

Phase II summary report



Floating Wind Joint Industry Project



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- Turbine requirements and foundation scaling: Ramboll
- Heavy lift offshore operations: Seaway 7
- Dynamic export cable development: BPP Cable Solutions
- Monitoring and inspection: Oceaneering

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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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The Carbon Trust has been at the forefront of the offshore wind industry globally for over a decade, working closely with governments, developers, suppliers, and innovators to reduce the cost of offshore wind power by informing policy, supporting government and corporate strategy, and commercialising innovative technology.

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Executive summary

Floating wind is an emerging but growing renewable energy sector. The technology enables offshore wind turbine installation in deeper waters not suitable for bottom-fixed turbines, unlocking new areas for renewable energy generation. Pilot and demonstration projects 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 resource.

This report provides an update of the floating offshore wind sector following the release of the [Phase I summary report in 2018](#), and details market growth projections and technology challenges. The most notable industry developments during this time include the Hywind Tampen and Kincardine pilot projects, and advances in technology, such as the Ideol FloatGen (France) and Hibiki (Japan) demonstrators coming online.

Market growth

To date, 73MW of floating wind capacity has been installed globally, however there has been a relatively low level of new capacity installed since 2018. The lack of installation activity is not representative of the significant project development activity that has been ongoing with key industry players in preparation for the next generation of projects. The recent installation of EDPR's 25MW WindFloat Atlantic 2 floating pilot project will be followed by a series of pilot wind farms that are set to demonstrate the technical and commercial viability of floating wind technology.

Demonstration and pilot projects have been an important stepping stone in the technology development and de-risking process. These projects have shown that floating wind can achieve the same, if not higher yields and availability than bottom-fixed projects. They have also proven the viability of installing wind turbines on floating platforms in harsh conditions.

The time is now to transition from demonstration and pilot projects to focus on larger commercial-scale floating wind projects, especially considering that commercial project developments can take up to ten years. These large-scale projects will enable significant cost reduction and allow floating wind to compete with other energy generation. The pace and scale of deployment will be dependent on floating wind technology making a successful transition to large-scale projects.

Market growth will also be dependent on the level of political commitment in key lead markets. Without support, floating wind power could be limited to niche applications, struggling to compete in competitive auctions with more mature rival technologies. However, if a route to market can be achieved, large-scale commercial deployment could potentially unlock a multi-gigawatt pipeline of opportunities, with considerable value to be captured by local and regional economies.

The Carbon Trust has also undertaken independent analysis on the potential deployment of floating wind to 2040 and projects up to 10.7GW of floating wind by 2030 and 70GW by 2040. 70GW is estimated to have a project value of £195bn, demonstrating the opportunity for the supply chain globally to support and invest in floating wind.

Technology challenges

There are still significant technical challenges to be overcome to achieve large-scale deployment of floating offshore wind, which will require innovation from supply chain and developers. Both operational, and projects under development, will be key to providing lessons learned to increase understanding of these assets and de-risk future commercial projects. Many of these technical challenges are common to multiple floating wind designs, making them suitable for industry-led collaborative research and development efforts. The Floating Wind JIP Phase II projects addressed some of these challenges.

Next-generation turbines only need minor modifications for floating: A study on turbine requirements and foundations scaling, delivered by Ramboll, looked at the potential impacts of installing larger, next generation turbines on floating substructures. Aside from turbine towers and controllers, the study found that only minor modifications would likely be needed for future turbines, and that the required relative primary steel, secondary steel and mooring mass decreases for larger turbines.

New vessels or alternative lifting solutions needed for floating offshore heavy lift operations: A heavy lift offshore operations study undertaken by Seaway 7 investigated the challenges associated with floating heavy lift offshore construction and maintenance operations for turbines up to 20MW. It found that the limited availability and high cost of suitable floating heavy lift vessels in the market at present is a barrier to cost-effectively undertaking operations offshore. There is a need for vessels capable of undertaking the required heavy lift operations or alternative lifting solutions, such as climbing crane technology.

Dynamic export cable products for floating farms in development: This project, delivered by BPP Cable Solutions, investigated the challenges and assisted in the development of high voltage dynamic export cables required to transport power from floating offshore wind farms. Previous Floating Wind JIP studies have highlighted a lack of suitable dynamic cables currently available on the market. An international [competition was launched](#) to support cable manufacturers develop and test suitable designs. Five cable manufacturers are currently being supported by the Floating Wind JIP to make these designs available as products for future projects.

No 'quick win' solutions for floating monitoring and inspection: A study focused on monitoring and inspection undertaken by Oceaneering, looked at the techniques for assessing the integrity of floating wind farms. It concluded that improvement is needed in both the collection of data and its usage to inform and manage asset integrity for floating wind farms, and in particular for subsea assets. For this there were no immediately available solutions, but techniques such as a digital twin approach, or unmanned vessels, could support cost effective solutions.

List of key findings and priority innovation needs

Turbine requirements and foundation scaling

Key findings:

- 01 Existing turbines can be installed and operated on floaters without requiring major modifications (modification required to the tower and controller)
- 02 Loads are the main driver, and not accelerations, for assessing the impact of turbine components being installed on floaters
- 03 The operational wind turbine requirements, as set by turbine suppliers, are not overly conservative
- 04 Need for long term project experience in order to validate numerical analysis, such as floater-specific load on components and effects of extreme weather events
- 05 Across all concepts the required primary steel, secondary steel and mooring mass per MW decreases significantly for larger turbines

Priority innovation / technology needs:

- 01 An improved interface between turbine suppliers and floater designers, in order to have a more integrated design
- 02 Floating wind specific turbine designs may in the long term further reduce overall cost

Heavy lift offshore operations

Key findings:

- 01 Limited options and experience for offshore floating wind turbine installation
- 02 Limited vessel availability for large turbine lifts, in particular lift height will be at a premium for future offshore wind construction vessels
- 03 Motion compensation systems are being developed, however not focused on the specific requirements for floating wind
- 04 Alternative lifting solutions, such as climbing crane technologies, look to be promising solutions for maintenance of main components

Priority innovation / technology needs:

- 01 Future heavy lift vessels, for fixed and floating wind, will require better motion compensation combined with height and reach, rather than overall lift capacity
- 02 Need for the development and scaling of enabling technology such as 3D motion compensation and climbing cranes
- 03 Encourage turbine manufacturers to engage more openly with supply chain
- 04 Create opportunities to trial new installation technologies on fixed wind projects and floating wind demonstrators
- 05 Supply chain needs greater clarity on future turbine sizes and when they will come to market
- 06 Turbine suppliers to consider changes to the next generation of offshore turbines in order to make them more installation friendly
- 07 Supply chain needs greater visibility on substructure sizing and motion characteristics
- 08 Integration of maintenance strategies into design

Dynamic export cable development

Key findings:

- 01 Few HV dynamic cables have been produced for offshore energy generation projects
- 02 Lessons to be learned from faults that have affected dynamic MV submarine cables
- 03 Cross section design including material selection and component sizing needs to be diligently undertaken to ensure that the cable components have adequate and predictable strength and fatigue properties
- 04 Dynamic export cables will be heavier, stiffer, larger in diameter, and will have larger minimum bend radii and will be less tolerant of twisting

Priority innovation / technology needs:

- 01 A number of design and manufacturing challenges have to be overcome before HV dynamic export cables can be routinely produced
- 02 Handling techniques to be modified to safely manipulate HV dynamic export cables
- 03 Testing and qualification of HV dynamic export cables before implementation
- 04 Development and demonstration of cable condition monitoring technologies

Monitoring and inspection

Key findings:

- 01 There are no 'quick win' solutions but sensors used in the digital twin approach and unmanned USV or ROV can offer more cost-effective alternatives to manned operations
- 02 Remote monitoring options for mooring lines were found to be limited with methods for remote data transfer identified as a potential challenge area
- 03 The cost reduction offered by sampling regimes applied to floating offshore wind farms is considered great, but the current methodology is abstract and difficult to apply

Priority innovation / technology needs:

- 01 Development of probabilistic models linked to sensor inputs for digital twins is required, especially when considering computing power and correct representation of floating wind turbines
- 02 The implementation of monitoring devices on mooring systems including the provision of suitable power systems is identified as an area of development
- 03 Reliance on fibre optic cores for the monitoring of dynamic export cables and conservative risk assessments are identified as an area of concern
- 04 A framework for the assessment of mooring failure based on annualised failure probabilities should be agreed with classification societies
- 05 Classification societies, along with other key stakeholders, should be engaged to agree on a way to reduce mooring failure risk and inspection costs

Abbreviations

AC	Alternating Current
AHV	Anchor Handling Vessel
CfD	Contract for Difference
DC	Direct Current
DEC	Dynamic Export Cable
EPCI	Engineering, Procurement, Construction and Installation
GW	Gigawatt
HLV	Heavy Lift (crane) Vessel
HMPE	High-Modulus Polyethylene
HV	High Voltage
JIP	Joint Industry Project
LCOE	Levelised Cost of Electricity
MV	Medium Voltage
MW	Megawatt
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OTM	Offshore Transformer Module
PPA	Power Purchase Agreement
R&D	Research and Development
RAO	Response Amplitude Operator
RBI	Risk Based Inspection
RNA	Rotor and Nacelle Assembly
ROC	Renewable Obligation Certificate
ROI	Return on Investment
ROV	Remotely Operated (underwater) Vehicle
SSCV	Semi-Submersible Crane Vessel
TLP	Tension Leg Platform
TRL	Technology Readiness Level
WTG	Wind Turbine Generator
USV	Unmanned Surface Vehicle
UXO	Unexploded Ordnance

Introduction

Introduction to the Floating Wind Joint Industry Project

The Floating Wind Joint Industry Project is a collaborative research and development (R&D) initiative between the Carbon Trust and 15 leading international offshore wind developers: EDF Renewables, EnBW, Equinor, Kyuden Mirai Energy, Ørsted, OW Offshore (a joint venture between ENGIE and EDPR), Parkwind, RWE Renewables (including the former renewables business of innogy), ScottishPower Renewables, Shell, SSE Renewables, TEPCO, TOTAL, Vattenfall, and Wpd.

Since its formation in 2016, the JIP has been delivered in 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, which includes four phases of work.

Key findings for [Phase I projects have been published](#) and this report presents the key findings from Phase II projects (see chapters [2-5](#)). Phase III projects are due to be completed in 2020. A series of follow on projects will be delivered in 2020 as part of Phase IV. Refer to Chapter 5 for an overview of Phase III and IV projects.



Image: Hywind Scotland (Equinor)

Objectives and scope

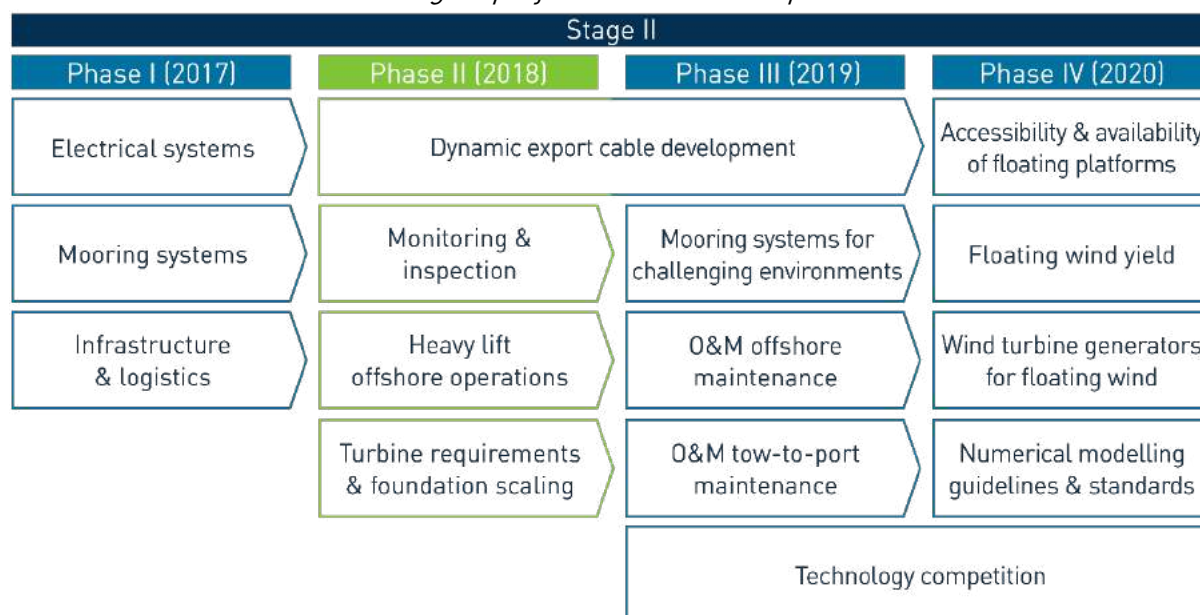
The primary objective of the Floating Wind JIP is to investigate the challenges and opportunities for the deployment of large-scale commercial floating wind farms. The JIP is technology-focused, with a particular emphasis on:

- **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 power 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 JIP is guided by the need to deliver cost reductions ensuring that floating wind power becomes a competitive energy technology in several global markets. Cost assessments are included within the scope of most JIP projects in order to build a robust estimate of the cost projections and cost drivers for future commercial projects.

Overview of the Phase II Floating Wind JIP Studies

Below is a summary of the projects in Stage II Phase II of the Floating Wind JIP. The full summary reports, innovation and technology needs can be found in Chapters 2-5. An overview of the current research being undertaken can be found in Chapter 6.

See below for an overview of Stage II projects delivered and planned.



Turbine requirement and foundation scaling

Turbine size is increasing rapidly, with 13-15MW turbines expected to be on the market by 2025, the same period by which the first commercial-scale floating wind farms are expected to be installed. Current assessments and understanding of 2-10MW floating wind turbines are not necessarily fully transferrable to the first commercial farms to be deployed with larger turbines. In increasing turbine size, it is important to understand the effect of this scaling on substructure design (dimensions, mass, etc.), and hence cost.

Floating substructures have specific design requirements compared to turbines for bottom-fixed offshore wind that need to be better understood. This study was initiated in order to initially assess the suitability of the next generation of turbines for commercial-scale floating wind farms.

The scaling of the turbine rating (power output) will be one of the key drivers of cost reduction so it is critical to define the estimated scaling factors for different floater types. The study concluded that there were no expected obstacles for using the future large turbines on floating wind platforms for commercial floating wind projects. Across all concepts the required relative primary steel, secondary steel and mooring mass per MW decreases significantly for larger these turbines.

Heavy lift offshore operations

Commercial-scale floating wind farms will require a different approach to fixed offshore wind due to the water depth and likely size of future turbines. Deep waters and large turbines pose challenges to undertaking large lifting operations offshore. For several floating wind concepts, port-side operations are unlikely to be feasible due to draft and/or towing constraints. Even for concepts advocating port-side maintenance operations, there are challenges regarding the economic and technical viability of such an approach. In a large-scale floating wind farm, it is possible that undertaking more operations in-situ at the offshore site could be advantageous, and in some cases, essential.

The study showed that, while there is significant knowledge and availability of heavy lift vessels in the oil and gas sector, these vessels are focused on lifting capacity rather than the lift height and reach that is needed for floating wind. There is therefore a need for vessels capable of undertaking the heavy lift operations or alternative lifting solutions, such as climbing crane technology. These solutions will need to be scaled up and opportunities to trial new innovative installation and maintenance technologies. In order for the supply chain to provide solutions to meet the heavy lift challenges for floating wind, more visibility is needed of the future turbine specifications as well considering adaption of turbines to facilitate heavy lift operations.

Dynamic export cables

Early prototypes and first arrays of floating wind turbines have been connected to shore using MV power cables (of 22-66kV). Large commercial-scale floating wind farms at deep-water sites (>100m depth) will need floating substations to increase the voltage before exporting power back to shore. The export cables will need to be more robust than conventional static

cables to withstand the motions due to being connected to a floating substation. These cables are known as dynamic export cables and previous Floating Wind JIP studies have highlighted a lack of suitable dynamic cables currently available on the market for future floating wind projects.

This project has assessed the challenges of the development of high voltage dynamic power cables for export purposes in floating offshore wind farms. A competition was launched for cable manufacturers to develop suitable designs and carry-out cable testing to accelerate the development of these HV cables. Five cable manufacturers have been supported to develop and test their designs in preparation for product qualification and future manufacturing.

Monitoring and inspection

Ensuring the integrity of assets in an offshore wind farm over the full lifetime of the project is vital to maximising the economic value for its owners and manage project risk. This is especially true for floating offshore wind farms, given the importance of station-keeping and the novel risks presented by dynamic and active systems. Monitoring and inspection methods for bottom-fixed offshore wind farms have improved considerably in recent years, with several R&D initiatives underway to better inform monitoring and inspection strategies. However, floating wind farms introduce novel elements that may require alternative approaches and new technologies such as: the hull, ballast systems, mooring and anchoring system, and dynamic cables.

These novel elements can result in more conservative monitoring and inspection requirements and higher operation and maintenance costs across the wind farm. While technologies exist in both the fixed offshore wind and offshore oil and gas industries, the associated cost and risk profile will differ for floating wind farms, which may require alternative technologies and methodologies. There is a need to better understand current and future requirements and identify technology innovations that could reduce requirements and associated costs.

The study assessed monitoring and inspections requirements based on national and international guidelines and standards, as well as the technologies available to undertake these strategies. The study found that there are no 'quick win' solutions but that there are techniques in development, such as use of the digital twin approach or unmanned vessels, that will support cost effective solutions for floating wind. In general, an improvement is needed in both the collection of data and its usage to inform and manage asset integrity for floating wind farms, and in particular for subsea assets. This approach to asset integrity managements needs to be combined with better engagement with the relevant classification societies and regulatory bodies in order to agree on common approaches to optimise inspection costs while minimising risk of failure.

1. Floating wind market status

The Carbon Trust has undertaken a floating wind market analysis which covers an overview of projects in operation and under development, as well as providing expected growth of the industry up to 2040. This analysis is not part of the Floating Wind JIP project and aims to provide an overview of the current and future market as a reference.

1.1 Market growth

We expect to see market growth characterised through the following phases of projects, with the ambition to reach commercial-scale projects:

- **Demonstration projects** (single/multi-MW unit): Most projects installed to date have been single-unit demonstration projects. Demonstration projects provide important learnings for de-risking technology ahead of large-scale deployment, which is expected within the next decade.
- **Pilot projects** (small arrays): There are currently 55MW of pilot projects installed (Hywind Scotland and WindFloat Atlantic), 50MW in construction and 126MW worth of contracts awarded. These projects with three or more turbines will double the capacity of floating offshore wind by the end of 2020 and are expected to increase capacity almost fivefold by 2023. The relative fast increase in capacity will commence the process towards commercialisation and bring a better understanding of how multiple floaters will behave.
- **Pre-commercial projects** (50-200MW): Hywind Tampen, an 88MW project, is currently the only pre-commercial project with FID. This scale of project provides a stepping stone to bridge the gap between pilot and commercial projects. Projects of this scale will test supply chains by manufacturing and installing multiple units of the technology and will enable be a step change in cost reduction.
- **Commercial-scale projects** (>200MW): Large-scale deployment will bring costs down further by enabling efficiencies in project development as well as seeing projects become investment grade assets. This scale of projects will require industry collaboration in order to meet the expected technical and logistical challenges. It is expected that most commercial-scale projects will be significantly larger than 200MW.

1.1.1 Floating wind deployment to date

As of publication, a cumulative total of 73MW of floating offshore wind power has been installed in countries in Asia and Europe, which will increase to 124MW by the end of 2020 (Table 1 and Table 3). A series of prototypes installed between 2009 and 2018 have demonstrated the viability of the technology in single units, performing well in harsh environmental conditions and paving the way for larger arrays.

