scenario 2: Shared anchor points**

One of the main mooring systems costs is anchor installation, largely due to the installation duration and limited number of anchors which can be carried offshore at any one time. Sharing anchors between two mooring lines offers an obvious CAPEX and installation cost saving. This is especially true where pile/suction anchors are concerned as the anchor rating does not need to be increased significantly.

Shared anchors have been deployed for a limited number of use cases until now, partly due to different ownership of assets and insurance difficulties in the event of failure. They are however due to be used for the Hywind Tampen project where 19 anchors will be used to secure 11 turbines. The use of a shared anchor will require a specific anchor type that works in multiple directions, increasing individual unit cost, but reducing total anchor CAPEX cost.

For shallow water, anchors are mainly heavily loaded during extreme weather events, as during benign weather most of the mooring line is on the seabed which will have significant seabed friction, reducing anchor loads. By contrast, in deep waters the anchors are constantly loaded. For the load cases considered in this study the results showed no issue with anchor sharing in that it does not increase the overall maximum load. However, in shallow waters, the requirement to take load from different directions, a shared pile anchor would have to be specified, rather than a drag anchor.

In both the very deep and very shallow water environments, there is potential to optimise the combination of mooring line length and turbine spacing to reduce overall cost. In reality this optimisation will need to take into account the specific water depths, environmental conditions, substructures and turbines used. The installation of shared anchors is not expected to be significantly more complicated, however some concerns related to redundancy were noted.

**Scenario 3: Shared moorings**

**5** **Shared moorings have the potential to reduce the amount of offshore equipment to be installed, but are more complex and risky to install and repair, and may not result in the desired level of cost savings.**

This novel approach (see Figure 14), which is only viable in deep waters, includes sharing anchors and part of the mooring line between FOWTs. At first glance, shared moorings would appear to offer an advantage by reducing the amount of equipment to be installed offshore. However, the perceived cost saving may not be as large as hoped, for several reasons, namely;

- The installation and hook-up process vastly increase in complexity and risks, with the anchoring and buoyancy arrangement of the ‘virtual anchoring point’ being very expensive to install.
- The number of potential failure modes increases exponentially the more complex and interconnected the system becomes, and the risk of catastrophic multiple failure is a significant threat.
- The method to repair any damage will involve potentially extremely complex and risky intervention methods.

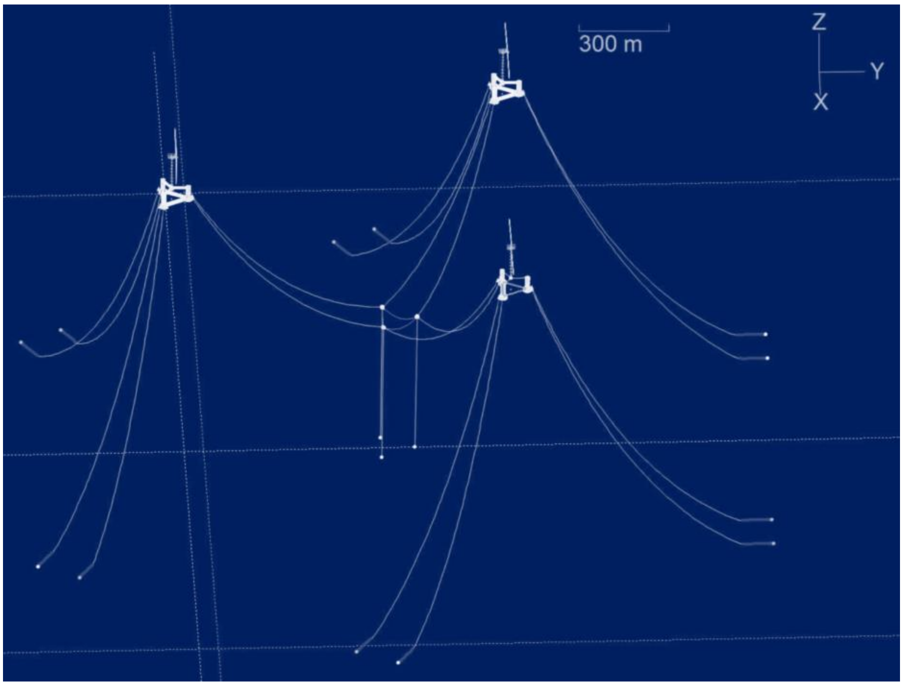



**Figure 14: Shared mooring model layout**

Therefore, while shared moorings may be considered an opportunity, they may not be practical in many circumstances since additional components, multiple failure modes and very complex installation may offset any saving in the mooring line cost.

To draw any real comparison of cost savings, the level of mooring lines 'shared' must be quantified along with the cost of the installed baseline for each FOWT. Furthermore, the threats and risks associated with failure of a single (or multiple) mooring lines must be considered, together with the risk of cumulative failure or reduction in lifespan of adjacent components due to that failure. It is vital that the emergency procedures and methods to recover the situation must be in place for all practical combinations of failures. The greater the connectivity between mooring lines, the greater the number of potential failure scenarios and the more complex it becomes to repair.

The use of shared moorings may require specific anchor types which may be more expensive than individual anchors. Therefore, while the sharing of mooring lines appears a 'quick-fix' the level of integrity assessment required for a highly coupled system and the need to ensure provisions are in place for recovery of a failure situation, may result in a system which has a much higher OPEX and insurance risk.