Hywind Scotland, installed in 2017, is the first of a series of pilot projects, proving that the technology can perform in array formation and with larger turbines. The performance of

Hywind Scotland to date has exceeded expectations¹, with high yields confirming the technical and commercial viability of the technology. WindFloat Atlantic 2, a second pilot project installed in 2020, demonstrates an alternative floating platform design, with the largest turbine used in a floating wind project (see [Box 1](#)).

There has been relatively little capacity installed since 2018 when the Phase I report was published, however this will change rapidly with the completion of a series of pilot wind farms, as shown in Table 2. The lack of installation activity has hidden significant technological developments that have been progressed by key industry players in preparation for the next generation of projects, which is highlighted in the commercial projects section.

Table 1: Commissioned and in-construction floating wind projects

First power	Country	Project	Total capacity	Turbine rating	Project developer	Technology developer	Concept	Turbine supplier
2009	Norway	Hywind I	2.3MW	2.3MW	Equinor	Equinor	Hywind	Siemens
2011	Portugal	WindFloat Atlantic Phase 1*	2MW	2MW	EDPR, Repsol, Chiyoda, Mitsubishi	Principle Power	WindFloat	Vestas
2013	Japan	Kabashima	2MW	2MW	Toda Corporation	Toda Corporation	Hybrid Spar	Hitachi
2013	Japan	Fukushima FORWARD	2MW	2MW	Marubeni	Mitsui Engineering and Shipbuilding	Semi-Sub	Hitachi
2015	Japan	Fukushima FORWARD**	7MW	7MW	Marubeni	Mitsubishi Heavy Industries	V-Shape Semi-Sub	Mitsubishi
2016	Japan	Fukushima FORWARD	5MW	5MW	Marubeni	Japan Marine United	Advanced Spar	Hitachi
2017	UK	Hywind Pilot Park	30MW	6MW	Equinor	Equinor	Hywind	Siemens
2018	France	FloatGen	2MW	2MW	IDEOL	IDEOL	Damping Pool	Vestas
2018	Japan	IDEOL Kitakyushu Demo	3MW	3MW	IDEOL and Hitachi Zosen	IDEOL	Damping Pool (Steel)	Aerodyn
2019 (2020)	UK	Kincardine***	2MW (50MW)	2MW x1 (9.5MW x5)	Pilot Offshore, Cobra	Principle Power	WindFloat	MHI-Vestas
2019	Norway	TetraSpar demonstration	3.6MW	3.6MW	RWE Renewables, Shell, Steisdal OT	Steisdal Offshore Technologies	TetraSpar	Siemens
2020	Portugal	WindFloat Atlantic 2	25MW	8.3MW	EDPR, ENGIE, Repsol, PPI	Principle Power (PPI)	WindFloat	MHI-Vestas
2020	Spain	DemoSATH	2MW	2MW	Saitec	Saitec	SATH	TBC

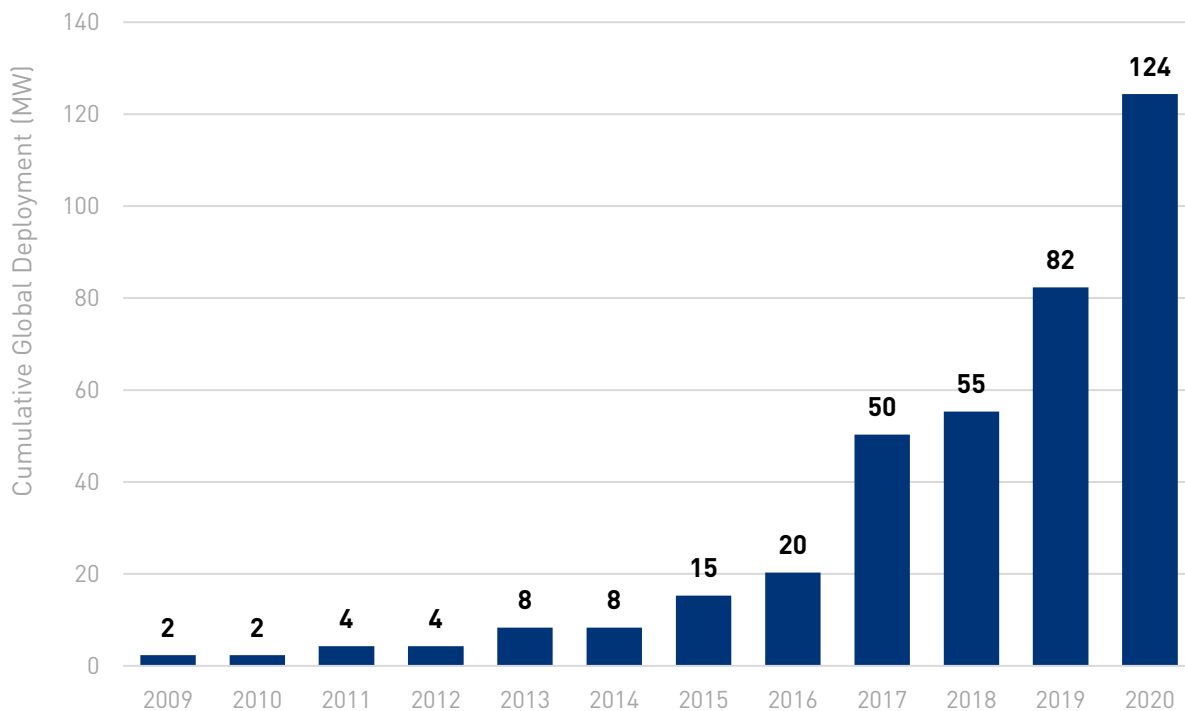
* WindFloat 1 decommissioned in 2016. The WindFloat 1 substructure redeployed in the Kincardine pre-commercial project in Scotland.

** Mitsubishi 7MW floater is being decommissioned, works started in early May 2020 and scheduled to be completed by Spring 2021.

*** As yet only Windfloat 1 device (2MW) has been installed and is producing power, remaining 5 devices (48MW) due for commissioning in 2020.

¹ <https://renewablesnow.com/news/hywind-scotland-trumpets-65-capacity-factor-601823/>

Figure 1: Cumulative global deployment of floating offshore wind (2009-2020)

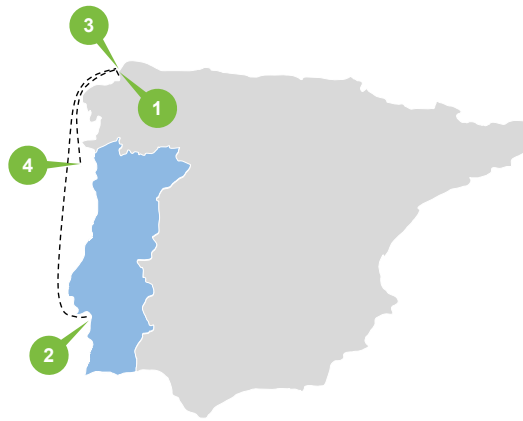


Box 1: Case study – WindFloat Atlantic

The 25MW floating offshore project off the Coast of Portugal, which as of the time of publication is moored and final commissioning works are being completed. The project forms the next stage in platform evolution from Principle Power Incorporated (PPI). The project is being developed by WindPlus, a consortium made up of EDP Renewables, ENGIE, Repsol and Principle Power.

The project will feature three MHI Vestas V164 turbines, each with a capacity of 8.4MW, mounted on PPI's floating semi-submersible platforms, giving a total project capacity of 25MW.

The platform construction (now complete) was undertaken partially by A. Silva Matos (2 units) and partially by the Navantia-Windar joint venture (1 unit), who were responsible for the 5 spar units for Hywind Scotland and five further WindFloat units for the upcoming Kincardine project. Construction has been divided between the Fene shipyard in Ferrol, Spain (1) where one platform is being fabricated, and the Lisnave shipyard south of Lisbon, Portugal, where the remaining two platforms are being fabricated (2). The platforms were towed to a deep-water quayside facility in the Outer Port of Ferrol (3) for fit-out where the turbines, supplied by MHI Vestas were installed via shore-side crane.



The units were towed to the installation site 20 km off the Coast of Viana do Castelo, Portugal (4), where they will be hooked up to a hybrid synthetic/chain mooring system with Vryhof supplied drag embedded anchors. The array cables are JDR supplied 66kV cables (operated at 60kV) and power will be exported to land via a static 150 kV export cable (operated at 60kV), developed by Hengtong. The overall installation process has been overseen by Bourbon Subsea Services.

The WindFloat Atlantic site has a water depth of 85 to 100 metres and an average wind speed of 7.8 metres per second (m/s). Although this wind resource is not as high as Hywind Scotland (10.31 m/s) or Kincardine (9.93 m/s) the challenging met-ocean conditions will be key to validating the commercial-scale design. This new iteration of the WindFloat platform design will see a MW capacity increase of over 4 times versus a primary steel increase in the order of 1.75 times, showing a positive scaling correlation for this type of floating platform.

PPI plan to build on this project with a contracted total of 105MW installed capacity by the end of 2021 (WindFloat Atlantic - 25MW, Kincardine - 50MW, and Golfe du Lion - 30MW). To achieve this, the company aim to reduce the amount of time required for fit out at the quayside, so as to avoid logistical bottlenecks and target a one platform hook up per day on site.



1.1.2 Upcoming pilot projects

Building on the demonstrations to date, there is a pipeline of pilot projects that will further demonstrate the technical and commercial viability of a range of floating wind designs, as well as the supporting infrastructure and component technologies (mooring systems, dynamic cables, etc.). The majority of activity will be located in Europe, with additional demonstration projects in the United States and Japan. By 2021, installed capacity is expected to reach about 200-260MW, utilising 5-6 concept designs.

Table 2: List of upcoming floating wind projects

First power	Country	Project	Total capacity	Turbine rating	Project developer	Technology developer	Concept	Turbine supplier
2021/2022	France	Les éoliennes flottantes de Groix and Belle-Île	28.5MW	9.5MW (V164)	Shell/Eolfi, China Guangdong Nuclear (CGN)	Naval Energies	Sea Reed	MHI-Vestas
2021/2022	France	Les Eoliennes Flottantes du Golfe du Lion	30MW	10MW (V164)	Engie, EDPR, Caisse des Depots	Principle Power (PPI)	WindFloat	MHI-Vestas
2021/2022	France	EolMed (Gruissan) Pilot Farm	30MW	10MW (V164)	Quadran	IDEOL	Damping Pool	MHI-Vestas
2021/2022	France	Provence Grand Large	25.2MW	8.4MW (SWT-8.0-154)	EDF EN	SBM Offshore	TLP	Siemens-Gamesa
2021/2022	Japan	Goto City	22MW	2-5MW	Toda Corporation	Toda Corporation	Hybrid Spar	TBC
2021/2022	Norway	Hywind Tampen*	88MW	8MW	Equinor	Equinor	Hywind	Siemens-Gamesa
2022	Ireland	AFLOWT	6MW	6MW	EMEC, SEAI, SAIPEM	SAIPEM	Hexafloat	TBC
2020	USA (Maine)	Aqua Ventus I	12MW	6MW	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

1.1.3 Commercial projects and market growth to 2040

Following on from the pilot projects, floating wind will need to be deployed in large-scale projects in order to achieve cost reduction and validate the technology. The timescale and rate of deployment for commercial projects is still uncertain, but current market conditions suggest that the first large-scale projects are to be installed by the late 2020s.

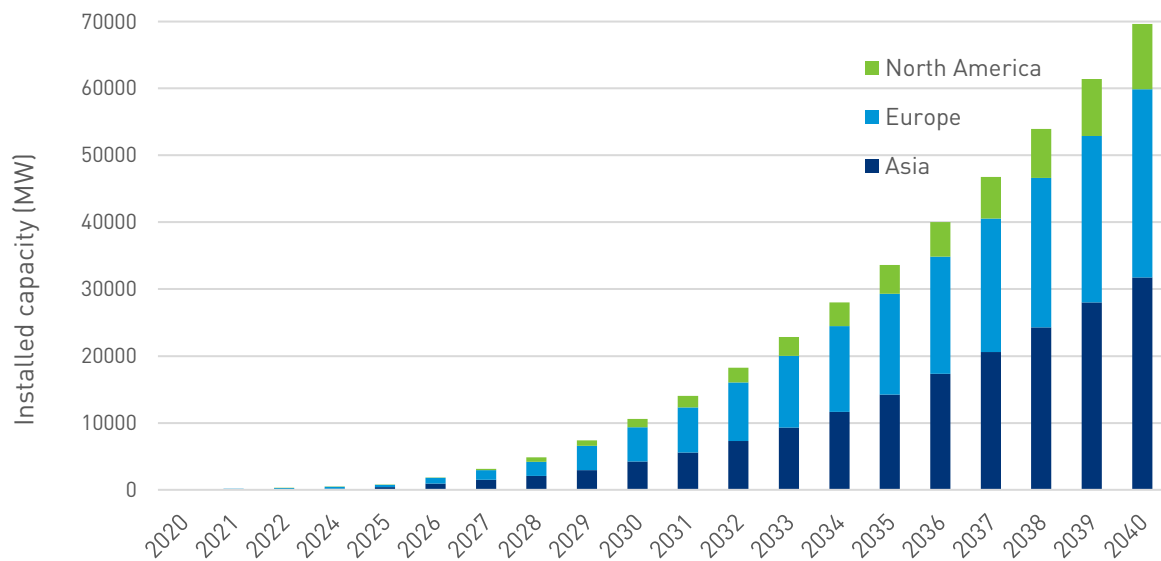
Given typical development timescales in Europe of up to ten years, projects for commissioning by the late 2020s would need to already be in active development, and a pipeline of projects for 2030 would need to be established within the next two years. Pipelines will need to be of sufficient magnitude to account for project delays and attrition, particularly in uncertain regulatory regimes and competitive auction systems.

The analysis below outlines the floating wind deployment the Carbon Trust expects up until 2040. It is challenging to predict targets of individual countries, particularly as the route to market for large-scale commercial projects is being developed between the industry and policymakers. The Carbon Trust has taken a bottom-up assessment of projects where there is market visibility and combined this with a longer-term assessment of the global floating wind market. Its forecast is based on:

- Potential resource for floating wind (ceiling value)
- Market demand for floating wind (for example as part of national decarbonisation plans)
- National policy and route to market
- Capability of supply chain to deliver the required capacity for future projects, or ability to import capacity

The Carbon Trust expects up to 10.7GW of floating wind is feasible by 2030 and 70GW by 2040. Figure 2 shows the predicted growth of floating wind across Asia, Europe and North America. This is a slightly revised down 2030 prediction from the 12GW by 2030 outlined in the Phase I report, as 2029 or 2030 will mark a significant step change for the pace of development. From 2030, the build out rate is expected to increase to over 3GW/year, therefore 12 GW is expected to be exceeded in 2031.

Figure 2: Global floating wind deployment



The size and location of future deployment will be largely dependent on conducive government policies, supportive regulatory frameworks, and the pace of technology innovation in the industry. Table 3 outlines global floating wind deployment for three scenarios:

- **Expected deployment:** Favourable policies in the key floating wind markets, enabling an increase in project size and investment and the transition from pilot to commercial-scale projects.
- **Slow deployment:** No clear route to market for floating wind and deployment is constrained. In this case, build out rate would be expected to grow much more slowly following on from pilot projects.
- **Accelerated deployment:** Policy support and technology commercialisation is accelerated across several markets combined with an aggressive cost reduction pathway, enabling floating wind to compete with other technologies.

Table 3: Industry deployment ambitions to 2040

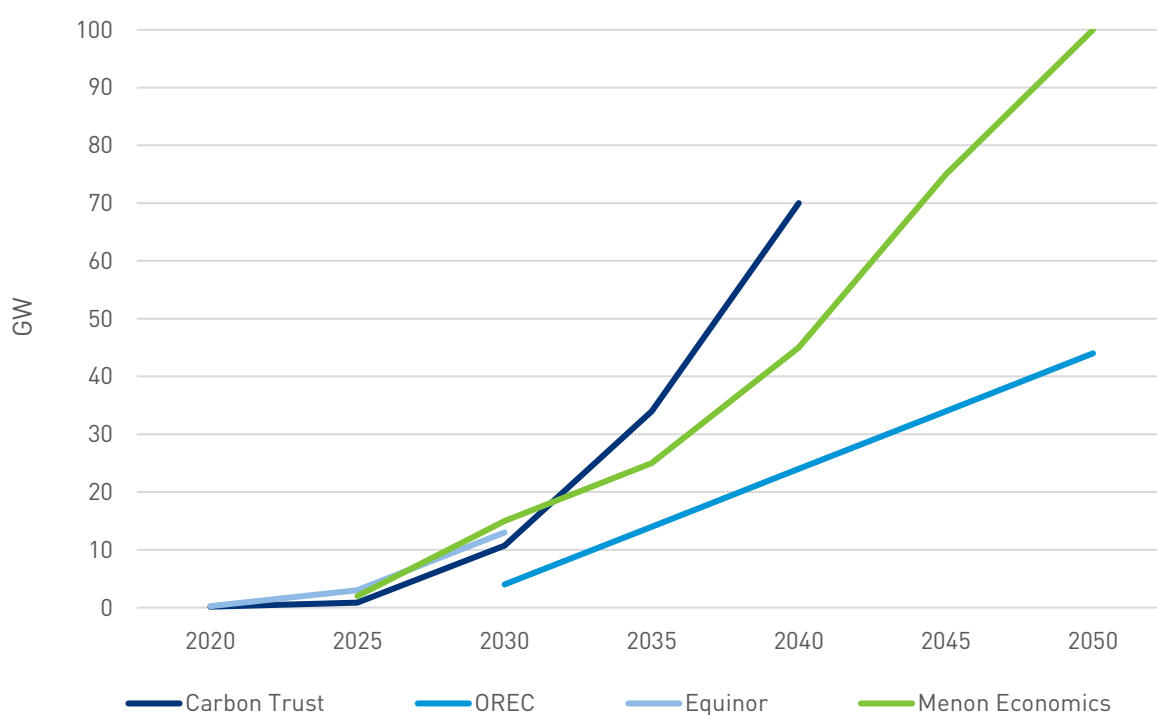
Country	Installed (MW)	Expected (MW)	Estimated Deployment (MW)			
	by end 2020	2022	2025	2030	2035	2040
EUROPE						
UK	80	80	142	1,100	3,800	7,400
France	2	116	116	1,550	5,100	8,900
Other Europe*	31	125	160	2,450	6,200	11,900
Europe (slow)	-	255	296	2,300	6,300	11,000
Europe (expected)	113	320	420	5,100	15,100	28,200
Europe (accelerated)	-	355	449	5,950	21,900	45,600
ASIA						
Japan	12	30	80	930	4,200	11,000
China	0	0	20	495	2,500	7,000
South Korea	0	3	320	1,600	5,000	10,000
Asia (slow)	-	25	210	1,800	5,900	12,900
Asia (expected)	12	33	420	4,300	14,300	31,800
Asia (accelerated)	-	40	520	5,300	21,200	56,200
UNITED STATES						
US (slow)	-	0	0	370	1,500	3,700
US (expected)	0	12	12	1,270	4,300	9,800
US (accelerated)	-	12	12	1,800	6,600	17,500
GLOBAL						
Global (slow)	-	280	511	4,500	13,800	27,800
Global (expected)	125	365	848	10,750	34,000	70,300
Global (accelerated)	-	407	971	13,100	50,100	120,200

*Other Europe includes Portugal, Spain, Norway, Greece and Turkey

1.1.4 Comparison of market projections

In Figure 3 a comparison has been made against other floating wind market projections. There is relatively close alignment between the Carbon Trust's projections, and those of Equinor (2017 projections) and Menon (2019 projections) to 2030². However, the Carbon Trust expects to see a faster ramp up floating wind installations from 2030, leading to higher projections for 2035 and 2040 compared to Menon's projections. Equinor have not published projections further than 2030. OREC Catapult have considerably lower projections for both 2030 and 2040 which is due to a conservative approach of assuming a 1GW per year build out up to 2030 and 2GW per year from that point. This is more in line with our slow deployment scenario.

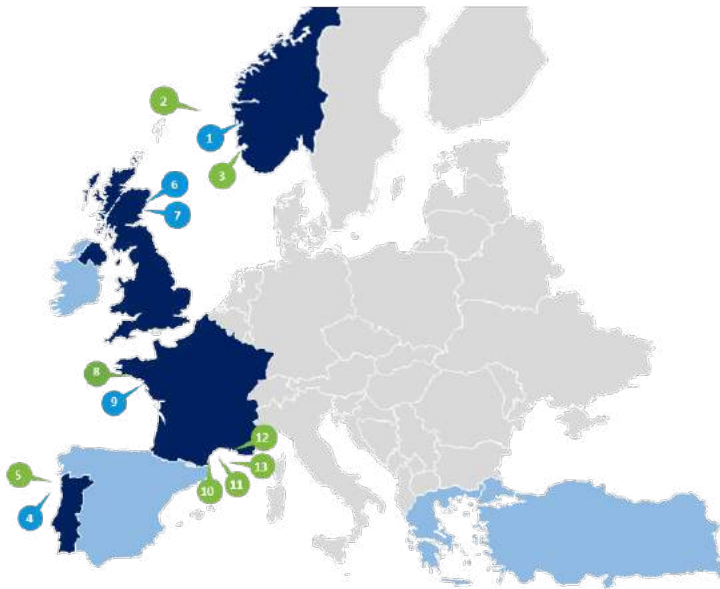
Figure 3: Comparison between floating wind deployment projections made by Carbon Trust and other organisations



A map and list of installed and pipeline floating offshore wind projects in the three key regional markets can be seen in Figure 4.

² <https://www.menon.no/wp-content/uploads/2019-69-Verdiskapingspotensialet-knyttet-til-utviklingen-av-en-norskbasert-industri-innen-flytende-havvind-1.pdf>

Figure 4: Regional floating wind deployment



Europe

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
United Kingdom	
6. Hywind Pilot Park	30
7. Kincardine	50
France	
8. Commercial tender (2021)	250
8. (bis) Groix & Belle-Ile	28.5
9. FloatGen	2
10. Golfe du Lion	
11. EolMed	30
12. Provence Grand Large	25
13. Commercial tender (2022)	250 x 2

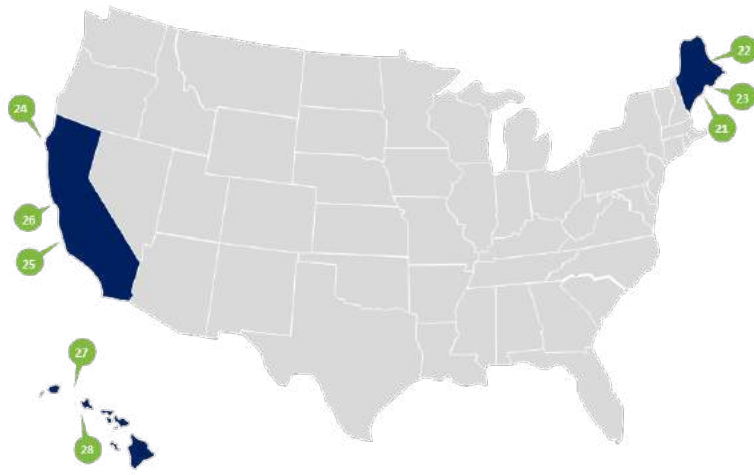
* Windfloat Atlantic 1 now decommissioned

Asia



Project	MW
Japan	
14. Sakiyama	2
15. Fukushima FORWARD: Phase 1	2
16. Fukushima FORWARD: Phase 2	12
17. IDEOL Kitakyshu demo	3
18. Goto City	22
Taiwan	
19. Eolfi Taiwan	500-2000
China	
20. CGN Jiayang	500-3000
South Korea	
21. Shin-Gori Pilot	1
22. Ulsan Prototype	5
23. Donghae Sites	500-1500

United States



Project	MW
Maine	
21. Aqua Ventus I	12
22. Aqua Ventus II	450
23. Aqua Ventus III	450
California	
24. Humbolt Coast	150
25. Morro Bay	700-1000
26. Diablo Canyon	700-1000
Hawaii	
27. Oahu Northwest	400
28. Oahu South	400



Image: WindFloat prototype, Portugal

1.2 Policy assessment

1.2.1 Overview of key markets



United Kingdom

Opportunities for floating wind

The most attractive sites for floating wind in the UK are concentrated off the Coast of Scotland, where near-shore deep-water sites are located, with suitable geology and met-ocean conditions for floating devices. The South West of the UK also has sites suitable for floating wind technology.

The UK's offshore wind sector deal between government and industry has an objective of 30GW of offshore wind by 2030, and the UK government has made a manifesto commitment to increase the target to 40GW by 2030. The industry also has a long-term ambition of 75GW by 2050. The UK has significant offshore wind potential in shallow water depths, however the 2030 and 2050 targets will be difficult to achieve without floating wind projects.

Floating wind could also support the UK's industrial strategy by utilising well established supply chains from both the offshore wind and oil and gas sectors. A number of UK companies can leverage decades of experience working in the North Sea, with many suppliers actively looking to diversify and adapt their products and services for the renewables sector.

Projects

Scotland is host to the first floating wind farm, Hywind Scotland. The 30MW project has achieved higher than expected capacity factors and survived several harsh winter storms in its first years of operation. The next floating project is the 50MW Kincardine wind farm, which will be constructed in two phases, with a 2MW semi-submersible unit installed in 2018 followed by five 9.5MW units in 2020. A further two projects – Dounreay Tri (10MW) and Forthwind (60MW) – struggled to meet the closure of the enhanced Renewable Obligation Certificates (ROCs) subsidy regime and are unlikely to proceed. A recently announced 96MW project, Erebus, in Wales is currently making a seabed licence application.

The Crown Estate Scotland's³ upcoming leasing round, ScotWind Leasing, is expected to open in 2020 and will aim provide up to 10GW of project capacity. Alongside this, Marine Scotland are close to completing their Sectoral Marine Plan for Offshore Wind which has already identified a significant proportion of deep-water sites suitable for floating projects.

The Crown Estate's Offshore Wind Leasing Round 4, focused on English and Welsh waters, is currently ongoing and is expected to award up to 8.5GW of new seabed rights. Round 4 is focused on shallower (<60m) waters and is unlikely therefore to be suited to commercial-scale floating wind projects. However, the tender includes incentives for projects that include pre-commercial innovations, including floating wind, helping to encourage developers to incorporate new technologies.

³Jurisdiction of The Crown Estate: managing offshore wind leases for the seabed around England, Wales and Northern Ireland

The Crown Estate also provides ongoing opportunity to access the seabed for the testing and demonstration of emerging offshore wind technologies including floating wind, for projects of up to 100MW in scale. Through this process, the 96MW Erebus project is expected to be granted seabed rights off the Coast of Wales in 2020. Although no decisions have yet been taken, future leasing rounds undertaken by The Crown Estate may include deeper waters, which would unlock the potential for the first UK commercial-scale floating wind sites outside of Scotland.

Policy support

Policy support for floating wind in the UK has been previously driven by the enhanced ROCs available in Scotland for floating wind technology, reinforced by Scotland's goal to generate 100% of its electricity from renewables by 2020. The enhanced ROC regime closed in 2018 and without a successor mechanism there has been a lull in the market; visible from the lack of UK pipeline beyond 2020.

The UK government has opened up a consultation to consider Contracts for Difference (CfDs) for floating wind. CfDs are the UK government's main mechanism for supporting low carbon electricity generation and have enabled the significant cost reduction seen in offshore wind. The consultation proposes to either continue with existing groupings or create a definition for floating in Pot 2 (emerging technologies) and move offshore wind into its own separate pot (a new Pot 3). It is noted that "nascent technologies such as floating offshore wind could have a role in the long-term decarbonisation of the UK, but they need to deliver value for money and have the potential to both achieve cost reduction and contribute significantly to decarbonisation".⁴

CfD auctions are expected to occur approximately every two years, the next will be Allocation Round 4 (CfD AR4). The Carbon Trust's market outlook assumes that floating wind will be considered in future CfD rounds (from AR4 onwards), which will provide a route to market for future commercial projects.

It is expected that the following types of project will be commissioned in the UK:

- **Hybrid and pilot projects:** depending on the qualification of a floating wind CfD unit, sites currently scoped for bottom-fixed projects could bid for both bottom-fixed and floating CfD. This would reduce investment risk in sharing common assets across the projects; such as the substation, export cables, and installation vessel spread. There are likely also to be standalone floating wind sites, enabled under The Crown Estate's parallel leasing for test and demonstration projects of up to 100MW, for projects such as Erebus.
- **Commercial-scale projects:** ScotWind will provide the first large-scale deep-water sites. It is expected that these projects could achieve Commercial Operation Date (COD) in 2029 or 2030. Allowing projects sufficient time for consenting, it is expected they would bid into CfD AR6 (2025). Following on from these first commercial projects, a pipeline of floating wind will be developed if the technology can prove value for money in successive CfD auction rounds.

⁴https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/885248/cfd-ar4-proposed-amendments-consultation.pdf

Figure 5: ScotWind leasing round with expected key stages highlighted



Opportunities for floating wind

France has recently increased its ambitions for offshore wind with a government target of between 5.2-6.2GW of offshore wind capacity installed by 2028, including floating wind. There are suitable sites for floating projects in both the Mediterranean and Atlantic waters off the West and South Coast of France. Sites in deeper waters will allow project developers to tap into higher wind speeds, in contrast to sites in shallow waters, which are often outperformed by Northern European counterparts. For several coastal regions, floating wind will offer an alternative to nuclear power and other less suitable renewables, such as onshore wind or solar PV.

France has emerged as a leading floating offshore wind market, partly due to the presence of a number of leading technology developers, such as IDEOL and Naval Energies, which aligns with an industrial strategy to leverage strengths in its maritime, construction, civil engineering, and oil and gas industries.

Projects

France's first offshore wind turbine – bottom-fixed or floating – was installed in May 2018. A 2MW Vestas turbine is supported by IDEOL's concrete Damping Pool floating technology. The FloatGen project has leaped ahead of several bottom-fixed projects that have experienced delays due to permitting and supply chain issues.

Following this first full-scale prototype demonstration, France has awarded contracts to four pilot floating wind farms; three in the Mediterranean and one in the Atlantic (see Table 2). The projects will receive a feed-in tariff set at €240/MWh, with commissioning expected from 2020 to 2022.

The pilot projects are due to be followed by three 250MW projects in Brittany and the Mediterranean, expected to be commissioned in 2027/2028. Figure 6 gives an overview of when projects are expected to be commissioned (COD) based on the tendering timeline. These projects will mark an important stepping stone in project scale before moving to large-scale commercial projects where costs are expected to drop significantly.

Policy support

France's most recent multi-annual energy program (*Plan de programmation pluriannuelle de l'Energie (PPE)*), announced in April 2020 has set a target of between 5.2-6.2GW of offshore wind capacity installed by 2028. In order to achieve these targets, they have confirmed tenders for 8.75GW of capacity from 2020 to 2028, made up of bottom-fixed and floating wind projects.

Figure 6 gives an overview of the timeline and capacity of the floating wind tenders that will provide revenue support for selected floating projects. There is concern however that some of the 500MW projects' timelines will slip due to expected long development timelines. The policy set out in the PPE gives a clear pipeline of 0.85GW of floating projects to be tendered out over the next 2 years. From 2024, 1GW/year of offshore wind capacity will be tendered out, with fixed and floating competing in the same pot. It is expected there will be floating wind allocated in these annual tenders considering it aligns with France's industrial strategy, however floating will need to demonstrate cost reduction in the previous tenders.

Other considerations are likely to be site availability, demand and environmental impact. Wind industry group France Energie Eolienne (FEE) has outlined a target of at least 3GW of floating offshore wind capacity by 2030. In order to meet this target, floating projects will have to compete in these fixed/floating auctions.

Recent regulatory reforms for offshore wind in France will also aim to streamline the development process and transfer responsibility for offshore transmission infrastructure to state operator RTE (*Réseau de Transport d'Électricité*), reducing consenting and construction risk for developers.

Figure 6: Overview of expected COD for French tenders



South Korea

Opportunities for floating wind

South Korea has huge potential for floating wind, especially on the East Coast where water depths are above 60m. Average wind speeds closer to shore are lower than in the North Sea and challenging seabed conditions may limit the feasibility of bottom-fixed in some areas. There is strong political and public will to increase the share of renewable energy generation in order to reduce reliance on fossil fuel imports, improve air quality and reduce emissions. The government has set a target to source 20% of power generation from renewables by 2030, including 12GW of offshore wind. Given that it is starting from an installed capacity of less than 0.05GW this is an extremely ambitious target and has led to a spike in interest in the market from domestic and foreign investors. The scale of the target and the proportion of coastal waters above 50m depth suggests that a significant proportion of new capacity will come from large-scale floating wind farms.

There are strong domestic manufacturing capabilities existing in the country including three turbine manufacturers. The government is also keen to take advantage of the new economic opportunity to boost jobs and industry. Ulsan in particular has been identified as an ideal hub for floating wind due to its strong industrial heritage and proximity to deeper sea areas, and its local government is aggressively promoting floating wind development.

Projects

Floating wind plans in South Korea are very focused on the Ulsan metropolitan city region, where the local government has identified it as one of the key priorities of its regional energy plan and has an ambition to foster Ulsan as an export base for floating wind. The city has a clear plan to proceed with R&D and planning of larger scale power generation facilities in parallel, beginning with a 750kW pilot turbine, followed by the development and demonstration of a 5MW turbine, followed by a 200MW energy complex and 2GW of capacity installation through public-private partnership. The focus on R&D for the demonstration projects, in collaboration with local universities, is an attempt to localise the technology as much as possible.

The 200MW project is being developed by a local consortium including Ulsan Metropolitan City, Ulsan TechnoPark and academic institutions. Completion is estimated for 2025.

For the 2GW public-private partnership Ulsan city has been open to receiving business proposals from foreign investors, in most cases through joint ventures with local companies. By the end of 2018 it had received proposals exceeding three times the original 2GW target and it has since signed MOUs with the following companies/consortia for the exploration of floating wind opportunities:

- Coens - Hexicon - Royal Dutch Shell joint venture
- SK E&S - Copenhagen Infrastructure Partners (CIP) joint venture
- Macquaries's Green Investment Group (GIG)
- Korea Floating Wind Power (KFWind), founded by WindPower Korea with investment from EDP and Aker
- Equinor - Korean National Oil Corporation (KNOC) joint venture

Known details on planned projects are:

- CoensHexicon, the joint venture between Swedish engineering company and floating platform supplier Hexicon AB and Korean service provider Coens, announced in 2019 that they will collaborate with Shell to develop a floating offshore windfarm 40km from Ulsan coast. The size of the project has not yet been disclosed.
- SK E&S and CIP's Ulsan White Heron Project proposes to construct up to 1.2GW of offshore wind in three 400MW phases by 2027.
- GIG's Gray Whale project is a greenfield 1.5GW floating wind farm in a former waste dumping zone off the Ulsan coast. GIG announced plans for phased development in June 2019 with an installation of the first floating LiDAR system. The first 400MW phase is targeted for completion in 2022.
- Equinor is collaborating with KNOC, 100% state-owned energy company, which is considering the feasibility of developing a 200MW floating offshore wind farm at the site of Donhae gas platform, located 58km off the South-East Coast of the peninsula. Equinor also has a proposed 800MW project 60-70km off the Coast of Ulsan which is currently undergoing a feasibility study.
- WindPower Korea, EDP Renewables and Aker Solutions have formed a consortium to develop a 500MW floating wind farm through significant investment into KFWind.

Beyond the 2GW public-private partnership there is a plan to develop a regional industry cluster consisting of R&D centres, power generation systems and operations and maintenance support centres to train personnel. It is also planned to include another 1GW floating wind power complex by attracting private investors.

Although Ulsan has taken centre stage, other regions are likely to capitalise on the floating wind opportunity. Dutch company GustoMSC have secured partnerships with Halla Wind Energy and Korean Maritime Consultants to design floating foundations for the 100MW Dongbu wind project at Jeju Island, where local government ambitions exist to meet 100% of energy needs with renewables by 2030.

Policy support

Having commissioned their first offshore wind pilot farm in 2017, South Korea are advancing plans for increased offshore wind deployment. An abundance of suitable deep-water sites means that this could include floating wind technology. Under the 8th Basic Plan for Long-term Electricity Supply and Demand, the South Korean government have set renewable energy targets of 20% by 2030, which would require an increase from 11.3GW to 58.5GW. It is understood that 30.8GW of this requirement would come from solar power generation and an estimated 16.5 GW from wind, including 12GW from offshore wind.

South Korea has a Renewable Portfolio Standards (RPS) policy for renewable energy promotion, which mandates power producers with 500MW and above of power generating capacity to provide at least 8% of their electricity from new and renewable sources as of 2020 – this target has been increased by 1% each year to reach the initial goal of 10% in 2022. Renewable Energy Certificates (RECs) are issued for renewable energy facilities and offshore wind benefits from generous weightings to enhance their value (Table 4). Although there are no specific subsidies for floating wind, they are likely to receive the higher weightings due to the distance from shore.

Table 4: South Korea REC weightings for offshore wind. Source: Korea Offshore Wind (2nd Edition), Linklaters⁵

Standard	Weight value
Interconnection distance of 5km or less	2.0
Interconnection distance of more than 5km but less than or equal to 10km	2.5
Interconnection distance of more than 10km but less than or equal to 15km	3.0
Interconnection distance of more than 15km	3.5

⁵https://lpscdn.linklaters.com/-/media/files/insights/2019/november/linklaters_korea_offshore_wind_report_2nd_edition_a_turning_point.ashx?rev=81c6742b-0e63-4504-8586-db0d4d980638&extension=pdf



Opportunities for floating wind

Seabed bathymetry and environmental conditions in Portugal are highly favourable for floating offshore wind. According to the government's Industrial Strategy for Ocean Renewable Energies (EI-ERO), total potential for floating wind is estimated at about 40GW, which far exceeds the approximately 3.5GW of bottom-fixed offshore wind potential. Grid transmission issues and the low cost of onshore renewables are near-term barriers, but the medium to long-term potential for floating wind is significant.

Projects

Portugal hosted the world's second multi-MW floating wind installation, a 2MW WindFloat semi-submersible unit installed 5km off the Coast of Aguçadoura in 2011 (WindFloat 1). Following five years of strong performance, including surviving harsh Atlantic storm conditions and registering high load factors, the unit was decommissioned in 2016. This 2MW unit has now been recommissioned and moved to Kincardine in Scotland, a novel benefit of floating platforms.

Building on the prototype demonstration, a 25MW second phase, consisting of three 8.3MW turbines, is in the final stages of commissioning and all units are due to be installed in 2020 (WindFloat Atlantic 2). See [Box 1](#) Case Study for further details of the project.

Policy support

Both the WindFloat 1 and WindFloat 2 projects will have benefitted from considerable funding from the European Commission, including through the Demowfloat and NER300 initiatives, in addition to revenue support from the Portuguese government.

Future support for commercial projects will be contingent on national government support and there is currently a lot of uncertainty about future floating projects in Portugal.