**Scenario 4: Shared export cable and mooring line**

There is a potential cost saving and overall design benefit from supporting the export cable along the mooring line. This may reduce cable design requirements, buoyancy requirements and loads. Tis has been carried out in wave and tidal on a few bespoke projects.

The effect of clamping the cable to the mooring line at various points was found to have negligible change on the loads. The results showed that with even a basic cable support mechanism (i.e. not bend stiffeners, restrictors or buoyancy) a suitable support can be achieved.

Combining the shared mooring design from the previous section (which has little if any benefit in isolation) with a meant to support the cable, could make the system worthwhile. However, it is recommended to research each combination in more detail before reaching a firm conclusion.

**Scenario 5: Impact and different requirements for anchor types under the effects of soil liquefaction**

In a number of locations across the world where floating wind is likely to be considered it is known that there is a significant risk of ground movement due to trigger events (earthquakes, volcanoes, etc.). Liquefaction is a phenomenon characterised by a drastic reduction in the strength and stiffness of the soil during a trigger event. It can have a major impact on the stability and reliability of FOWT foundations. This study provided a high-level overview of the suitability of different anchors for regions at risk of earthquakes and mitigation measures for anchor damage or removal caused by soil liquefaction.

The risks associated with liquefaction are different for each type of anchor, but it can be concluded that installing floating wind turbines with anchor piles is an adequate solution in areas where there is a high risk of liquefaction. In this case, the piles would be oversizing to mitigate the loss of soil strength. The amount of oversize required is highly project specific and depends on soil conditions, mooring conditions and seismic activity. It should be noted that having a slack mooring line configuration is preferable in ensuring the stability of the floating structure.

It is highly advised that in areas where there is a risk of trigger events that the probability of these events be established. Where the probability is seen to exceed an acceptable limit, the return period and peak ground acceleration should be mapped and site response analysis undertaken to establish load cases on the mooring system, loss of soil strength due to events and the potential for liquefaction in soil strata. All of these risks should be considered when establishing the ultimate limit state and serviceability limit state of the mooring design.

**Scenario 6: Axial load reducing mechanisms**

**6** **Axial load reducing technologies help reduce snatch loads in shallow waters, making previously untenable designs workable and providing cost benefit.**

The intrinsic motions of the FOWT result in high risk of snatch loads on catenary moorings. This is due to the mooring connection point on the FOWT moving backwards and down fast, such that the middle section of the mooring line cannot drop down quick enough.

Chain catenary moorings have difficulties dealing with this response and thus highly elastic components, such as elastomeric tethers, nylon (if it can be developed for long-term use) and shock absorbers (load reduction devices) are a potential option to avoid having to move to a more complex mooring arrangement. The use of high modulus ropes in the upper catenary do not resolve the snatch issue and thus are not the solution. The use of combination of polyester rope, chain and buoyancy can give significant reductions in the mooring line tensions and hence in combination with other load-reduction technologies, provide a more optimal pathway.

Several companies are proposing ways of reducing axial loads in the mooring lines – these are not solely focused on snatch reduction systems, but also overall load reduction, which can reduce mooring line lengths, reduce peak loads (and potentially the number of mooring lines), and reduce anchor sizes. This could reduce mooring and substructure costs if these technologies can be validated and expanded to the load rating and longevity required by commercial floating wind projects. This is particularly true for shallow water sites because in deep water, the longer mooring line length allows for the first order pitch and heave motions of the substructure to be more easily accommodated. This means the effectiveness of the load reduction devices is less significant, so the cost impact is reduced in deep water.

Two such load reduction technologies that were assessed as part of this review were the TfI polymer mooring spring and Exeter Tether, outlined in the case study boxes below.

### Case study - TfI polymer mooring spring

The SeaSpring changes the response of a mooring system to the needs of the platform and environment. The FOWT components offer a degressive response, stiff up to turbine thrust loads and responsive around these, resulting in a reduction in ULS loads of >50%. Variable loads are reduced across all sea states delivering a 30% reduction in Fatigue.

Components are currently undergoing LTM certification and are available at sizes of up to 2MN MBL now, and >10MN MBL from 2023.

### Case study - Exeter Tether

Elastomeric products could be extremely useful in reducing peak loads while also keeping other components under tension, thus increasing their fatigue life.

The Exeter Tether is a simple spring and while development is in the early stages, load reduction of up to 50% in extreme conditions were observed, but the exact level is dependent on the system and loading condition

**Scenario 7: Performance improving components (clump weights and buoyancy)**

The use of clump weights, buoyancy and synthetic ropes offers a smart alternative to traditional catenary moorings. By using fairly standard components the mooring loads can be greatly reduced compared to an all-chain system. This study concluded that these components offer a simple, technical benefit that will also help to optimise costs for mooring in challenging environments. However, there are very few standard designs for these components (and numerous possible configurations) and installation can be challenging for maritime contractors. Further study is recommended to identify optimal design configurations and their cost, installation and O&M challenges.

**Scenario 8: Hook-up/removal tensioning tools**

**7** **Traditional hook up techniques with larger vessels or tensioning on the seabed appeared to be the most beneficial out of those assessed.**

There are two distinct phases to the hook-up (connecting the floating platform to the pre-laid mooring line); the first is to get the mooring line engaged and connected. The second is the tensioning phase where the length is adjusted, usually by chain, to achieve the correct pre-tension in the mooring line. Typical hook-up locations are shown in Figure 15.

The top connection location is challenging as it requires a winch system to pull-in the mooring line under high tensions. Different options are available for this but many lead to complicated rigging arrangements which make for a complex operation under high loads either on the installation vessel and/or at the FOWT connection point. A safer and more promising hook up location is the seabed section, since the tensions are low, both ends of the mooring line are static on the seabed and, subject to the water depth, the top section of the mooring line can be used as the towing element.

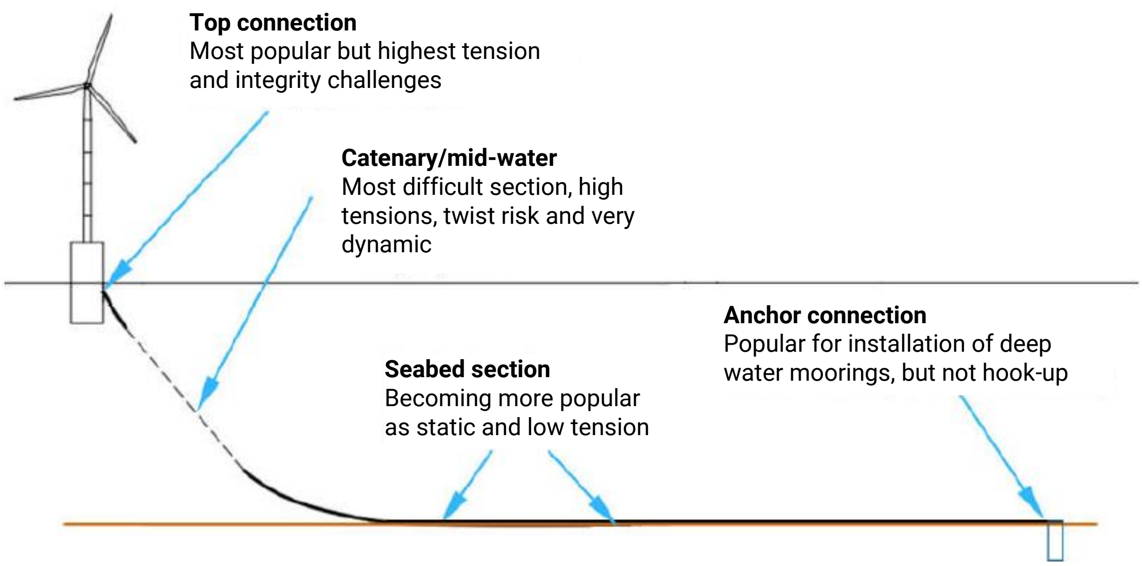



**Figure 15: Typical hook-up locations (Courtesy of First Energy Development)**

The main objectives when considering hook-up techniques are to minimise personnel risks, installation time and overall cost. The study assessed different hook up methodologies and their applicability to mooring lines in deep and shallow waters, with different vessels and hook up locations. The challenge with hook-up is to minimise the risks, time taken and overall cost whilst ensuring the FOWT doesn’t move excessively, and overcoming high tensions on pull-in (or connecting at a lower tension and subsequently pulling the chain in to a predetermined tension). Several companies are in development of connection and disconnection tools to assist with reducing loads, but the key aspect is where the connection is to be made and what supporting equipment is required.

The biggest factor when considering hook-up is the location and while all hook up methodologies have some merit, there are different characteristics for each mooring line configuration, equipment which could be used, weather dependency and amount of manual handling. Traditional connection methodologies with larger vessels (using an anchor handling vessel (AHV)) or tensioning on the seabed, were determined to realistically be the safest and most reliable options.

**Scenario 9: Quick disconnect tools to aid O&M (recovery of substructure)**

If the O&M strategy is to recover the FOWT to tow to port, a quick disconnect tool or mooring connector aids the recovery and re-installation of the FOWT. The mechanisms of this mooring connector have to consider the safe lowering of the mooring lines and cables, together with the marine operational risks of working in a congested area. This is particularly true in deep waters where the long mooring line lengths result in high risk of handling damage. The mechanism of how this connection is made and where and how the preload is re-established also needs to be considered. This technology is an enabler for some tensioning tools as the hook up/removal are carried out under load.

The full true advantage of quick disconnect tools is dependent on the O&M strategy of the wind farm. For O&M strategies where operations are carried out in-situ, quick disconnect tools are unlikely to deliver a cost benefit. However, given the height of the nacelle on a floating structure and current lack of floating cranes able to access such heights, tow-to-port operations are likely to continue to play a role for the foreseeable future, and these quick disconnect tools could reduce the lifetime LCOE of the windfarm.

## Cost analysis

**8** **Mooring equipment holds a higher proportion of total cost for the shallow base case all chain scenario, whereas mooring installation costs are higher for the deep base case scenario.**

A cost analysis was carried out for mooring systems and technologies which were deemed to be the most suitable for meeting the requirements for challenging environments, highlighting potential cost savings.

The wind farm analysed was assumed to consist of 33 turbines of 500MW total capacity, with a project life of 25 years and no removal or replacement or mooring components. Each turbine was 15MW (based on scaling up a 10MW DTU turbine) situated in the centre of a semi-sub sub-structure. Different mooring setups, configurations and technologies were assessed.

A base case mooring was added to the substructure for a shallow water and deep-water scenario and analysed until realistic loads were exhibited. Table 7 shows the percentage of total mooring system lifetime cost each component represents in both the shallow and deep water base cases.