Opportunities for floating wind

The United States is a potential major market for floating offshore wind, particularly on the West Coast and in Hawaii, due to the rapid drop-off of the continental shelf. In states with high solar and hydroelectric penetration, such as California and Oregon, floating offshore wind could also play an important role in delivering consistent and high load factors to stabilise energy generation, particularly at times of peak demand, or in replacing aging coal and nuclear generation.

Bottom-fixed offshore wind technology is expected to dominate on the East Coast in the near and medium-term, but some coastal states, such as Maine, have attractive sites and are

actively pursuing commercial deployment of floating wind installations, and so could compete with the West Coast as a first-mover.

Projects

The United States installed its first offshore wind turbine in 2013, a part-scale prototype of University of Maine's VoltturnUS concrete semi-submersible concept. This is due to be followed by the first full-scale floating wind turbine, through the (up to) 12MW Aqua Ventus I project, consisting of one 9.5-10MW turbine mounted on a full scale Voltturn US concrete semi-submersible platform. The project, whose partners include the University of Maine and Cianbro, is slated for installation in late 2021 with ultimate commissioning likely in 2022. There are aspirations for large-scale commercial deployment beyond 2022, but no firm timeline or government support has been established.

The first commercial-scale projects are more likely to emerge on the West Coast. Several commercial projects are being explored for development, including: the up to 1GW project in Morro Bay (California), up to 150MW project off the Humboldt Coast (California), and three 400MW projects in Hawaii. Projects in California have however seen a number of delays due to consenting issues, namely objections from the US military (see below).

Policy support

The Aqua Ventus I demonstration project will receive up to US\$40m of grant funding from the Department of Energy, and fixed revenue support provided the Maine Public Utilities Commission (PUC) continues to support a previously approved power purchase agreement (PPA). Future commercial projects in all US states will be seeking revenue support, although alternative support mechanisms may be required if projects must secure PPAs and compete on a merchant electricity market. Support will vary by state.

The US Department of Energy recently announced US\$28 million in funding for a new Advanced Research Projects Agency energy programme – Aerodynamic Turbines Lighter and Afloat, with Nautical Technologies and Integrated Servo-control (ATLANTIS). This project will aim to develop technology for floating offshore wind turbines and “advance American offshore wind production and the accompanying job, manufacturing and investment growth for the nation” (ARPA-E, 2019).

Federal policy is most evident in the role of the Bureau of Ocean Energy Management (BOEM) in undertaking leasing for prospective sites. Having received unsolicited leasing requests for sites in California and Hawaii, BOEM is planning competitive lease auctions to assign development rights.

In October 2018, the Bureau of Ocean Energy Management (BOEM) – part of the U.S. Department of the Interior - identified three Call Areas for offshore wind energy development. The Humboldt Call Area is situated along the North Coast near Eureka. The Morrow Bay and Diablo Canyon Call Areas are located farther south, along the Central Coast. The U.S. Department of Defense (DoD) has expressed ongoing concerns about the Central Coast Call Areas due to combined military operations in the area.

After a consultation process that included federal legislators DoD, BOEM, the National Ocean and Atmospheric Administration (NOAA), the California Energy Commission (CEC), and other state and local officials, a map was released that identified several new areas for discussion believed to be compatible with DoD operations. The discussion of these areas is ongoing and

will continue through at least July 2020 due to Covid-associated delays. The results of these consultation processes will likely determine BOEM's ability to proceed with auctions for offshore wind lease areas in California later this year.

In June 2018 the Department of Energy announced the formation of the National Offshore Wind research and Development Consortium. The consortium, led by the New York State Energy Research and Development Authority in partnership with the Renewables Consulting Group and the Carbon Trust is a nationally focused, independent, not-for-profit organisation dedicated to managing industry-focused research and development of offshore wind to maximise economic benefits for the United States. A key pillar of research will be the development of floating offshore wind technology in US waters.

Japan

Opportunities for floating wind

Japan has vast potential for floating technologies due to significant depth constraints for bottom-fixed offshore wind. The best wind conditions are located around the northern prefectures of Hokkaido and Tohoku, with attractive sites also situated further south in Kyushu. Despite having taken a pioneering role in demonstrating several floating wind concepts, deployment has since slowed in response to the high initial costs of these prototypes, as well as several market and regulatory barriers, namely: a lack of clarity on energy policy post-Fukushima, onshore grid transmission constraints, and a slow and fragmented consenting regime. However, recent developments could support an acceleration of deployment, with floating wind set to play a major role in a growing offshore wind industry.

Projects

Japan has 19MW of installed floating wind capacity from a series of full-scale demonstrations at Fukushima (Eastern Coast) and Kabashima (Goto Islands of the Nagasaki prefecture). A further demonstration, supported by Japan's New Energy and Industrial Technology Development Organisation (NEDO), was installed off the Coast of Kitakyushu in 2018, using a 3MW steel edition of IDEOL's Damping Pool technology. Toda Corporation are also planning an up to 22MW array off the Coast of Sakiyama, Goto City, part-funded through the issuance of green bonds. Several additional pilot and commercial projects are also being assessed by developers, including a "multi-hundred megawatt" collaboration between IDEOL and Acacia Renewables. Environmental Impact Assessments (EIA) have previously taken up to six years, casting doubt on the feasibility of commercial-scale floating wind being commissioned in the 2020s. However, EIAs are expected to be expedited thereby reducing the average time to 2.5 years. This would mean completion of commercial-scale floating wind in Japan could be possible from the mid-2020s onwards.

Policy support

Although Japan is still lacking specific targets for offshore wind or floating wind specifically, in November 2018 Japan's National Diet passed a bill promoting offshore renewable energy, which included an announcement that certain promotional zones would be designated for offshore wind projects. Of the 11 'promising' offshore wind promotional zones announced by

the Ministry of Economy, Trade and Industry (METI) and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in 2019, all but one (the small Goto islands area) are near shore and expected to be limited to bottom-fixed projects. However, it is expected that in the coming years more promotional zones and auction rounds specifically for floating wind will be announced.

Several Japanese ministries have already invested heavily in floating wind demonstration projects, but the progression to pilot and commercial projects has been slower than expected. In March 2020 METI confirmed that from 2020-21 bottom-fixed offshore wind would move to a competitive auction system and the previous fixed feed-in tariff of 36 JPY/kWh for offshore wind now only applies to floating wind. This creates a generous floating specific revenue support; however, it is unlikely any commercial project would receive this given the long consenting process.

Other

In addition to the lead markets mentioned above, there is the potential for other coastal regions with high energy demand to become 'follower' markets as the cost of energy from floating offshore wind falls and becomes competitive with other energy technologies. Some of the most attractive follower markets for floating wind power, both in the near and long term, include:



At present, Ireland has only one offshore wind farm, the 25.3MW Arklow Bank site commissioned in 2004, which demonstrated GE's 3.6MW offshore wind turbines. The Irish Government's offshore renewable energy development plan has however, identified the potential for 27GW from floating offshore wind within Irish waters, with 2.9GW under active development. Ireland's Climate Action Plan has called for at least 3.5GW of offshore wind to be installed by 2030. Ireland's long-awaited Renewable Energy Support Scheme (RESS) commenced in March 2020 with the first of a series of regular auctions scheduled at frequent intervals. It has a minimum auction capacity of 1,000GWh and a maximum auction capacity of 3,000GWh with a maximum offer price of €120/MWh. The results of this first round of RESS are due in Q3 2020 with an offshore wind specific auction scheduled for Q2 2021. The Marine Planning and Development Bill is to be enacted in 2020 while grid connection offer(s) are to be made to offshore wind applicants by Q2 2020.

A four-year floating wind demonstration project, located at a Sustainable Energy Authority of Ireland (SEAI) test site near Belmullet, County Mayo, has secured €31 million in funding from Interreg North West Europe. The project, known as AFLWOT (Accelerating market uptake of Floating Offshore Wind Technology), will be managed by the European Marine Energy Centre (EMEC) in partnership with SEAI and other organisations across Europe. The project aims to have a full-scale floating offshore wind turbine installed by 2022 and to support supply chain development in the region. The platform of choice is expected to be the Hexafloat design, developed by oil and gas contractor Saipem. The design incorporates a counterweight suspended beneath a hexagonal tubular steel structure.

 **Norway**

Despite pioneering the world's first full-scale prototype demonstration in 2009, Norway has to date not extended its offshore wind fleet due to an abundance of cheap hydroelectric power. However, several potential commercial-scale sites are being explored in order to enable domestic suppliers to showcase the considerable industrial expertise and capabilities that exist in Norwegian firms.

The TetraSpar concept, developed by Stiesdal OT will be deployed at the Marine Energy Test Centre near Stavanger, Norway. The innovative modular concept, which could offer significant cost reduction potential for floating wind, will support a 3.6MW Siemens direct drive turbine, and should be fully commissioned in 2020.

As part of Norway's target to reduce emissions for offshore oil and gas fields, Equinor is developing the Hywind Tampen project. The 88MW floating wind project will supply energy directly to the Snorre and Gullfaks oil fields. With eleven 8MW Siemens turbines mounted on the Hywind Spar platform, of similar design to Hywind Scotland, it will be the world's largest floating wind farm. It is understood that these new platforms will be constructed out of concrete and use synthetic mooring systems, rather than steel and chain used in Hywind Scotland. The project is projected to supply 35% of the annual power demand to five Snorre A and B and Gullfaks A, B and C platforms. Offshore construction is expected to start January 2021 with commissioning towards to the end of the same year. Equinor are aiming for a 40% to 50% reduction in cost per MW between the Hywind Scotland project and Hywind Tampen, taking them towards a goal of large-scale industrialisation by 2025/2026.

Large-scale deployment in Norwegian waters is likely to be contingent on an expansion of electricity export to an integrated European market, rather than supply to domestic markets. However, Norway is expected to remain a key exporter of floating offshore technology through the Equinor Hywind programme and novel concepts such as the Steisdal TetraSpar.

 **Spain**

Having been a leading market for onshore wind generation, with over 23GW installed, regulatory changes have stalled the Spanish wind power sector in recent years, including growth of offshore wind. Offshore wind power in Spain has so far been limited to a handful of demonstration projects in Gran Canaria, largely benefitting from European funding.

Among the projects under development is an up to 25MW pilot project led by ACS Cobra, FLOCAN 5, which would consist of three to five concrete semi-sub/spar hybrid devices supporting 5-8MW turbines. However, considerable delays and limited development activity has created uncertainty that the project will be realised, especially given that projects applying for NER 300 funding are required to enter operation by the 30 June 2020.

A 1:6 scale prototype of the two turbine W2Power concept was installed at the PLOCAN demonstration site (also located off Gran Canaria) in June 2019 and decommissioned in October of the same year.

On the Spanish mainland, several technology developers are pursuing potential demonstration opportunities at the Biscay Marine Energy Park (BIMEP) test site, which has up to 20MW of capacity available. Limited funding at national level means that projects may be reliant on support from the European Commission. Although water depths in Spain are well suited to floating wind, commercial-scale deployment is unlikely to progress without a radical change in government policy. However, long-term potential exists if floating offshore wind can reach maturity to compete with other energy technologies.

Taiwan

Due to its specific geological and environmental conditions, Taiwan has considerable wind resource in deep waters relatively close to shore that are suitable for floating wind technology. Shallow sites for bottom-fixed offshore wind are also plentiful, but complex seabed conditions could favour anchor technologies with lower penetration requirements than fixed monopole and jacket foundations. Long-term offshore wind ambitions are likely to require floating wind technology, however the focus to date has mostly been on bottom fixed projects.

EOLFI Greater China and ACS Cobra have partnered to pursue the development of commercial floating offshore wind projects in the Taiwan Strait (up to four projects of around 500MW capacity). However, based on recent developments, their ambitions have been set back by a failure to gain permitting approval due to navigation concerns in the proposed locations. Future allocations will follow a competitive auction system, with price as the defining criteria. Floating wind projects are likely to require additional support in the near-term before being able to compete in competitive auctions.

Aegean Sea (Turkey and Greece)

Despite no previous activity in offshore wind, Turkey recently announced ambitious plans to build the world's largest offshore wind farm in the Aegean Sea. While a limited number of shallow sites exist for fixed foundations, the majority of the up to 32GW of offshore wind potential lies in deeper waters better suited to floating technology. This potential also extends into Greece, where Seawind and Olav Olsen have been earmarked for pilot demonstration projects under the Clean Energy for EU Islands Initiative. Discussions between the governments of Norway and Greece indicate that Norwegian developer Equinor has an interest in developing floating offshore wind within the Aegean Sea, but at present, no formal proposals have been announced.

China

China is set to become the largest offshore wind market within the next few years, using conventional bottom-fixed foundations due to an abundance of shallow water conditions. It is expected that China will focus predominantly on bottom-fixed offshore wind for their initial projects, however once this shifts to floating wind they will likely become market leaders as they have in the bottom-fixed offshore wind sector.

Floating wind has attracted some interest to date, particularly in Guangdong, where state utility China Guangdong Nuclear Power Group (CGN) are looking to develop up to 3GW of floating wind power. CGN have also invested in Eolfi's 24MW pilot farm in Groix, France.

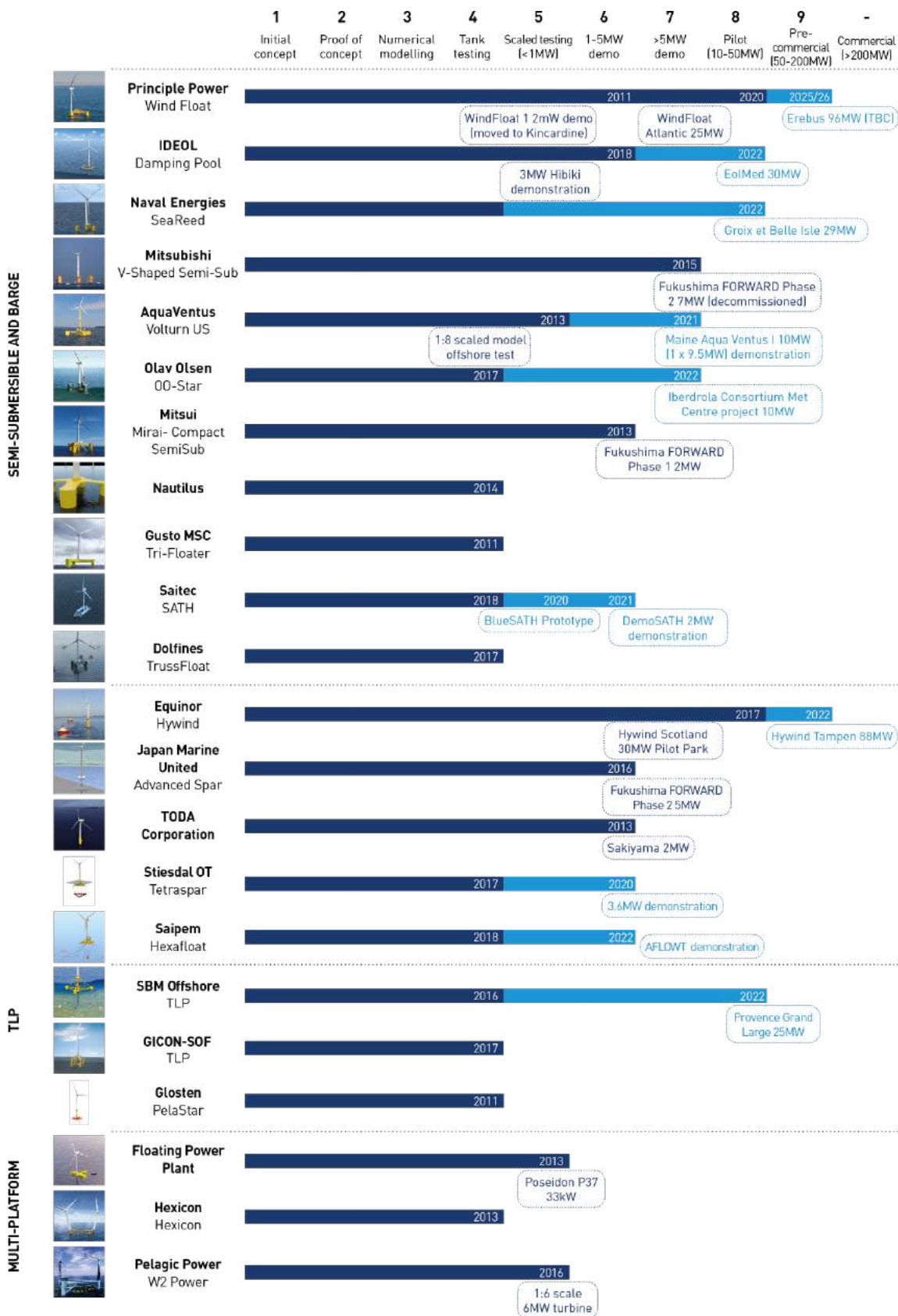
China also plan to develop a five turbine pre-commercial array using domestic technology. The development, known as the Shanghai Deep and Far Sea Offshore Wind Major Demonstration, was initially slated for completion in 2020, but as yet no further information has been provided. There is little visibility of the pipeline of projects and the policy to support the projects, it is likely this will become clearer from the mid-2020s.

1.3 Technology status

There are approximately 40 different floating wind concepts at various stages of development, broadly categorised by four dominant foundation types (see Appendix 1 for definitions). Figure 7 includes a list of concepts we consider to be the most active and advanced. We have only focused on the floaters that will support conventional horizontal axis turbines, as provided by the major offshore wind turbine suppliers. While a large number have successfully completed tank testing, the progression to full-scale demonstration has proved more elusive, largely due to the step change in investment required. Nevertheless, there is a healthy pipeline of pilot projects up to 2020/21 for several leading concepts, which will de-risk these technologies for application in fully commercial projects.

While there remains scope for other technologies to bridge this gap, the industry will naturally see some consolidation to a handful of leading designs suitable for different markets and site conditions. These leading concepts are expected to emerge from European and US companies, given the apparent slowdown in the development of Japanese concepts. Market consolidation will also manifest in commercial and industrial partnerships, as evident in the recent industry collaborations outlined in Box 2.

Figure 7: Floating wind technology readiness level (TRL) status



N.B. Future technology development has only been included for concepts with firm projects with a high probability of realisation (i.e. sites identified/permited, government contracts secured). It is noted that several concepts listed are aiming for demonstration, pilot, and commercial projects within the next 5-year period. For simplicity, barge concepts have been grouped with semi-submersible designs.

Box 2: Industry partnerships

Total and Simply Blue

Total has formed a partnership with Simply Blue Energy to develop the floating wind project Erebus located in the Celtic Sea, Wales. The project will have a capacity of 96MW and will be installed in an area with water depth of 70 metres.

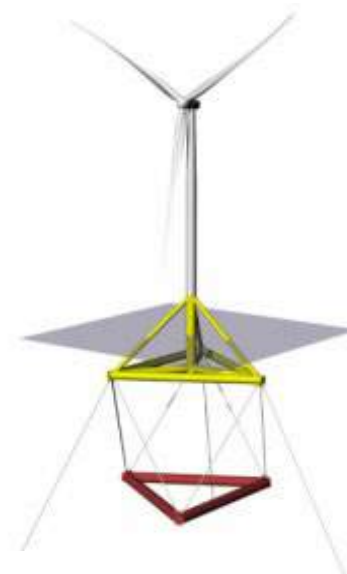
Shell and Eolfi

Shell acquired Eolfi in late 2019, enabling them to increase their floating wind capability and expertise. Eolfi has been a pure-play floating developer and are currently developing a pilot floating wind project in France, Groix et Belle Isle. Eolfi also have a significant floating pipeline in Taiwan. This move brings Shell's experience and track record in the offshore sector together with Eolfi's floating wind development expertise. It also enables Shell to move into the French market, where Eolfi are at the forefront of floating wind development.