**Table 7: Cost split for shallow and base water cases**

| Cost element | Shallow base case | Deep base case |
|---|---|---|
| **Mooring equipment** | 38% | 27% |
| **Mooring installation** | 24% | 35% |
| **Anchor cost** | 21% | 15% |
| **PME and survey** | 5% | 7% |
| **Tow and hook-up** | 4% | 6% |
| **Survey alone** | 2% | 3% |
| **Cost of failures** | 1% | 2% |
| **O&M and decommissioning** | <1% | 5% |

The main conclusions that can be drawn from Figure 16 are:

- The simplest and most cost-effective implementation is to share anchors (this applies to both shallow and deep water). It should be noted in these cases the mooring line lengths of the reference wind farm happened to coincide with the turbine spacing, so no additional mooring line was required.
- Having fewer mooring and anchor lines (non-redundancy) has some cost reduction benefit (mainly in deep water) – however the possible consequential costs from a failed mooring (and loss of revenue) are not factored and may alter this conclusion.

- The shared mooring (deep water only) represents a significant increase in cost and risk – however if this can be connected to the export cable, this may result in savings in the electrical infrastructure costs of the wind farm.
- Load reducing technologies have a potential to open up shallow water sites to be technologically feasible. These technologies are most useful in shallow water to reduce snatch loads and reduce component and installation costs. In deep water their impact is less useful as the snatch loads are easier to deal with through the mooring line.
- Using synthetic mooring lines, buoys and clump weights in a mooring design can achieve a similar effect to the load reducing technologies at a similar cost, but with established components, which have failure rate data available to assess project risks.
- In general drag anchors (used where possible) represent the cheapest form of anchoring per ultimate holding capacity, followed by suction piles (where ground conditions allow), then driven piles with drilled piles being the most expensive. The installation of drag anchor at very high loads can however erode this commercial advantage significantly and thus caution should be exercised in stating which will be the most economical solution for a particular project, without first undertaking project specific analysis.

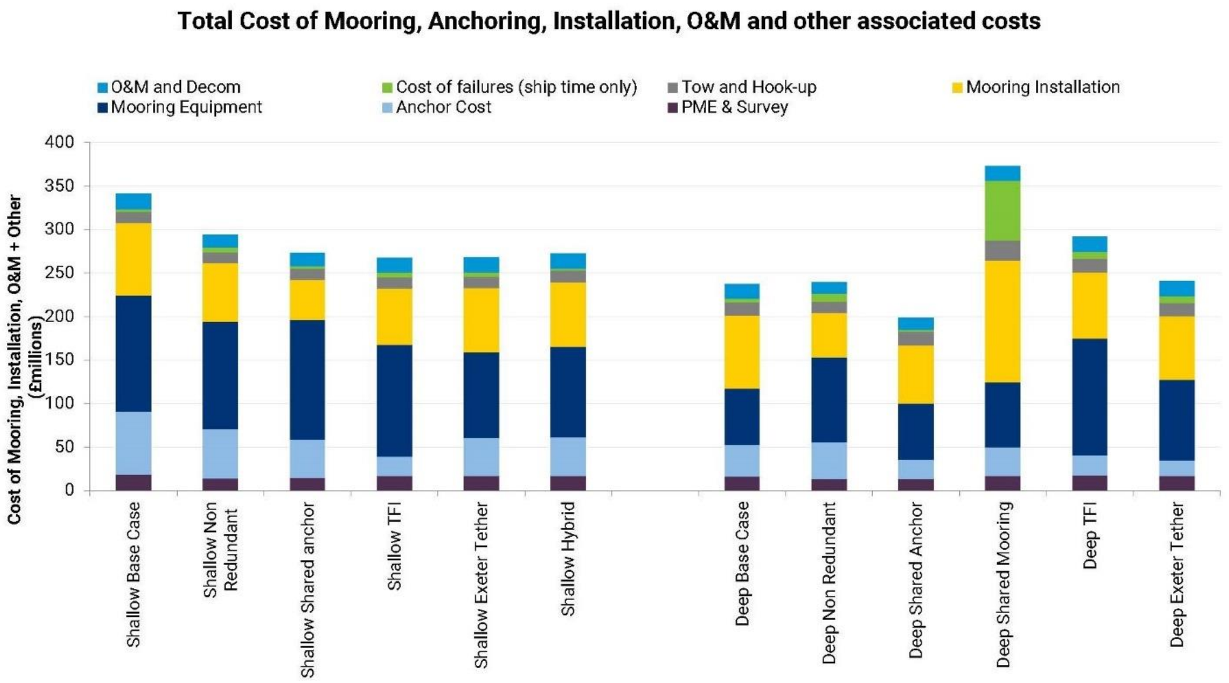



**Figure 16: Breakdown of costs for each scenario**

## 4.3 Innovation/technology needs

There are few obstructions to the floating wind industry moving forward with standard mooring and anchoring conventions. However, there are some requirements the industry needs to address in order to progress. These are highlighted below.

Certain developments (like sharing anchors) are based on proven technology and can be implemented now. Other installation tools can be developed fairly quickly to adapt to optimised use in floating wind, but the view from industry is that the market potential needs to be ascertained before heavily investing in R&D.

In order to understand the true benefit of these technologies and the impact of a mooring design, a holistic design approach for the whole wind farm must be considered, understanding how the mooring design impacts installation costs, umbilical design, substructure loads, O&M strategy and the turbine performance.

### Mooring requirements

**1** **There is a requirement for mooring materials to be developed that can axially stretch by an engineered length upon a load threshold being reached.**

When mooring in shallow waters using an all-chain system, high snatch loads can occur due to the coupled motion of the FOWT. Therefore, a key characteristic for mooring lines is to have the ability to stretch axially, to reduce or eliminate snatch loads, rather than relying on a normal chain catenary profile. Polyester is currently the most established material for providing elasticity, but to reach sufficient stretch a long length of polyester is required. This increases mooring line cost, but conversely may allow for a more cost-effective shared anchor configuration. Nylon is known to have greater stretch properties, but its suitability for long-term moorings is far less certain due to fatigue and internal abrasion, therefore it is likely that the nylon would have to be replaced at least once in service.

There is a need for industry to develop materials that can axially stretch more than polyester rope and/or stretch by an engineered length upon a load threshold being reached. There may be potential for polyester/nylon hybrid to allow more stretch than polyester but higher integrity than nylon.

Adoption of other existing methods can also reduce loads (and hence CAPEX); for example, a 'hybrid' arrangement of synthetic rope and buoyancy modules in an inverted catenary is widely used in the O&G and wave industries. This hybrid arrangement can also reduce hook-up tensions in deeper waters, but the disconnected arrangements of the mooring lines must be considered carefully due to the hazard of many mid-water buoys. Furthermore, there is no standardised buoy design and at present there are still many reported failures, that have hindered widespread deployment.

**2** **Though existing systems are sufficient, development of FOWT specific mooring systems would ease installations and reduce costs.**

For deep water mooring conditions, it has been established that current mooring components available on the market are sufficient to provide a fit-for-purpose mooring system. However, these designs are not fully optimised so there is scope to further improve the designs from the perspective of load-reduction, ease of installation and overall cost. Currently there is no industry guidance on how this may be done, as most previous projects have been bespoke and there have been limited opportunities for cost-optimisation and supply chain alignment.

Conversations with industry members raised the following as potential areas to develop:

- In-line tensioners
- Polymer components in the mooring line to reduce peak loads.
- Multi-line interfaces were stated as another issue.
- Rapid connection and disconnection systems needed.

In addition, equipment and installation costs alongside offshore maintenance cost and decommissioning, are seen as important areas to improve and optimise, particularly handling requirements during maintenance operations. More dialogue between classification societies, equipment suppliers and installers is required to deliver this.

**3** **Further development of specific equipment to aid with hook-up is required to reduce loads (especially present in shallow and deep water) and reduce health and safety risk.**

Installation methods are being developed which require specific tools/ equipment to aid the hook up process by reducing the loads and making the operation safer. These combine new operational methods and specialist equipment. With most previous floating wind mooring systems being bespoke, there has been difficulty in justifying investment in standardised hook up solutions, but with the expected rate of growth of the offshore wind industry, investing in the development of more efficient, robust, standardised systems can have a business case.

## Anchoring requirements

**4** **Existing anchor types are sufficient for FOWT but further cost reductions, through development of FOWT specific anchors are possible.**

Opportunities to standardise anchoring solutions are less apparent as they will be highly dependent on the mooring type (catenary, semi-taut, tension leg), but more importantly dependent on the seabed properties. Therefore, standardisation of anchor design will be classified by seabed condition. While it is understood there are no show stoppers with regards to anchoring in any conditions (shallow/deep water or soft/hard seabeds), there are costs associated with different conditions.

Cost reductions can be brought about by industrialising the manufacture and installation of an anchor type and/or improving the cost effectiveness of anchor holding power.

As well as reducing the cost of existing anchor designs, new anchors are being developed including:

- **Hybrid suction/gravity anchors** combine the upsides of suction caisson installation with the permanent resistance to uplift of gravity anchors and can be cost effective and reliable in the right conditions.
- **Torpedo anchors** are suitable for deeper floating sites as they are quiet, small and efficient.
- **Screw piles** can deliver high anchoring capacity without being too intrusive in the environment. The installation device required to provide installation torque can be reused across a large number of installations, to spread the cost.
- **Rock anchors** are always drilled and grouted and can be especially material efficient when rock outcrops on or close to the seabed.
- **Saucer style gravity anchors** are a variant of traditional floated gravity-base with the saucer filled with rocks dropped from the fall-pipe of a dredging vessel.
- **Industry best practice guidance** should be kept up to date to reflect latest development in anchor design.

**5** **As the installation of large commercial floating wind farms gets nearer, there is more need for accurate and easily available geotechnical data to correctly choose anchor size and type.**

A common concern from industry was the difficulty in acquiring and understanding the seabed geotechnical data to correctly choose and size the anchor type. This data would greatly assist with selecting the appropriate installation method. While this is less critical for floating than fixed offshore wind, the potential for large commercial farms with large numbers of drag anchors, pile and suction anchors compounds the need for this. In prototype or small projects, with smaller budgets, geotechnical data has not always been available which has led to installation issues.

## Industry requirements

**6** **Industry standards, certification and new design requirements need to include variability of all soil types and geographical locations.**

This study highlighted several areas of opportunity for technology development to optimise mooring systems in challenging environments. A common theme across all these areas was the need to develop standard design types whilst developing sufficient knowledge and understanding of how to adapt components and designs to specific environmental conditions. Designing solutions which also minimise environmental and HSE risk will also be vital, alongside learning from the past mistakes of the oil and gas industry.

It is important to reflect the development of technologies and best practice approaches to design in standards, certification and design requirements and communicating these across the industry.