SOT, RWE Renewables and Shell

RWE Renewables, Shell and Stiesdal Offshore Technologies (SOT) have formed a partnership to build the TetraSpar floating wind demonstrator. The demonstration project will be tested off the Norwegian Coast in 2020. The project received final investment decision in February 2019 and has a budget of €18 million.

The TetraSpar has a modular layout that consists of a tubular steel main structure with a suspended keel. It is expected to offer important competitive advantages over existing floating wind concepts, with the potential for leaner manufacturing, assembly and installation processes with lower material costs.



Source: TetraSpar

RWE Renewables and Saitec

RWE Renewables has partnered with Saitec Offshore Technologies to set up a joint pilot project, DemoSATH, aimed at testing new ways to affordably install and operate offshore wind farms in deep waters.

As part of the collaboration, a 2MW floating platform will be tested off the Basque Coast in 2021 with a project duration of 3.5 years. SATH technology is based on a twin hull made of a modularly prefabricated and subsequently braced concrete element.

Source: Saitec Offshore Technologies



2. Key findings: Turbine requirements and foundation scaling

2.1 Study overview

Turbine size is increasing rapidly, with 13-15MW turbines expected to be available by 2025, the same period by which the first commercial-scale floating wind farms are expected to be installed. The scaling of floating substructures will be a significant driver of procurement costs, as well as logistics for fabrication and installation.

This study, delivered by Ramboll, was commissioned to assess the specific design requirements of wind turbines for floating wind compared to turbines for bottom-fixed offshore wind. In addition, the impact of turbine size on the floating foundation design and particularly weight was investigated.

An initial estimate of scaling factors showed that the scaling of turbines on floating platforms may be less sensitive than fixed foundations, allowing for larger turbines – a potential advantage for floating wind. It is also considered that modifications will be required to conventional offshore wind turbine designs to ensure suitability for application on floating structures.

This project was delivered through two interrelated studies:

1. **Turbine requirements:** Review of wind turbine design requirements and modifications for optimal performance during operation, including limitations for allowable inclination and acceleration.
2. **Foundation scaling:** Analysis of the impact of larger turbines on substructure and mooring system design. The study considered 6MW, 10MW and 15MW turbines as a baseline to evaluate the potential cost savings from adopting larger next generation turbines.

By gaining a deeper understanding of the relationship between turbine performance and optimum foundation size, the study has helped to increase confidence in less conservative design requirements and identify opportunities for lower cost integrated designs.

2.2 Key findings

Turbine requirements

01

Existing turbines can be installed and operated on floaters without requiring major modifications (modification required to the tower and controller)

The study concluded that existing offshore wind turbines can be installed and operated on currently available floating substructures without requiring major modifications to the main turbine components.

This finding is reflected in the fact that currently all demonstrator and pre-commercial floating wind projects utilise wind turbines originally developed for bottom-fixed offshore application, often designed according to IEC class 1B. However, as floating wind turbines exhibit motions in six degrees of freedom and also have different structural dynamic characteristics due to the flexibility/compliance of the floating substructure at the tower bottom, wind turbine requirements are affected.

The study found that the primary wind turbine components affected by being installed on a floater are the tower and control system. These two components will have to be modified for most floating wind projects. The tower for floating wind substructures needs to be redesigned due to loads increasing from floater motions and the global 1st tower bending eigenfrequencies increasing into the 3P region due to free-free boundary conditions. For the controller, application of conventional pitch and torque control leads to negative damping on a floating substructure, requiring modifications of the controller along with modifications to reduce loads and optimise power production. The only possible exceptions not requiring tower and controller modifications are certain TLP designs, which constrain motions in all directions except for heave motion.

Components which may require modification depending on the motion characteristics and resulting loads are any systems containing liquids and free fluid surfaces (air-conditioning systems, etc.) affected by inclinations (mean and dynamic) such as oil reservoirs for lubrication, oil level sensors, pumps, as well as components affected by changed control systems, such as blade pitch drives and yaw drives.

Most other mechanical and structural components need to be re-assessed for floating wind applications on a project-by-project basis to ensure the loads remain within their load envelopes and specifications. However, to date in demonstrator and pre-commercial projects applying turbines from the major offshore wind turbine manufacturers these listed components did not have to be modified: blade bearings, main bearings, yaw bearing, mainframe, hub, blades, and gearbox.

In the study it was found that the electrical equipment in the wind turbine to date has not been affected, however this is an area that has not been assessed in detail.

This study and the component modifications, and experience with current floater projects strongly indicate that there are no obstacles for commercial floating wind projects with respect to using conventional offshore wind turbines on floaters.

Key stakeholders and internal experts were consulted to evaluate the impact on various turbine components being installed on a floater. A qualitative ranking was made based on project experience and represents stakeholder inputs received, as well as Ramboll internal evaluations. No quantitative analyses were performed.

The study concluded that the acceleration itself is not a governing parameter and requirement, but that the resulting loads to which the accelerations contribute are. In the table however, for simplicity accelerations and loads are assessed as one parameter. The table is generic and does not consider different floater concepts, WTG types and specific project conditions, which will affect the results.

The stakeholders were also consulted to qualitatively evaluate the sensitivity of turbine components regarding floating-specific effects. Table 5 provides indicative insight into the sensitivity of the different components to floating-specific effects. Note that the scoring is influenced by the actual substructure characteristics (primarily its motion characteristics, but also the applied control strategy, site conditions and other factors).

In more generic terms, the more load increases the Rotor and Nacelle Assembly (RNA) components experience (which is mainly a combination of accelerations, inclinations, frequency characteristics, controller and site conditions), the more technically challenging and expensive the re-assessments and potential required modifications become. This is particularly true once the loads increase beyond load envelopes of specific components; if loads remain within load envelopes, even if increased compared to the bottom-fixed system, the impact is limited.

A notable result is the low ranking of the gearbox and main shaft. There is a lot of academic literature on the topic of floater motion effects on drivetrains. However, from the discussions with companies working in this field, as well as the wind turbine manufacturers, this seems to be much less of a concern (except for bearings) than in practise.

This subjective and indicative ranking does not directly allow for conclusions if particular components actually need to be modified. Rather, it provides information on what components are potentially most affected by the floater and which should therefore be reassessed and considered in the floater project design phase. Furthermore, it should be noted that long-term experience with floating wind turbines and RNA components is still missing; the longest operational floating turbine has been operating since 2009. Thus, it is important to state that the assessment and ranking presented is still preliminary and may need to be updated as new information becomes available over time.

Table 5: Ranking of WTG components regarding their sensitivity to floating-specific effects

WTG component		Required floating-specific modifications
1	Tower	Significant fatigue and ultimate load increase due to loading Resonance problems with 3P and possible stiff-stiff configuration
2	Controller software	Major modification required for avoiding negative damping, improving motion characteristics and loads, and power production
3	Hydraulics/ sealings	Generator Accounting for inclinations, e.g. by pressurizing
4	Blades/ bearings	Increased bending moment and low frequency loading Tower clearance needs consideration (also w.r.t. tower modifications) Generally no modifications expected
5	Pitch system	Possibly more load cycles with increased means (depends on controller) Pitch drive upgrade may be required
6	Main bearings	Increased loading, reassessment; no modifications expected
7	Yaw system	Increased loading, reassessment; no modifications expected
8	Hub	Increased loading, reassessment; no modifications expected
9	Controller hardware	New software implementation; changes in channels/ capacity
10	Coolers	Minor changes possible due to inclinations
11	Main frame	Different loading; no modifications expected
12	Monitoring	Add modification in floater; integration into SCADA; oil level monitoring expected
13	Gearbox	Increased inclination and changed loading requires re-assessment; no modifications expected
14	Main shaft	Increased loading, reassessment; no modification expected
15	Converter	Not affected
16	Generator	Electrical parts not affected, only mechanical (bearing, mounts) reassessment

Based on both literature and stakeholder statements, strict design limits on accelerations and inclinations are inadequate for assessing turbines for floating substructures. No solid basis or justification for setting specific limits on accelerations and (to most extent) inclinations exists, as components are driven by loads, which can only be accurately determined by performing coupled design load analyses.

In summary, turbine acceleration and inclination limits may be useful in early floating wind concept phases as an indicator for the expected load level increase, but may be misleading; for example, stiffer bottom-fixed structures may actually exhibit similar peak acceleration values, though at much different frequencies. Ultimately, coupled load analyses must be performed in order to accurately assess if component loads are within their respective design envelopes.

From the understanding of the assessment methodologies of wind turbine requirements for floaters it was concluded that there is generally no increased conservatism in the requirements.

In the early concept phase, initially applied quantitative motion limits may be conservative but they are typically not enforced by standards, contractually or with other hard limits. Instead, they serve as an initial starting point for designers. Every project at some stage initiates a loads analysis process according to standards, where the design load envelopes of components are checked against the calculated design loads. In these analyses, only the safety factors according to the standards are used and no further conservatism is added compared to bottom-fixed turbines, except for some additional design load cases which focuses mostly on the mooring system, not the turbine.

The longest operating floating wind turbine is the Hywind Demo project, a 2.3MW turbine installed in 2009, which has now been operating for 11 years. The only currently operational pilot farm, Hywind Scotland, has been operating since 2017. It will soon be joined by WindFloat Atlantic in Portugal when fully commissioned.

Given this limited operational experience and the still existing uncertainties in modelling of loads for floaters (particularly on the detailed component and stress level, and regarding fatigue), weather conditions, and other unknowns, there is a reasonable likelihood that there will be unexpected issues and failures over the coming years. It is likely that these will be particularly related to the fatigue influence of floater-specific load characteristics on various wind turbine components, and ultimate limit conditions resulting from extreme events (severe storms) close to the currently applied 50-year recurrence periods.

The long-term assessments from this study are currently based on numerical modelling and numerical predictions only – little practical experience and measurements are available yet to verify long-term effects. However, the industry's knowledge and experience will grow as the number and age of the current and next generation demonstration and pilot projects increases.

Foundation scaling

05

Across all concepts the required primary steel, secondary steel and mooring mass per MW decreases significantly for larger turbines

An analysis was undertaken of the impact of turbine size on floating foundations design and scaling for large future floating offshore wind farms. This study aimed to assess scaling trends for the different elements of floating substructures such as primary and secondary steel mass, and mooring and anchor mass. Stakeholder interviews and information shared and obtained during these discussions also fed into the study.

The approach taken was to use a conceptual design basis aligned with current state-of-the-art industry practice, trends in the floating wind market, and site conditions representative of likely future commercial floating offshore wind farms. The following parameters for the study were established:

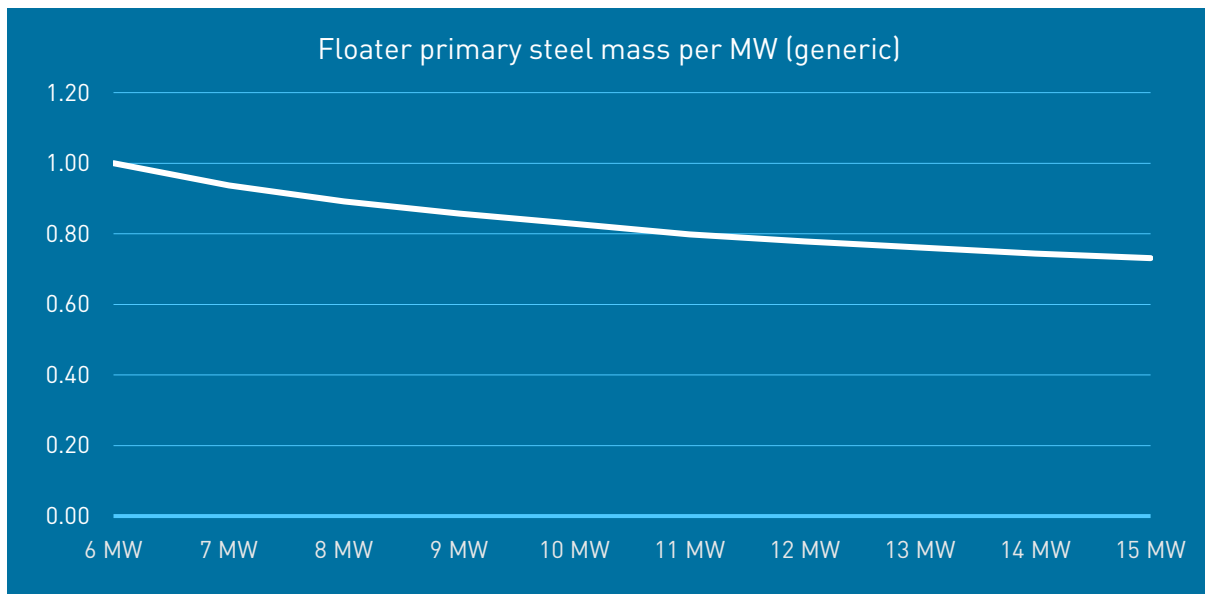
- Turbine sizes: 6MW, 10MW and 15MW (generic)
- Four generic substructure types covering all generic stability classes: semi-submersible, spar, barge and TLP (See Appendix 1 for further information on floating wind typologies)
- A generic site located in the Scottish North Sea was selected; this is representative of a location which is economically attractive for floating wind development and features good average wind conditions combined with a medium to harsh wind and wave climate

This study did not aim to assess whether one concept may be more favourable than another for a specific offshore floating wind farm project. This must be determined on a project-by-project basis with consideration of the overall wind farm cost and relevant constraints.

The trends presented below are only valid for the above outlined generic assumptions and within the limitations of the study, thus do not necessarily represent commercial floater designs and trends may differ.

A general trend could be identified that across all concepts, the required primary, secondary and mooring mass per MW decreases for larger turbines; this scaling trend is also seen in bottom-fixed offshore wind. Figure 8 shows the decreasing average normalised trend for primary steel mass per MW. This implies that when doubling the WTG rating from 6MW to 12MW (i.e. an increase of power by 100%), the primary steel mass of floating substructures on average only increases by 55%.

Figure 8: Normalised trend for primary steel mass per MW



Each concept is characterised by such a decreasing trend with increasing turbine size. This clearly indicates that for floating substructures, larger WTGs are very favourable regarding mass and thus procurement cost per MW of the substructure.

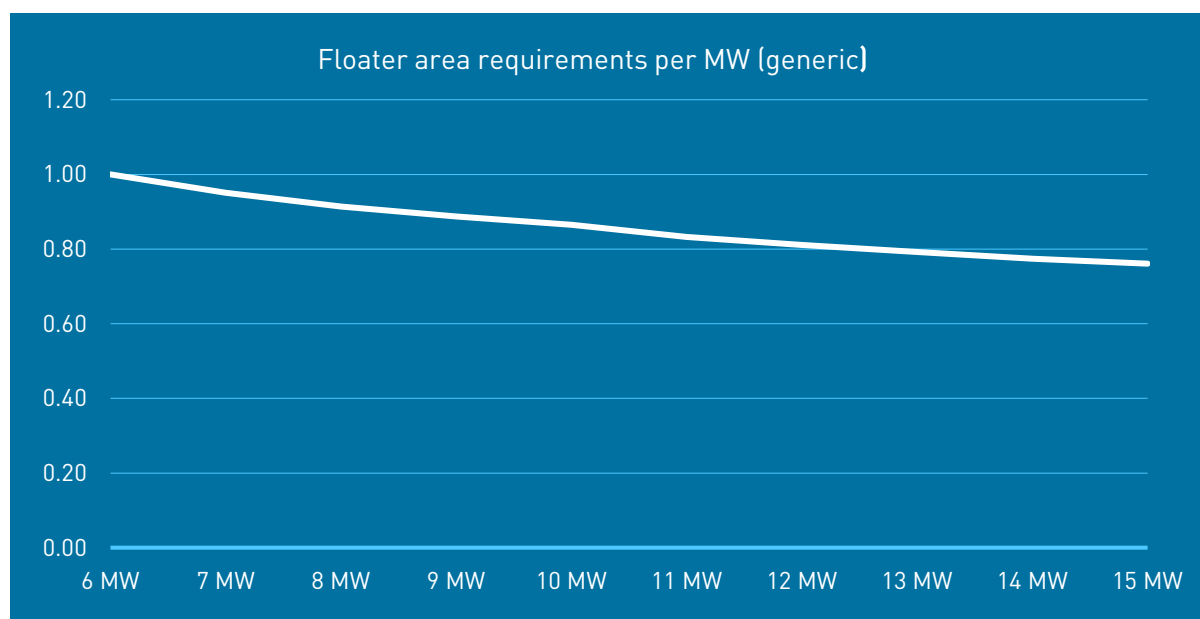
Laydown area requirements

The manufacturing, storage and handling of floating substructures requires a significant amount of yard area, particularly important for commercial-scale projects where a large number of structures will need to be manufactured. This study evaluated the required yard area for the different substructure and assessed the scaling trends regarding main dimensions.

Figure 9 shows the decreasing normalised trend for the average area requirements per MW. This implies that a doubling of turbine rating, from 6MW to 12MW, results in an area requirement increase of only 62% on average.

However, it must be stated that the area increase for many concept types can be influenced by the designer, as there are usually multiple parameters which can be adjusted to accommodate larger WTG ratings, such as column diameters, draft or waterplane area. Furthermore, for port logistics not only the area but also the shape of the footprint is relevant. For example, there is a considerable difference between a spar (high aspect ratio rectangular footprint, when transported horizontally) and barge type floater (square footprint).

Figure 9: Floater area requirements per MW (generic)



The bearing capacity (i.e. allowed mass per area) is another factor that might limit the applicability of a yard. As shown in Figure 9, the decreasing mass and area scaling trends demonstrates that the required bearing capacity remains relatively constant across different ratings. The strengthened quayside designed to the requirements of today's floaters are therefore likely to be suited for future larger units, if the infrastructure can accommodate the larger dimensions. For very large turbines, the limiting factor regarding maximum bearing capacity may well be the weight of the wind turbine nacelle, not the floater.

It can be concluded that the substructures, independent of concept type, scale very favourably with increasing wind turbine rating. This applies for the geometrical dimensions (which is relevant for manufacturing and transport) and the primary and total system steel mass (mostly relevant regarding cost and logistics in port).

Mooring systems

Generic mooring systems were conceptually designed for different turbine ratings accounting for both operational and survival conditions for the floating concept designs. To investigate the scaling trends, basic steel chain catenary mooring systems with drag anchors for the barge, the spar and the semi-submersible substructure were conceptually designed. Spiral strand steel wire ropes were selected for the tendons for the TLP substructure.

The required mass of the mooring systems depends on several parameters:

- Environmental and site conditions
- Floater Motion behaviour
- Drift and drag forces on the floater
- Wind turbine thrust

- Fairlead/tendon position
- Accessories
- Material selection

Most of above parameters are influenced favourably by the previously described positive scaling trends for the substructure. The scaling study results for the mooring system show a decreasing trend for overall mooring chain/tendon and anchor mass per MW, as well as a decrease in anchor radius per MW.

2.3 Innovation/ technology needs

Turbine requirements

01

An improved interface between turbine suppliers and floater designers, in order to have a more integrated design

A floating wind turbine is a highly coupled integrated system, making isolated design and optimisation very challenging. From a substructure designer view, early availability of information about the wind turbine is crucial for optimising the design and reducing project timelines. This explains the interest in acceleration and inclination limits as a most simple interface in early stages but also other simplified interfaces exist (e.g. RAOs).

A further challenge is related to the tower and controller design, which is typically in the scope of the turbine supplier, but influences the substructure design considerably, and vice versa. The substructure designer is not directly involved in the analysis of RNA components and the interface is typically the provision of updated floater and mooring system designs, based on input and requests by the turbine supplier. One option to better integrate the two is for substructure designers to use representative generic wind turbine models at the early stages. Once the project is more advanced, turbine suppliers are more willing to share data and collaborate in load and design iterations. It is noted also that controller modifications can only be done in close cooperation between floater designers and turbine suppliers.