# 5. Technology Acceleration Competition

## 5.1 Competition overview

To stay at the forefront of floating offshore wind innovation, the Scottish Government decided to invest £1 million to support innovations that would overcome key technology challenges, in particular those identified by the Floating Wind JIP which found electrical systems, mooring systems, infrastructure and logistics to be areas with significant technological challenges[3].

The Carbon Trust, in collaboration with the offshore wind developers in the Floating Wind JIP, designed the Floating Wind Technology Acceleration Competition (FLW TAC) to identify, assess and support technologies with the greatest potential to support floating wind development in the following four areas:

- Challenge 1: Exchanging large turbine components on moving floating foundation structures
- Challenge 2: Disconnection and re-connection of foundation structures, when they are towed to and from ports for maintenance
- Challenge 3: Monitoring and inspection of mooring lines, cables and foundation structures
- Challenge 4: Manufacturing, installation and maintenance of mooring lines and anchors

The competition was open to technologies between Technology Readiness Level (TRL) 3 and 7, and projects could be delivered by organisations of any size and in any location. Applicants could apply for up to £250,000 of grant funding.

The competition was launched on Wednesday 11th September 2019 on the Carbon Trust website. The eight projects selected started in early 2020 and ran until March 2021.

[3] The Carbon Trust (2018). Floating Wind Joint Industry Project – Phase 1 Summary Report

## 5.2 Competition winners

The Carbon Trust have published a report summarising the FLW TAC competition and the achievements of each of the eight projects, which can be found here. A summary of the winning projects and the funded activities is given below:

**Aker Solutions**

Aker Solutions is a global offshore energy engineering company with headquarters in Norway.

Aker Solutions developed a splice box concept connecting two dynamic array cables, allowing them to be wet-stored on the seabed when a turbine is towed to port for maintenance operations. As the cables are electrically connected in the splice box, this will also enable an array of floating wind turbines to remain operational when one floating substructure is removed for maintenance.

The FLW TAC project supported the development of their Splice Box design, installation procedures and successful testing of Splice Box components.

**Conbit**

Conbit is a lifting contractor that offers alternatives to cranes and crane vessels with a strong engineering background. As part of Mammoet, they perform lifting projects all over the world.

FLW TAC funding supported the development of the design of their modular lifting solution – a temporary platform installed at the top of the wind turbine (on top of the nacelle) which includes a crane to allow large components, such as a wind turbine blade or gearbox, to be replaced offshore. The project also evaluated different methods for carrying out heavy lifting of these components offshore.

**Dublin Offshore**

Dublin Offshore is an Irish engineering company that supplies marine energy solutions. The Load Reduction Device (LRD) is integrated in-line with the mooring system and passively delivers controlled mooring compliance in response to the movement of the floating substructure. This dampening significantly reduces mooring dynamic load, delivering cost savings largely through CAPEX reductions on the substructure and mooring line systems.

The LRD has progressed from TRL 4 to TRL 7 over the course of the FLW TAC project. Dublin Offshore first validated the technology through tank testing at 1:60 scale and obtained a Statement of Feasibility from DNV. A ¼ scale prototype was installed at an ocean test centre in Galway, Ireland and successfully completed 1,200 hours ocean testing including operation through 22m full-scale equivalent waves during Hurricane Epsilon. The results, certified by EMEC to IEC6260-10, demonstrate the robustness of the system with no damage or performance degradation observed.

**Floating Wind Technology Company and RCAM Technologies**

The Floating Wind Technology Company (FWTC) is a start-up company created to design and commercialise innovations in offshore wind including turbine components, control systems, floating substructures, anchors and hybrid-foundations. RCAM Technologies is a start-up that uses 3D printing technologies with concrete to manufacture wind turbine towers, foundations, and anchors, at or near the installation sites to reduce cost and increase domestic content.

The project developed detailed designs for a 3D-printed concrete suction anchor (3DSA) based on two sites in Scottish waters with different soil conditions, and examined the installation procedure for the 3DSA, including different forms of towing to site. In addition, key elements of the 3DSA design were printed using concrete 3D printing facilities in the Netherlands and the project also undertook an assessment of the feasibility of carrying out 3D concrete printing of the 3DSA on the quayside of a Scottish port.

Both the use of concrete in anchor design and manufacturing using 3D printing are novel elements in this project and have the potential to deliver cost savings compared to more conventional steel suction anchors.

**Fugro, AS Mosley, and University of Strathclyde**

Fugro is global company, headquartered in the Netherlands, which has offices in Scotland and provides geo-data for many applications, including asset integrity solutions. AS Mosley is a Scottish engineering design consultancy. The University of Strathclyde is a public research university in Glasgow, Scotland.

The project team created a physics-based simulation model of the Hywind Scotland floating turbine and generated motion and position signals to demonstrate that a simple monitoring system installed on the floating hull could accurately determine the service life of its mooring system. Fatigue was estimated using traditional S-N curves and a state-of-the-art peridynamic analysis. These are key to targeting offshore inspection work at the locations it is needed most, thus reducing costs and improving safety. Such a remote and fully automated monitoring system was also able to identify anchor drag and snagging of trawler nets. These capabilities also assist with operation and maintenance activities, making floating wind more feasible.

**Intelligent Moorings and University of Exeter**

Intelligent Moorings is a new UKbased company launched around this design. The University of Exeter is a public research university in Exeter, England. They are developing a pressure-based dampener which sits between the platform and mooring line to reduce the load on mooring lines and floating substructures. This can reduce the capital cost of the mooring systems and associated structural elements.

During the course of the FLW TAC project, the design progressed from TRL 4 to 5 with successful testing of the Intelligent Mooring System (IMS) at 1:3 (Froude Scale) at the DMaC facilities at the University of Exeter. The project team have secured funding to test their mooring line dampener on the Offshore Renewable Energy (ORE) Catapult’s Marine Energy Engineering Centre of Excellence (MEECE) test buoy in the Milford Haven Waterway. The mooring line dampener will be tested at an intermediate scale to assess its durability and performance in a real marine environment.

**TfI Marine and CSignum**

TfI Marine supply the commercial mooring market with innovative mooring components which reduce the loads experienced by the mooring system. They are based in Dublin, Ireland, with a primary focus on the global floating offshore wind and aquaculture markets. CSignum is based in Scotland and specialises in subsea wireless communication and automation. Together, they demonstrated a solution which integrates mooring load sensing, power generation and wireless subsea communications into an existing spring to enable autonomous full life fatigue monitoring. Incorporating monitoring equipment into the mooring line spring reduces the need for physical inspection of mooring lines and enables a risk-based approach to monitoring.

The spring also acts as a dampener on mooring lines which can halve the maximum load on a mooring line, reducing the size and cost of mooring systems, and reduce the fatigue experienced by the mooring line. The monitoring equipment is powered by movement of the spring, using a piezo-electric generator, which removes the need for an external power source.

The FLW TAC project supported design development and prototype testing at the LiR National Ocean Test Facility (NOTF) in Cork, Ireland, and the University of Exeter's DMaC facilities.

**Vryhof**

Vryhof is a Dutch company that specialises in mooring and anchoring solutions. They have developed an adjustable lock (Stevadjuster®) which sites on the seabed and is used to adjust the tension of the mooring lines. This is an alternative to a winch sitting on the turbine substructure, and enables vessels to adjust the tension of mooring lines at a safe distance from the substructure.

This project accelerated the design, certification and manufacture of a commercial-scale Stevadjuster®. The acceleration of this process enabled Vryhof to launch the Stevadjuster® as a commercial product.

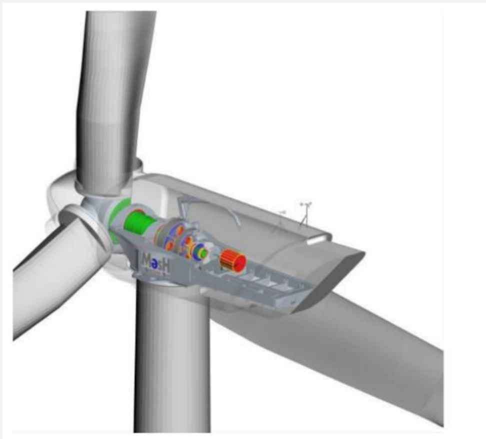
# 6. Projects for Phase IV

**Assessment of Wind Turbine Generators for Floating Wind Farms**

**Contractor: Ramboll and MESH**

**Challenge:**

Predicting turbine failure rates is key to developers successfully delivering returns for investors. Failure rates have an impact on turbine availability – hence the turbine Annual Energy Production (AEP), which is a critical factor for commercial viability of future floating projects. There is growing experience with increasing floating wind deployment, however this is limited to turbine suppliers and developers with specific project experience. Additionally, offshore turbines are increasing in size for floating projects, with expected commercial-scale floating wind projects having greater than 15MW capacity.



The project will build on previous Floating Wind JIP work that assessed WTGs for floating wind, and additionally support WTG suppliers, directly or indirectly, to investigate floating wind specific risks to their mechanical/electrical componentry. The project is targeted at conventional horizontal axis WTGs (as developed for bottom-fixed offshore wind) to understand their expected performance in floating wind. It aims to make recommendations about floating wind specific analysis and testing, potentially leading to modifications that can be made to improve installation and operation, if necessary.

**Project overview:**

The Floating Wind JIP would like to better understand and predict expected WTG failure rates for commercial-scale (greater than 500MW) floating wind projects and engage with key suppliers to support the commercialisation of floating wind. The main objectives of this work are to:

1. To build on previous Floating Wind JIP work undertaking floating WTGs and support OEMs towards investigating floating specific risks to their mechanical/electrical componentry.

2. Act as a forum to engage with WTG suppliers.

3. To support, advise and lobby to accelerate the technology for improved floating AEP and increase confidence in large scale floating wind project investment.

### Floating Wind Access and Availability

**Contractor: Seaspeed Marine Engineering and SeaRoc**

**Challenge:**

Predicting accessibility, and hence availability for floating wind farms is key to developers successfully delivering returns for investors. The accessibility and availability of bottom-fixed offshore wind is relatively well known, however in floating offshore wind there is more uncertainty. There are a number of factors affecting accessibility of floating wind turbines, namely environmental conditions, the method of access, floating substructure type and the geometry of the substructure both below and above the water line.


The factors affecting accessibility:

- Environmental conditions; wave height/period/direction, current, wind speed, marine fouling
- Access method including CTV, SOV (daughtercraft and walk to work), helicopter
- Floating substructure type - TLP, semi-submersible, barge, spar
- Floating substructure geometry, including consideration of geometry below and above the waterline for potential clashes or limitations of accessibility such as eccentric tower position, location of cranes and boat landings, underwater obstacles etc.