Time constraints in projects are a challenge, because for any reasonable evaluation with coupled simulations sufficient time is required. Therefore, in early phases, inclination and acceleration limits are communicated, or a set of minimum information from the substructure designer is requested according to developed procedures and templates enabling preliminary assessments. If a component must be modified or not is in the final decision solely based on a detailed load analysis of all relevant Design Load Cases (DLCs) – without such analysis no final go/no-go decision will be taken by a turbine supplier.

Given the greater interaction between turbine and floater dynamics, in principle prohibiting a decoupled design approach, the interface between turbine supplier and floater designer is critical to the success of projects, particularly in early phases. Efficient methods to interact are needed at different project stages to arrive at a similar level of maturity as bottom-fixed projects, where they have already achieved a streamlined load iteration process with substructure designers. A key challenge to overcome in this respect is to enable interaction and thus optimisation of the design in a holistic manner, but at the same time protecting critical intellectual property of both parties. For more detailed analyses and simulations, models and load cases run by turbine suppliers and floater designer need to be aligned such

that no critical conditions are neglected by either party and the models are validated against each other.

In later project phases, another important aspect is improved interaction regarding design optimisation. Due to the considerably more coupled behaviour of floating wind turbine systems compared to bottom-fixed wind turbines, design optimisation in floating wind should follow a more holistic approach. For example, optimising the tower and controller with respect to the floater and mooring design. Additionally, there is also a need for more efficient processes in order to achieve the overall lowest possible project cost.

02

Floating wind specific turbine designs may in the long term further reduce overall cost

The market-leading offshore wind turbine suppliers do not expect to offer a floating wind specific turbine in the near future and the already developed and upcoming generation of turbines will need to be utilised in floating wind. This implies that no major components will likely be designed specifically for floaters in the near term and that there is a clear need to utilise the existing turbine hardware. The changes expected to these conventional turbines are limited to items such as controller adaptation, de-rating in certain conditions, other software updates, or application of existing tower dampers or other mitigation measures to reduce loads. In the current market, there are only a few large turbine suppliers who have the capacity to develop the future large turbines, as their development requires very significant investment.

However, once the floating wind market becomes sufficiently large, floating-specific designs may increasingly be developed by these leading turbine suppliers. A holistic optimisation approach allowing major turbine hardware modifications may become attractive in the future, if the cost advantage of the facilitated savings in the substructure would be large enough to justify the hardware changes in the turbine. Regarding this aspect, there is still a lack of knowledge and research. From basic considerations a turbine optimised for floating applications may include:

- Reduction of RNA mass
- Further controller and blade pitch system optimisation to reduce loads and increase power
- Advanced tower designs to reduce mass and address resonance issues
- Specific rotor design in combination with advanced control to address the mean and dynamic inclination and reduce the negative impact on power generation. Furthermore, it may be analysed if the additional energy introduced to the system by the waves may be utilised to increase power production and reduce motions.
- Targeted re-design of specific RNA components to allow higher loads introduced by floater motions, thus relaxing constraints on motions, accelerations and inclinations to enable lighter substructure designs allowing for more motion

3. Key findings: Heavy lift offshore operations

3.1 Study overview

The Floating Wind JIP's Phase I Infrastructure and logistics study identified that, for several floating wind concepts, port-side operations are unlikely to be feasible due to draft and/or towing constraints. Even for concepts advocating port-side maintenance operations, there are challenges regarding the economic and technical viability of such an approach. In a large-scale floating wind farm, it is possible that undertaking more operations in-situ at the offshore site could be advantageous, and in some cases will be essential.

At present, the limited availability and high cost of suitable floating heavy lift vessels is a barrier to cost-effectively undertaking operations offshore. However, the development of next generation floating heavy lift vessels, which are expected to become a readily available option for the bottom-fixed offshore wind industry, could improve the business case for undertaking turbine installation and major repairs offshore.

Nevertheless, operations for floating wind turbines will bring additional challenges due to the complexity of floating-to-floating lifts, which could limit the opportunities to undertake heavy lift operations. For example, increased met-ocean limitations could impose heightened constraints, particularly for heavy lifts of major components. The availability of suitable auxiliary components, such as guiding systems, is also a potential challenge which may require further technology development.

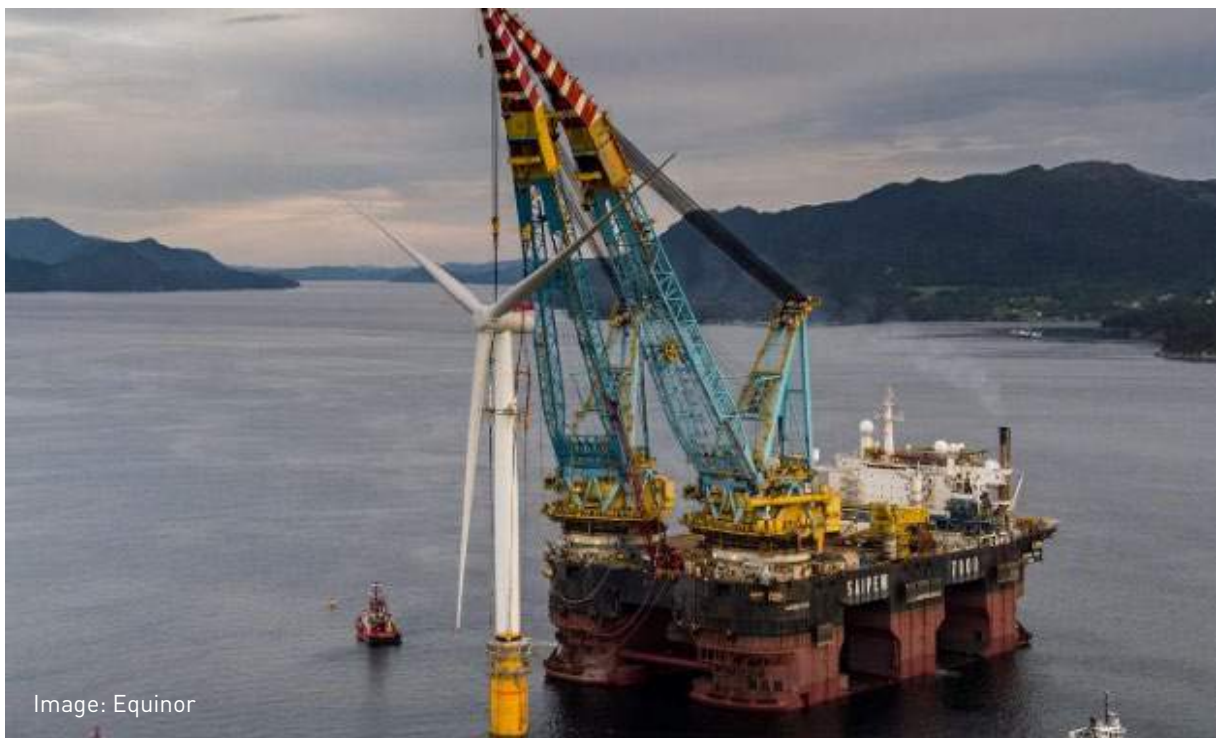


Image: Equinor

Study overview

This study investigated the technical feasibility and challenges associated with heavy lift offshore operations in a floating wind farm, during both installation and heavy maintenance. This included:

- A review of state of the art and innovative heavy lift methods and technologies
- Development of detailed method statements for several heavy lift operations
- Identification of key technology development needs

This study assessed the same baseline 6MW, 10MW, and 15MW turbine ratings analysed in the 'Turbine requirements and foundation scaling study', but also extended its investigation to 20MW turbines to future proof the study in light of the long lead-times and high investment costs required for such technologies. The study was supported by a peer review panel consisting of several of the leading heavy lift contractors.

3.2 Key findings

Future turbine sizes

A key consideration for heavy lift vessels in offshore wind is the size of turbines to be installed – this affects the lift height, capacity and reach required to lift either individual components or the whole turbine.

In this study, the main weights and dimensions of 6, 10, 15 and 20MW turbines were developed and used to assess the capability of heavy lift vessels for these turbine sizes. 20MW turbines were included because a new investment in a heavy lift vessel needs to consider these larger future turbines. The 20MW turbine is anticipated to have a rotor diameter of 252m and a hub height of between 162 and 190m. A single integrated lift of the 20MW turbine would have an estimated weight of just under 3,500 tonnes.

The weight of wind turbine towers for floating wind is expected to be heavier than for the same turbine on a fixed offshore turbine, in order to sustain an extra bending moment in a roll and pitch environment. There is uncertainty about how much turbine towers will increase in weight when comparing a floating application to a fixed one. For this study it has been assumed that there is 25% growth.

There is no clarity in the industry about the design philosophy for turbine hub heights, which determines the distance between the sea surface and rotor. The hub height is very important when it comes to determining required hook height and vessel selection for lifting. There are some trends in the industry to have the hub height at a higher elevation than the minimum; for example, in the UK concern over conflicts with low flying migrating birds on some projects is resulting in increasing hub heights.

Heavy lift vessels and other technologies

01

Limited options and experience for offshore floating wind turbine installation

There is some good experience from around the world on the use of floating vessels for installing wind turbines. However, much of this experience is in relatively sheltered locations in China and Japan. It is difficult to obtain detailed information about these projects and the vessels used. There is however good experience, shared in the public domain, from the lessons learned from the Hywind Scotland project. In total the process of installing the 5 turbines on the spar foundations took just over ten days and the final turbine installation took just 3 hours.

The current fleet of heavy lift vessels was broken down in to Semi-Submersible Crane Vessels (SSCV), Heavy Lift crane Vessels (HLV) and Sheerlegs. It was found that none of the current fleet has the capacity to install 15-20MW turbines in single lift due primarily to height constraints. In order to install a turbine in a single lift a vessel with two cranes is required.

When looking in detail at the lift capacity and hook height range of the existing fleet of SSCV, HLV and Sheerleg crane vessels it can be seen that there are very limited options for lifting anything larger than a fully assembled 6MW turbine with a single boom. Anything larger will require two booms, complex installation aids or a new design of vessel. The existing fleet of vessels is focused on heavy lifting at radius than at extreme height, particularly vessels coming from the oil and gas industry.

Box 3: Case study – Saipem 7000

The Saipem 7000 is a self-propelled dynamically positioned semi-submersible unit. The Saipem 7000 was used to install the five 6MW turbines for Equinor's Hywind Scotland project.

Length overall: 197.95m
Upper platform: 175m x 87m x 8.5m
Depth to main deck: 43.5m
Free deck area: 9,000m²
Deck load: 15,000t
Operating draft: 27.5m
Survival draft: 18.5m
Transit draft: 10.5m
Transit speed: 9.5 knots



Image: Equinor

Historically, the most successful and profitable heavy lift vessels have tended to be the largest because it is easier for them to lower their price than for a competitor to increase lifting capacity. Another factor for profitability is being the most flexible vessel in terms how they can be used in different markets. Therefore, much of the new build heavy lift designs are focused on serving oil and gas construction, decommissioning and offshore wind rather than just one market.

For new designs of vessels and vessels under construction, there tends to be a high degree of secrecy around how market critical information like crane curves is disseminated, in order to give a commercial advantage. This information can change at almost any time up to vessel delivery and is not readily available in the public domain.

Box 4: Case study – Offshore Wind Logistics OWL 1

Offshore Wind Logistics have configured a Naval Dynamics DeltaCat proprietary design for WTG installation, operation and maintenance, the OWL1 Semi Sub Crane Ship.

The Huisman crane has a hook height of 145m above sea level working at operating draft:

- Lift capacity 240t, 3D motion compensated to 5cm accuracy
- 600t crane capacity non-motion compensated with fly-jib rigged
- 800t crane capacity non-motion compensated with fly-jib de-rigged



Source: Offshore Wind Logistics B.V.

It is forecast that there will be demand for two to three additional high-end jack-ups and perhaps one additional vessel to service the floating wind sector. 12GW in 10 years with 12MW turbines = 100 turbines per year, less than 300 days per year. Only one vessel could install all the floating wind turbines globally up to 2030. It is noted that growth rate is likely to be non-linear, but this highlights that the business case needs to be clear for a new vessel, and ideally it would be able to work in both fixed and floating sectors.

02

Limited vessel availability for large turbine lifts, in particular lift height will be at a premium for future offshore wind construction vessels

Lift height will be at a premium for future offshore wind construction vessels as WTG sizes increase. The balance between lift height and capacity will probably be adjusted in favour of lift height as future designs appear. Future 15MW+ turbines will cause some real challenges for load-out and installation on fixed and floating offshore wind projects.

03

Motion compensation systems are being developed, however not focused on the specific requirements for floating wind

Motion compensation systems aim to control and/or remove the motions of a vessel at sea. Several technologies are being developed to compensate motions during lifts, however they are predominately not focused on the specific requirements for floating wind (floating to floating operations) and more focused on the oil and gas and bottom-fixed offshore wind markets.

There are three main areas under development that provide relevant 3D motion compensation technologies:

- Walk to work systems on dynamically positioned vessels
- Crane tip motion compensation
- Crane base motion compensation

There are also a number of discrete technologies that solve part of the motion compensation problem, like passive heave compensation, active heave compensation and anti-pendulation systems. All the main crane developers have some ongoing developments related to active or passive heave compensation systems. This technology is usually associated with lowering through the water column and on to the seabed and is used to reduce dynamic loads. Much of this is focused on the speed of hook movement.

In recent years, there has been interest in the development of full 3D motion compensation. This has been fuelled by the demand for walk to work systems in offshore oil and gas and renewables projects. These systems allow people to walk safely from a dynamically positioned floating vessel to a fixed or floating structure whilst taking out the relative motions of the floating vessel. There are technologies being brought forward using active heave compensation in heavy lift (around 800t) and passive systems to minimise the energy required.

04

Alternative lifting solutions, such as climbing crane technologies look to be promising solutions for maintenance of main components

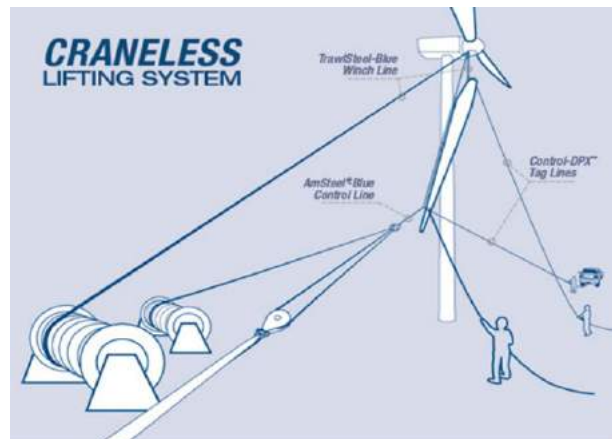
Offshore wind turbines are reaching physical limits as they become higher than conventional crane vessels may reach. This also affects the efficiency of wind turbine maintenance activities. Climbing cranes can enable wind turbine manufacturers to further increase the capacity of their turbines with greater height and scale. In addition to physical limitation of vessel cranes, the offshore operation can be significantly more cost effective using a climbing crane rather than mobilising a heavy lift vessel.

Currently, there are only onshore wind farms utilising climbing cranes for the installation and replacement of major turbine components. In principle, climbing cranes use the turbine's tower as a point of support, allowing them to lift and lower components to greater heights than possibly a conventional crane can achieve. However, limitation to the climbing crane capacity is imposed by the tower design. It is foreseen that local modifications to the support points on the tower can ensure ultimate capacity of the climbing crane for installation and replacement of major components. Several companies have developed climbing crane solutions for the change out of turbine components. These are mostly targeted at onshore turbines up to 2.5MW but the technology looks scalable to larger turbines.

Another challenging operation is changing blades offshore, this may be required for a number of reasons. For example, it may be a one off as a consequence of a lightning strike or longer campaign to replace blades suffering from leading edge erosion. Mobilising a crane vessel to change out a single blade would be an extremely expensive operation for offshore wind, especially on future larger floating wind turbines. There are several companies developing blade change technologies. Some of these are very simple rigging solutions. Others have developed a range of tools to undertake this operation. Most of these systems are designed for blades up to 20 tonnes and will need to be upgraded for future turbines.

Box 5: Case study – Dutch Heavy Lift Consultants

One of the first applications of craneless blade technology was in the US where large campaigns of wind turbine blade change out required finding a lower cost method of doing this. A method was developed by DHLHC that has been widely adopted by contractors, particularly in the US, and in other countries such as India, where it is expensive to mobilise a crane to undertake a blade change out.



Source: Sampson Rope

Summary of installation scenarios for heavy lift operations

Below is an overview of the feasibility of two installation scenarios that were assessed to understand the heavy lift operations. It was decided to concentrate on 15MW turbines with a semi-sub platform, the scenarios considered are an integrated installation using a SSCV and a stick build using a HLV.

Integrated installation using a Semi-Submersible Crane Vessel (SSCV):

- Installation of a fully assembled 15MW turbine onto the floater. The installation was considered feasible. A number of scenarios for the transportation of the turbines needed to be considered as the SSCV is too large to approach the quayside at many marshalling facilities. Therefore, the turbines with tower would need to be loaded out on to another vessel and transported to the SSCV. It was assumed that transportation would be done by a suitable barge with the turbine lifted off the barge at the final installation site. The erection of the turbines on the quayside is an expensive operation as plenty of space and a very large crane is required to lift out a fully assembled 15MW turbine.

Stick build using a Heavy Lift Vessel (HLV):

- Similar approach to that used by jack-ups onto monopiles in shallow water, which is typically the offshore assembly of three tower pieces, nacelle/hub and three blades. This was considered feasible using an existing monohull crane vessel. However, this stick-build methodology is not very quick, it is relatively weather sensitive and will require quite some modifications to the turbine to accommodate relative motions between vessel and floating foundations during installation.

Note on the semi-sub floater motions expected during turbine installation:

- In long period swell conditions, some heave, pitch and roll motions can always be expected. However, these will not include run-away resonant motions because the natural periods are even higher than the range of swell periods.
- In installation, conditions of approximately 2m significant wave height, in the absence of an underlying swell, maximum heave motion amplitudes of ca. 0.10m – 0.15m can be expected. Maximum horizontal motion amplitudes at the top of deck and at the nacelle of

between 0.5m – 1.0m can also be expected, these being the result of pitch and roll motions. Under the circumstances it should be possible to design installation aids that can accommodate the relative motions of the floater and turbine tower or nacelle by paying attention to the capture radius of stabbing cones, etc. used to land the components into position and synchronise their motions with the floater.

- All the floating crane vessel types are susceptible to long period swells and that this is a more significant factor in determining feasibility than significant wave height.

A number of alternative solutions that didn't involve SSCVs or HLVs were also assessed. These focused on lower cost vessels and the use of climbing cranes and mechanisms to transfer loads between two floaters for component exchange were also studied. These technologies showed promise but the solutions need to be proven as well as scaled up for the larger turbines expected in the future.

3.3 Innovation / technology needs

A number of technologies have been identified to allow heavy lift operations to be undertaken on floating wind projects. Many of these technologies need to be scaled up and demonstrated in an offshore environment. There are a number of areas outlined for future technology development.

01

Future heavy lift vessels, for fixed and floating wind, will require better motion compensation combined with height and reach, rather than overall lift capacity

Following the initial screening exercise, it became evident that in simple terms, heavy lift vessels for the oil and gas industry have plenty of lift capacity, but very few have good lift height capability for the offshore wind market. It was also recognised that there was potential over supply in the heavy lift vessel market. This, combined with uncertainties in the floating wind market meant that it could be difficult to form a business case to build a new vessel at this time. Therefore, installation scenarios should start with looking at what could be done with existing vessels.

Any near-term investment is likely to need multiple sectors to work in. There is some headroom in the fixed wind market for higher specification vessels to enter in to the top of that sector and to work in both fixed and floating wind.

02

Need for the development and scaling of enabling technology such as 3D motion compensation and climbing cranes

There is a need to further develop technologies to enable the installation and replacement of large components offshore. For example, there have been rapid developments in 3D motion compensation for floating cranes. This technology looks promising but needs to be scaled up significantly. There is in general a lot of ongoing research in this area and there are a number of climbing crane technologies that could have a good niche in changing out major turbine components on floating wind. These systems need to develop commercially and be tested in an offshore environment.

Key recommendations for developers

03

Encourage turbine manufacturers to engage more openly with supply chain

Developers need to encourage turbine manufacturers to engage more openly with the supply chain and to make changes to the designs of the next generations of offshore turbines to make them easier to install and maintain; this is a particular challenge with floating wind due to the additional motions of the floating platforms. In collaboration with turbine suppliers, new ways of guiding blades and quickly capturing them should be introduced into the new platforms that are currently under development. Minor modifications can also be beneficial for integrating the crane free solution. An example is the hub hoist tool which can be accommodated in the hub; this will greatly ease blade replacement offshore.

Developers need to encourage the supply chain to improve the TRL of new and existing technologies. There are a great many potential technologies that could be deployed but most are at TRL 3/4 and need support to get up to TRL 7.

04

Create opportunities to trial new installation technologies on fixed wind projects and floating wind demonstrators

Developers should seek to create opportunities for early deployment of new installation technologies on fixed wind projects and floating wind demonstrators. This is likely to be a more cost-effective approach than waiting until the lifting technology is required to make a repair.

Many of the perceived installation challenges around motion control, load transfer and stability were solved for Hywind Scotland. However, this was achieved at an inshore location. The next step in evolution is to undertake these operations at an exposed offshore location. This could be part of a more conventional fixed foundation development. Project developers need to identify opportunities to realise an offshore pilot.

Key recommendations for turbine suppliers

05

Supply chain needs greater clarity on future turbine sizes and when they will come to market

The supply chain needs greater clarity on future turbine sizes and when they will come to market. All previous expectations for turbine size growth have been exceeded, and further turbine growth is needed to help deliver LCOE cost reductions for floating wind. However, when you go above the next generation of 12-15MW turbines there are very few options for installing them. Therefore, it would be beneficial to understand, for floating wind in particular, what the practical optimum turbine size is for minimum LCOE. It would also help the industry if there was a consensus on upper bound hub height.

06

Turbine suppliers to consider changes to the next generation of offshore turbines in order to make them more installation friendly

The supply chain, in particular the Tier 1 contractors, is calling for turbine suppliers to consider changes to the next generation of offshore turbines in order to make them more installation friendly. Some highlighted areas for consideration:

- Consider alternatives to flange to flange connections at the base of the tower, for example, the use of slip joints.
- Consider the use of bumpers, guides and other installation aids to control relative motions during installation without the need to for people to be involved.
- More clarity is required on the acceleration limits for transportation and installation. Typically, installation contractors are limited to accelerations of 0.1g. However, in their parallel study on turbine scaling Ramboll say that the turbines should be able to accommodate 0.6g. This could result in a significant reduction in installation costs.
- Eliminating the need for blade rotation during transportation and installation.
- Consider how climbing cranes can be deployed on to turbine towers in an offshore application, where power will be supplied from, and where best to react the crane loads.

Key recommendations for substructure (floater) developers

07

Supply chain needs greater visibility on substructure sizing and motion characteristics

The supply chain needs better visibility of floating substructure sizing, typical dimensions and scaling factors. This has implications for operations and logistics planning including crane reach, port facilities, etc.

On a similar basis the motion characteristics in normal seas for marine operations needs to be more public in order for marine operations to be planned. With and without turbine, idle turbine – floating technology providers need to be aware that underwater geometry could limit vessel operations alongside the floater.

08

Integration of maintenance strategies into design

It has been recommended that consideration for maintenance strategies are considered in the substructure design stage, these suggestions are outlined here:

- Some of the floating foundation designs have active ballasting systems and some have none. The ballasting procedures should be reviewed to take in to account the possibility and feasibility for lifting wind turbine components offshore.
- Consider some pre-investment to ease installation. For example, how a climbing crane could be deployed on to the floater. Is there sufficient working area and is it possible to tap into the power supply on the floater.
- Demonstrate the viability and cost benefit of tow-to-port strategies, and how this connection/disconnection operation is undertaken.

Note that the Floating Wind JIP is undertaking a project comparing the heavy lift maintenance and tow to port maintenance strategies (see overview of Phase III projects for further details).

4. Key findings: Dynamic export cable development

4.1 Study overview

Early prototypes and first arrays of floating wind turbines have been connected to shore using MV power cables (of 22-66kV). However, large-scale commercial floating wind farms will require power to be transmitted using higher voltage cables (of 130-250kV). Given the likelihood of requiring a floating substation in deep-water sites (>100m depth), a section of the export cable will need to have sufficient capacity to tolerate motion in the water column during operation.

Dynamic 22-66kV inter array cables are available from a number of manufacturers, but the Phase I electrical systems study identified a notable gap in the market for suitable HV dynamic cables. This represents a potentially significant challenge and a potential bottleneck to prospective commercial floating wind projects.

The headline objective of the dynamic export cable project, undertaken by BPP Cable Solutions, was to investigate the challenges and assist in the development of HV dynamic power cables for export purposes in floating offshore wind farms. The project commenced with a review of the current status and analysis of the technical challenges for HV dynamic cables. This initial work was followed by the launch of a competition for cable manufacturers. Five manufacturers have since been supported to develop detailed designs with the option to progress with further development work and/or qualification testing.

It is anticipated that the project output will significantly reduce the time to market and accelerate the development of commercial floating wind farms by ensuring that HV dynamic cables are available for the first large-scale projects within the next 5-10 years. HV dynamic power cables will also offer benefits to other industries, such as marine renewables and offshore oil and gas.

4.2 Key findings

Current status of dynamic export cable development

01

Few HV dynamic cables have been produced for offshore energy generation projects

Some R&D activities have been undertaken for specific projects but overall there is a limited track record with existing dynamic HV cables. Dynamic cables are currently used primarily for voltage levels up to 66kV. Such cables have been produced for specific projects, with varied levels of success. To date, few dynamic HV cables have been installed for offshore energy generation projects.

Only a small number of prototype dynamic HV cables have been produced and even fewer have been rigorously tested. Conversely, there is extensive experience of HV subsea cable use for static applications.

02

Lessons to be learned from a number of faults that have affected a number of 33kV submarine dynamic cables

Some valuable lessons have been learned through testing of dynamic cables and components and from faults that have affected a number of MV submarine dynamic cables. Known MV cable faults have mostly been caused by incorrect handling and premature in-service fatigue due to sub-optimal design of cables and protection systems. It should be noted however that the failure modes that affect MV cables are often not directly relevant to dynamic export cables due to differences in their construction. Furthermore, dynamic umbilicals are being successfully deployed by the oil and gas industry. While these products have a good track record of reliable operation, their internal structures differ from HV cables and these are also not directly comparable

Design and manufacturing challenges

03

Cross section design including material selection and component sizing needs to be diligently undertaken to ensure that the cable components have adequate and predictable strength and fatigue properties

There are a number of design procedures that apply to dynamic cables which are not required for their static counterparts. Designs need to be specified based on individual project requirements, particularly with respect to environmental conditions and the selected cable configuration.

Dynamic cables to date have typically been for AC transmission. There is less experience in the industry with dynamic HVDC cables, but the challenges are similar. Component design and material selection needs to be diligently undertaken to ensure that dynamic cables have adequate and predictable strength and fatigue properties. For metallic elements, this is affected not only by the shape, dimensions and composition of the component materials, but also by processes such as cold working and annealing.

Handling and installation

04

Dynamic export cables will require special handling techniques

Submarine power cables typically feature a single layer of helically wound armour wires. This provides strength and protection against installation and handling loads and is usually sufficient for static and mostly static service. This type of cable construction is sometimes able to accommodate and absorb a degree of twist that is applied during handling. For example, coilable cable designs should be able to tolerate a twist of 360° per coil.

Due to the variable loading conditions during service, dynamic HV cables and umbilicals are usually armoured with two or more layers of contra-helically wound armour wires. This

ensures greater strength and torsional stability than a conventional single armoured design, but it also increases the torsional stiffness. Consequently, cables with contra-wound armour should not be allowed to accumulate twist during cable handling or load-out operations. The stiffness characteristics result in contrawound cables being more difficult to manage. Handling procedures and equipment must be carefully selected so as not to overbend or impart twist onto the cable.

4.3 Innovation/ technology needs

The cable manufacturers have been generally positive about the prospect of supplying HV dynamic cables subject to the necessary R&D and qualification activities. There are however challenges to be overcome before dynamic export cables are widely available with sufficient reliability and assurance of performance.

Great care will have to be taken in relation to design of the cables system and selection of materials with appropriate properties. For metallic components, this is affected not only by the composition of the material, but also by processes such as cold working and annealing. The principal supply chain issues include:

01

A number of design and manufacturing challenges have to be overcome before HV dynamic export cables can be routinely produced

- Availability of suitable conductors with appropriate properties and component configurations
- Readiness of HV cable manufacturers
- Suitability of existing test facilities to perform full-scale fatigue testing
- Compatible subsea transition joints need to be developed

02

Handling techniques to be modified to safely manipulate HV dynamic export cables

Handling techniques will need to be modified to safely manipulate HV dynamic cables, which will have the following characteristics:

- High stiffness, intolerance of overbending and twisting, propensity for bird-caging, looping and kinking
- Sensitivity to plastic deformation - avoidance of the associated low-cycle fatigue requires further enhancements of many existing production facilities

03

Testing and qualification of HV dynamic export cables before implementation

The qualification process for HV dynamic export cables will be extensive, at least initially. It will involve mechanical, electrical and non-electrical tests. The full-scale fatigue test and the heating cycle voltage test in particular will take several months to complete. Qualification of dynamic export cables will mean that they are available as a product in the market and can be utilised in future commercial-scale floating projects where a floating substation is planned.

Cable condition monitoring technologies such as DTS and DSS would be highly beneficial to HV dynamic export cables during handling, installation, and operation, but many methods are in an early stage of development.

Such monitoring capabilities brings the potential for real-time conditional monitoring, fault detection, dynamic thermal rating functionality and mechanical load histories. The high costs and risks associated with HV cables are such that monitoring functionality should be rigorously pursued by the cable industry.

4.4 Dynamic export cable competition

Following on from the dynamic export cable study, an international competition, supported by BPP Cable Solutions, was launched to address the lack of availability of high voltage dynamic export cables for the transmission of power from wind farms to shore. The objective of the competition is to ensure that this necessary technology is a viable option for developers for commercial floating wind projects within the next 5 to 10 years.

The competition winners were:

- Aker Solutions (Norway)
- Furukawa Electric Co. (Japan)
- Hellenic Cables S.A. (Greece)
- JDR Cable Systems (UK)
- Zhongtian Technology Submarine Cable Co., Ltd [ZTT] (China)

Drawing on the expertise of existing offshore wind cable suppliers, as well as tapping into the oil and gas supply chain, the competition funding supported the design, initial testing and development of dynamic cables ranging from 130kV to 250kV to enable the efficient transmission of power from floating wind turbines to shore.

Results from the first phase of the project will conclude in Summer 2020, and will be used to inform subsequent project phases to support the deployment of dynamic export cables across the industry.

5. Key findings: Monitoring and inspection

5.1 Study overview

Ensuring the integrity of assets in an offshore wind farm over the full lifetime of the project is vital to maximising the economic value for its owners and managing project risk. This is especially true for floating offshore wind farms, given the importance of station-keeping and the novel risks presented by dynamic and active systems.

Our understanding of operational risks and monitoring, inspection, and maintenance methods for bottom-fixed offshore wind farms has improved considerably in recent years, with several R&D initiatives underway to better inform monitoring and inspection strategies. However, floating wind farms introduce novel elements which may require alternative approaches and new technologies, for monitoring, inspection and maintenance of the hull, ballast systems, mooring and anchoring system, and dynamic cables.

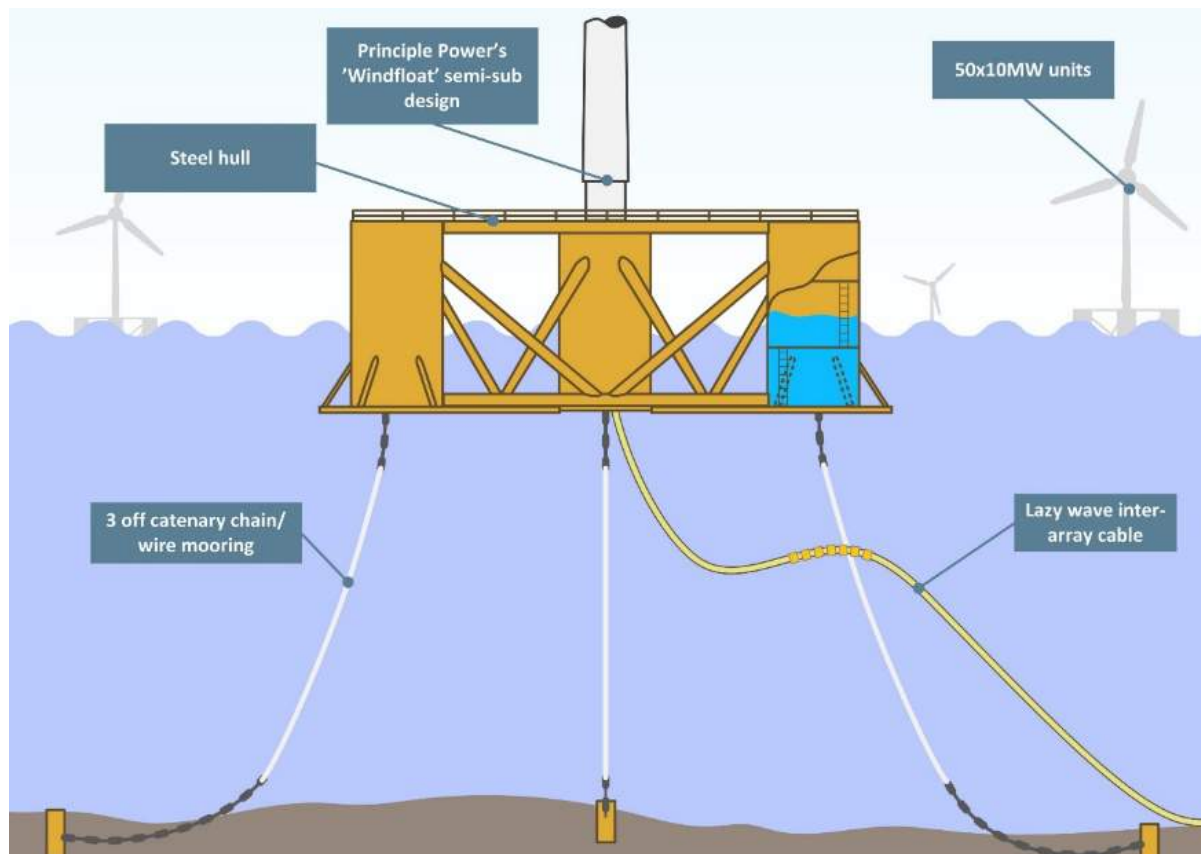
Importantly, this novelty and the adoption of standards from other industries (such as marine) can result in more conservative monitoring and inspection requirements and higher operation and maintenance costs across the wind farm. For example, some certification bodies require frequent hull inspections to be undertaken in a dry dock, which would add considerable cost to a large-scale floating wind farm. Likewise, the risk of failure of mooring lines is likely to be a key cost driver, requiring over-sized mooring lines, redundancy, and/or expensive monitoring and inspection. Dynamic cables may also require more intensive operation and maintenance requirements, particularly given the impact of marine growth on the dynamic properties of the cable and the possible need for frequent cable cleaning.

While technologies exist in both the fixed offshore wind and offshore oil and gas industries, the associated cost and risk profile will differ for floating wind farms, which will require alternative technologies and methodologies to monitor, inspect, and maintain a large number of assets across the wind farm. There is therefore a need to better understand current and future requirements and identify management strategies and technology innovations that could reduce requirements and associated costs.

The study

National and international guidelines and standards relating to the monitoring and inspection of floating offshore wind turbines were reviewed and compared. The review focused on the three components unique to floating units, namely the hull, mooring and dynamic power export cables, as demonstrated in Figure 10.

Figure 10: Components for the base case floating wind platform



The study also reviewed current and in-development inspection and monitoring technologies, evaluated on their potential for cost reduction compared to traditional inspections.

5.2 Key findings

Monitoring and inspection requirements

- There are no common international regulations for the monitoring and inspection of floating offshore wind units, with individual coastal states adopting different approaches and classification societies providing rules, many of which are based on marine and offshore practices.
- The majority of documented guidance still requires periodic inspection, based on 5-year cycles.
- There is little recognition of the impracticality, indeed inadvisability, of applying such an approach for sites containing potentially hundreds of units, and little apparent recognition of the opportunities and benefits afforded by multiples of identical units.
- The more progressive organisations are starting to accept, indeed promote the use of risk-based approaches to the definition of inspection frequencies and scope.
- Separate to, but in parallel with risk-based approaches, there is also a move towards sampling, where classification societies and regulatory bodies will accept inspection of representative spaces and indeed units. Inspecting 1 out of 20 or even 50 units is now being considered by the major societies.

- Monitoring solutions are increasingly being considered to augment, if not completely replace, physical inspection.
- Given the pace the industry is developing, much of the existing documentation is already out of date. Several of the major societies are currently working on updates and new guidance.

In the near term, it is expected that regulatory authorities will continue to require physical inspection, albeit with scope and interval increasingly driven by Risk Based Assessments (RBA). These inspection regimes will most likely incorporate sampling approaches with some reliance on the currently available monitoring techniques.

However, it is anticipated that as field sizes grow, and confidence in the technologies increases, reliance on physical inspection will decrease accordingly. Increased reliance on sampling and remote monitoring will shift the balance of assurance from regular physical inspection of individual units, to a point where assurance is provided by occasional inspection of representative units with only remote monitoring of the rest.

The remit for this study covered in-service inspection and monitoring, however for the above shift to be successful, it is important that through life requirements are identified and taken into account during the design and build phase and it is highly recommended that these aspects are considered in future work.

The timescale for this shift will in part be driven by the regulatory inertia, and in part by the availability and success rate of adequate and novel monitoring and inspection technology.

Technology assessment

01

There are no 'quick win' solutions but sensors used in the digital twin approach and unmanned USV or ROV can offer more cost-effective alternatives to manned operations

The report reviewed current and in-development inspection and monitoring technologies, evaluated on their potential for cost reduction compared to traditional inspections. No immediate solutions were found, but there are some technologies with potential for cost reduction: the two main contenders being sensors used in a digital twin approach as an alternative to physical inspections, and use of unmanned surface vehicle (USV) and remotely operated underwater vehicle (ROV) as a more cost-effective alternative to manned operations.

A number of other promising technologies are listed below, all of which could be relevant in either a digital twin scenario or used by a USV-ROV system.