Human factors are an important consideration for the accessibility and maintainability of floating turbines. The substructure motions will affect turbine access as well as the performance of technicians undertaking work in the nacelle, where substructure motions will be higher. Further to this, commercial-scale floating offshore wind will likely utilise larger capacity, 15 MW+ turbines which will affect the motions. The failure rates, or mean time between failures for these next generation turbines are an important consideration as they drive the requirement for accessibility and hence overall the turbine availability.

**Project overview:**

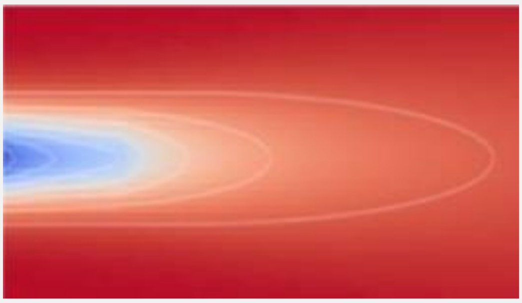
The Floating Wind JIP would like to investigate the accessibility and expected availability for future commercial scale floating wind farms. The main objectives of this work are to:

1. Estimate access performance for different substructure types (semi-sub, spar, TLP and barge) with different access methods.
2. Define and optimize the access strategy for the expected environmental conditions.
3. Understand the sensitivity of accessibility on WTG availability.

## Floating Wind Yield

### Contractor(s): Frazer Nash Consultancy, NREL

### Challenge:



A detailed understanding of the AEP is a critical factor for the successful delivery of commercial-scale floating wind farms. The actual AEP is a key unknown that needs to be better established for floating wind to increase investment confidence of future floating wind projects. The uncertainty is primarily related to the additional degrees of freedom and quality of yield modelling that could impact yield, but also controller modifications, additional downtime, and sustained pitch during operation.

The translational movement of floating foundation designs mean that fixed turbine layouts are no longer guaranteed; the motion of the turbines in general and particularly how motion differs between leading edge and waked turbines is not well understood or modelled. Searching for and investigating the dependencies affecting how floating foundations move within free stream and partially waked conditions will be an integral first step in being able to produce CFD and/or engineering models that can begin to quantify wake losses and their associated uncertainties.

The effects of movement and rotation in/around other degrees of freedom are known to impact turbine wakes, the pitching of a floating wind turbine platform can lead to unsteady aerodynamic effects. A better understanding of how both moorings and foundation design (spar, semi-sub, etc.) affect the extent of movement in the individual degrees of freedom of the platform, as well as associated coupled motions from the wind will be key to quantifying the sensitivities of platform design on wake loss.

### Project overview:

The Floating Wind JIP would like to further understand floating wind yield by investigating the sensitivities of drivers for wake loss, compared to fixed seabed turbines, with a further aim of updating the leading software to enable accurate prediction of floating wind yield. The main objectives are to:

1. Quantifying wake loss and associated uncertainties, as well as their sensitivities to key inputs.
2. Production of estimated yield (AEP) of turbines installed on floating platforms.
3. Understanding of the controller optimisation and trade-off against dampening.
4. Determine yield impacts for different floating foundation motions, and hence floating substructure types.

## Numerical Modelling Guidelines and Standards for Floating Wind

**Contractor(s): Innosea, Sowento**

**Challenge:**

Design guidelines are a key part of floating wind turbine design, and obtaining reliable results is an important requirement for the design iteration process to drive down CAPEX as well as ensuring consistent comparisons are made. There are many tools available for this modelling either as stand-alone analysis or as a fully coupled system model. However, there is limited best practice guidance, which identifies what tools to use for which aspects, or what load cases need to be considered.

The selection of the input load case is key to the modelling process. Load cases can be considered on a coupled and de-coupled or aligned and misaligned basis.

At present, there is no consensus on load case selection relating to floating offshore wind. As floating wind matures to commercial-scale deployment, the appropriate selection of load cases for relevant standards will need to be defined.

**Project overview:**

The Floating Wind JIP would like to improve the understanding of guidance for the design of floating wind structures including: defining the relevant load cases and guidance for an optimised outline design, a review of numerical modelling tools for floating wind turbine design, and a review of the leading standards and opportunities to harmonise. The main objectives of this work are to:

1. To address improvements and clarity in the floating wind design process, including numerical modelling tools.
2. A review of which load cases could substantially impact the design for FWT.
3. A review of existing floating wind rules, guidelines and standards with regard to load cases.
4. Produce a best practice guidance on selecting and running tools, and on the recommended load cases to run.
5. Recommendations for appropriate load cases to be included in floating standards, and highlighting areas of discrepancy between standards.

# About the Carbon Trust

Established in 2001, the Carbon Trust works with businesses, governments and institutions around the world, helping them contribute to, and benefit from, a more sustainable future through carbon reduction, resource efficiency strategies, and commercialising low carbon businesses, systems and technologies.

The Carbon Trust:

- works with corporates and governments, helping them to align their strategies with climate science and meet the goals of the Paris Agreement;
- provides expert advice and assurance, giving investors and financial institutions the confidence that green finance will have genuinely green outcomes; and
- supports the development of low carbon technologies and solutions, building the foundations for the energy system of the future.

Headquartered in London, the Carbon Trust has a global team of over 200 staff, representing over 30 nationalities, based across five continents.

# Our mission:

CARBON TRUST

The Carbon Trust's mission is to accelerate the move to a sustainable, low carbon economy. It is a world leading expert on carbon reduction and clean technology. As a not-for-dividend group, it advises governments and leading companies around the world, reinvesting profits into its low carbon mission.

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