Remote monitoring technologies

- Acoustic emission fatigue monitoring - less common than strain gauging, has the benefit of detecting active fatigue damage and mooring failures and can be very cost effective if installed during construction. However, to adopt the technology a lot of engineering is needed to set up the system and its performance needs to be proven
- LiRA dynamic cable monitoring - comparatively cheap system that monitors cable impedance and can detect insulation degradation

- Distributed temperature and strain (DTS) sensing for dynamic cable and mooring monitoring – today is a relatively expensive system, but the most feasible option for strain monitoring of dynamic cables and mooring wires

Physical inspection technologies

- FiGS field gradient inspection - quick screening tool able to evaluate cathodic protection status, has the (unproven) potential for inspection of both concrete structures and dynamic cable insulation
- 3D imaging technologies, Rovco photogrammetry and Kraken SeaVision - tools for rapid visual screening of subsea structures, is limited by the presence of marine growth

02

Remote monitoring options for mooring lines were found to be limited with methods for remote data transfer identified as a potential challenge area

Remote monitoring options of mooring lines was found to be limited, with one big gap being a method of data transfer from mooring line sensors. Although there are options for subsea wireless data transfer, these require regular battery changes which may not be an economical long-term solution. Calibration requirements have also been found to be a potential issue; as it incurs an extra cost that in some cases may exceed those of regular inspections.

Maintenance protocol

The options and relative performance of five alternative Operation and Maintenance (O&M) strategies, or scenarios, for floating offshore wind farms were considered. Performance was measured/assessed in terms of implementation cost versus reduction in risk, where risk was quantified in financial terms as the cost of failure. The implementation cost is a combination of inspection and monitoring cost, while the cost of failure is a combination of cost to repair and consequential losses, primarily lost generation capacity. Five scenarios were considered:

- Base Case Scenario – using current inspection and monitoring technologies and rules
- Scenario 1 – current inspection and monitoring technologies, but less conservative rules
 - Risk-Based Inspection (RBI): adjusting the inspection intervals for each inspection type in order to have a medium risk profile (probability of failure as defined in DNVGL-RP-G101) for the final inspection regime
 - Return on Investment (ROI): adjusting inspection intervals to achieve a cost-beneficial inspection focussing on minimising cost and maximising revenue. Note that due to the current expected low probability of failure detection this inspection method will have a high-risk profile
- Scenario 2 – current rules, but innovative inspection technologies
- Scenario 3 – current rules, but innovative monitoring technologies
- Scenario 4 – fewer conservative rules and innovative inspection and monitoring technologies

The opportunities offered by sampling regimes were explored as part of Scenarios 1 and 4.

While the potential for cost reduction offered by sampling regimes applied to wind farms is considered great, the methodology is currently abstract and difficult to properly apply. Further development is required to develop protocols for the application of sampling in order to realise its full potential. The below inspection scenarios were selected in the study to assess expected through life costs. The costs take into account cost to repair and failure, primarily lost generation capacity.

The following key takeaways are relevant to each of the considered scenarios:

Base case scenario key takeaways (using current inspection and monitoring technologies and rules)

- Although normally considered conservative, in reality, the typical class inspection regime does not sufficiently mitigate risk.
- Mooring inspection represents close to half of the total inspection budget, yet the risk of mooring failure remains high.
- The majority of inspections have a negative ROI. This is primarily due to high inspection costs paired with a low probability of fault detection.
- Both ROI and RBI models suggest the base case intervals are too frequent for most hull inspections.
- Subsea inspections of mooring and underwater hull represent 77% of the total inspection cost. It follows this is the area with the greatest potential for cost reduction.

Scenario 1 key takeaways (current inspection and monitoring technologies, but less conservative rules)

- Standard class inspection intervals for topsides and tank internals are too frequent according to both ROI and RBI models.
- Both ROI and RBI models were aligned with the base case inspection intervals for bolted connections.
- ROI model indicates mooring inspection is too expensive to be justifiably done frequently, while RBI model indicates yearly inspections in order to mitigate risk. This indicates a need to develop more cost-effective monitoring technologies and methodologies.
- Sample-based approach is reliant on a significant amount of engineering assessment, the validation of failure data and the development of guidelines for sampling regimes.

Scenario 2 key takeaways (current rules, but innovative inspection technologies)

- Among the available and emerging technologies, the biggest potential for cost reduction is within tools that allow for rapid screening of large sections; these technologies include field gradient and imaging.
- Options are emerging for subsea delivery technologies, many of which are believed to have the potential for great cost reduction. The emerging options are numerous and there is room for a separate study on the best combination of solutions for each task.
- A break-even cost of £15,000 per turbine per year was determined for subsea inspection, which may be used as a guide for the selection of inspection tools.

Scenario 3 key takeaways (current rules, but innovative monitoring technologies)

- There is a technology gap for monitoring of corrosion on both topside structure and subsea mooring.
- Cost of full monitoring package for one unit is less than the base case inspection scenario.
- Negative ROI for most monitoring systems. There is the potential for streamlining with reduction of recurring fees, such as maintenance or calibrations.
- Quantifiable data from fatigue monitoring could act as a complement to non-quantifiable Non-Destructive Testing (NDT) inspection within a sample-based inspection regime.

Scenario 4 key takeaways (fewer conservative rules and innovative inspection and monitoring technologies)

- Fully autonomous units are not likely in the foreseeable future. Supplemental manned inspections will be required despite the presence of monitoring systems.
- The majority of fatigue-related risk is expected to be mitigated through monitoring a subset of units and extrapolating this data to the entire fleet through digital twin modelling technology.
- The greatest potential benefit comes with the application of risk-based strategies supported by focused monitoring and inspection technologies

5.3 Innovation / technology needs

The key to reducing costs and risks is to take a holistic approach to monitoring with rules, guidance, risk-based approaches and technology being applied through an aligned asset management strategy. This report identified the following specific key areas as worthy of further development:

- Digital twins
- Delivery technologies
- Moorings

The primary focus of innovative strategies is a reduction in inspection requirements or using monitoring technologies wherever cost-effective to do so. If that is not feasible, then the focus is to identify the ability to deliver the remaining inspections via autonomous or robotic means.

01

Development of probabilistic models linked to sensor inputs for digital twins is required, especially when considering computing power and correct representation of floating wind turbines

For digital twins, the report identifies a number of areas where development is required, particularly around the use of probabilistic models linked to sensor inputs. Some of this will rely on computing power and others on the correct representation of the multiple units in a floating offshore wind farm.

02

The implementation of monitoring devices on mooring systems including the provision of suitable power systems is identified as an area of development

For mooring systems, the study identifies some of the challenges around the implementation of monitoring devices on the mooring systems, particularly for componentry and areas where there are significant changes in material characteristics. In addition, the ability to provide a suitable power system to maintain sensors subsea is also identified as an area for development.

03

Reliance on fibre optic cores for the monitoring of dynamic export cables and conservative risk assessments are identified as an area of concern

In the area of dynamic cables, concerns are identified about the ability to rely on the fibre optic cores of these cables as methods for monitoring, and also the potential conservatism of current risk assessments. At present, there is limited published information on the failure rates of dynamic power cables, whether this is for inter-array or export cables.

Recommendations

The following recommendations with regards to the design guidance of floating offshore wind mooring arrays are made.

04

A framework for the assessment of mooring failure based on annualised failure probabilities should be agreed with classification societies

A framework for the assessment of mooring failure based on annualised failure probabilities should be agreed with classification societies to enable:

- Cost-effective determination of the design and design robustness of a mooring system
- A clear understanding of the rate of increase in failure probability and the effectiveness of inspection in re-baselining this probability
- A floating offshore wind array project to assess the cost risk-benefit of various design, inspection, fault-tolerance or repair strategies when considering projects whose mooring components number in the hundreds.

05

Classification societies, along with other key stakeholders, should be engaged to agree on a way to reduce mooring failure risk and inspection costs

Inspection strategies developed for 6 or 12 mooring legs, when applied to floating offshore wind arrays with significantly more components, are unlikely to deliver the whole array risk reduction required at an acceptable cost. Classification societies must therefore, be engaged to agree on an acceptable pathway to eliminate or significantly reduce inspections by:

- Collecting data on the performance of the floating offshore wind turbines against anticipated design parameters
- The remote monitoring of components where inspections are accepted to be of little benefit with a poor likelihood of detection
- Agreeing on a means to assess, by way of a Failure Mode Effects and Criticality Analysis (FMECA), those components whose design or design behaviours is not within the population of experience, or can be demonstrated to be vulnerable to event-based phenomena.

6. Projects for Phase III

Phase III overview

Three projects will be delivered in Phase III of the Floating Wind JIP, building on the findings from Phase II, again seeking to address common technical challenges for large-scale commercial floating wind farms. Projects will run throughout 2019 to Q2 2020. Each study will again, involve close engagement with wider industry in order to solicit opinion and expertise from experienced suppliers and to identify relevant technology innovations for the sector.

Heavy Lift Offshore Maintenance

Contractors:

London Offshore Consultants (LOC) Renewables and WavEC

Challenge:

While not desired, exchange of major turbine components, such as blades, gearbox, transformer, or entire nacelle, is often an inevitability and must be planned for. Heavy maintenance procedures in bottom-fixed offshore wind are well-defined and have been practised at scale in commercial wind farms.

These procedures make use of readily available jack-up vessels and crane technology to undertake blade and gearbox exchange. This can include large floating crane vessels or alternative 'crane-free' solutions that are able to utilise lower cost vessels.

This project will aim to undertake a detailed feasibility assessment of the options for undertaking major component exchange at the offshore site, with a particular focus on:

1. The technical feasibility and logistics of climbing cranes and rigging solutions.
2. Further assessment of large crane vessels using 3D motion compensation, building on the heavy lift study delivered under the JIP during 2018.

In addition to the technical assessment, this work will include a rigorous cost assessment, which can be benchmarked against a similar exercise in the tow-to-port maintenance strategy. Safety is a critical factor that will be paramount to any offshore operations. The technologies and procedures assessed in this study will need full consideration of the level of safety risk and how this can be mitigated.



Source: Offshore Logistics B.V.

Tow to port maintenance

Contractors:

London Offshore Consultants (LOC) Renewables and WavEC



Challenge:

Exchange of major turbine components is required for deep water floating wind sites. As an alternative to offshore lifts, several floating wind concepts are advocating, and developing project plans and business cases for, a plug-and-play strategy that would enable floating units to be disconnected and towed back to port for major correctives, such as gearbox or blade replacement. This approach could mitigate the need for expensive heavy lift floating vessels, as well as potentially reduce the risk of undertaking challenging operations in harsh offshore environments.



Source: Equinor ASA

However, this approach has yet to be demonstrated and there are several challenges that will need to be considered and mitigated before implementation, particularly in large-scale commercial wind farms.

Project overview:

The Floating Wind JIP would like to investigate the feasibility and cost benefit of undertaking tow-to-port maintenance campaigns in a floating offshore wind farm, including the assessment of running a campaign on all units of a large wind farm. The main objectives of this work are to:

1. Investigate the procedures for disconnecting and reconnecting floating wind units in a large-scale wind farm.
2. Evaluate key challenges and identify solutions to mitigate risks and costs.
3. Undertake detailed feasibility studies and produce detailed method statements for tow-to-port maintenance operations.
4. Produce robust cost estimates for different maintenance strategies in different conditions.
5. Evaluate technology development needs to enable and optimise tow-to-port operations.

Mooring in challenging environments



Contractors:

Leask Marine, Wood Thilsted, First Energy Development and Exeter University

Challenge:

Mooring systems are critical for the station-keeping of floating offshore wind turbines. Despite considerable track record and experience from the oil and gas sector, floating wind turbines will require tailored solutions to minimise cost and risk. While cost-effective solutions are believed to exist for more benign conditions (e.g. mild sea-state, 100-500m water depth, penetrable seabed) there is a lack of suitable solutions for more challenging environmental conditions, namely:

- Shallow water depths (50-100m)
- Deep water depths (800-1000m)
- Challenging seabed (complex, very hard, very soft)
- Seismic environments (risk of liquefaction)



This study aims to identify and evaluate state of the art and innovative mooring and anchoring solutions for a range of challenging environmental conditions.

Project overview:

The Floating Wind JIP would like to investigate the feasibility and technology development needs for mooring systems in a floating wind farm. The main objectives of this work are to:

1. Conduct an evaluation of current state-of-the-art and innovative mooring system solutions for challenging environments.
2. Develop detailed technical design specifications for a range of site conditions (shallow water depths, deep water depths, challenging seabed, seismic environments).
3. Develop realistic design scenarios, and create robust cost estimates for each scenario, including design, preparation, procurement, installation, and maintenance.
4. Evaluate technology development needs to commercialise innovative mooring and anchoring solutions.

Technology acceleration competition

This competition, funded by the Scottish Government, aims to address four key industry challenge areas: monitoring and inspection, mooring systems, heavy lift maintenance and tow to port maintenance. Eight technologies are being supported, and successful applicants are from a variety of sectors including oil and gas, IT and telecommunications, and engineering. The innovations range in maturity, therefore the funding will be used to support different activities from desktop studies to offshore demonstration.

The competition selection criteria did not consider findings from the ongoing Phase III projects reviewing these challenges, nor has the selection of competition winners prejudiced the outcome of the Phase III projects. The companies and their technologies are:

- *Fugro, AS Mosley, and University of Strathclyde (monitoring and inspection)*



Condition monitoring software which uses readily available acceleration and motion data points from floating offshore wind structures to extrapolate how the wider structure responds to stress. This competition will support a desktop study to validate the peridynamic modelling approach, with a particular focus on characterising the condition of mooring lines.

- *Technology from Ideas and WFS Technologies (monitoring and inspection)*



A load monitoring system to identify stresses on mooring lines and times when maintenance is needed. The monitoring system will be integrated into an existing spring, which also acts as a dampener on mooring lines, and is powered by a piezo-electric generator, which uses the motion of the spring to generate electricity. The competition will support design completion and testing of their load monitoring system.

- *Dublin Offshore (mooring systems)*



Dublin Offshore's passive load reduction device is installed part way along the mooring line and rotates in response to the movement of the floating platform to reduce the tension in mooring lines during wave conditions. For this competition they will build and demonstrate a scale version of the device and test it in a marine environment.

Technology acceleration competition (cont.)

- *Intelligent Mooring Systems and University of Exeter (mooring systems)*



A new pressure-based dampener which sits between the platform and mooring line to reduce the load on floating platforms. Funding and advice will support the building and testing of a scale prototype version of the dampener.

- *RCAM Technologies and the Floating Wind Technology Company (mooring systems)*



A concrete anchor, produced using 3D printing technology, which is sunk and then embedded in the seabed through suction. This competition will support the design, prototyping and testing of the 3D suction anchor, including identification of transport and installation options.

- *Vryhof (mooring systems)*



An adjustable lock on the seabed used to manipulate the tension of the mooring lines. This lock is an alternative to a winch sitting on the turbine platform, and enables vessels to adjust the tension of mooring lines at a safe distance from the platform. Funding and advice will support design certification, large-scale manufacturing and development of installation procedures for this subsea chain adjuster.

- *Conbit (heavy lift maintenance)*



A temporary crane which sits on top of the turbine (the nacelle) to winch parts up and down for maintenance. This could enable larger turbines to be serviced offshore than is currently feasible. Funding and advice will support the design development of the crane for heavy lift component exchange offshore. The project will also test the commercial feasibility of the design through market consultation

- *Aker Solutions (tow to port maintenance)*



A splice box connecting two dynamic array cables, and allowing them to be wet-stored on the seabed when a turbine is towed to port. This will also enable an array of floating wind turbines to remain operational when one floating platform is removed for maintenance. Funding and advice will support development of the design and installation method for the containment unit (splice box), as well as equipment testing.

Phase IV scoping studies

In preparation for Phase IV of the Floating Wind JIP, four scoping studies have been commissioned. These initial studies will consist of a literature review and scoping study in preparation of the larger content delivery. The four Phase IV studies are as follows:

Assessment of Wind Turbine Generators for floating wind farms

Contractors: Ramboll, MESH



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 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 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 projects) 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.

Floating Wind Access and Availability

Contractors: Seaspeed Marine Consulting, SeaRoc



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 platform type and the geometry of the substructure both below and above the water line.

The factors affecting accessibility:

- Environmental conditions such as wave height/period/direction, current, wind speed, marine fouling
- Access method including CTV, SOV (daughtercraft and walk to work), helicopter
- Floating platform type - TLP, semi-submersible, barge, spar

- Floating platform 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 platform motions will affect turbine access as well as the performance of technicians undertaking work in the nacelle, where floater motions will be higher. Further to this, commercial-scale floating offshore wind will likely utilise larger capacity, 15MW+ 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.

Floating Wind Yield

Contractors: Frazer Nash Consultancy, NREL



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.

Numerical Modelling Guidelines and Standards for Floating Wind

Contractors: Innosea, Sowento



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.

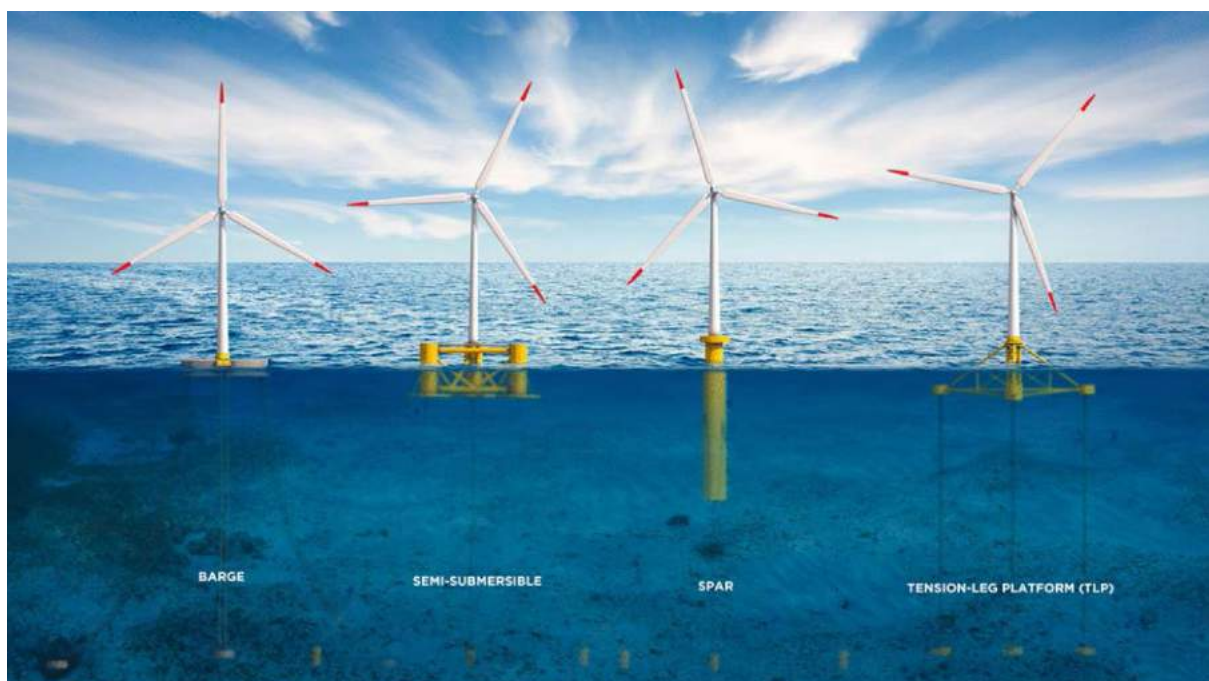
The Floating Wind JIP would like to improve the understanding of guidance for the design of floating wind structures including: defining the relevant load cases and guidance for an optimised outline design, a review of numerical modelling tools for floating wind turbine design, and a review of the leading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

Appendix

Appendix 1: Floating wind typologies

There are four dominant types of floating wind foundation:

- **Semi-submersible:** A semi-submersible is a free-surface buoyancy-stabilised structure with relatively shallow draft. It is a versatile structure thanks to its relatively low draft and flexibility to different site conditions. Generally, it is a heavy structure with a relatively high steel mass and manufacturing complexity due to the many welded connections.
- **Spar:** The spar is a ballast-stabilised structure with relatively large draft. It uses simple, well-proven technology with inherently stable design that exhibits high inertial resistance to pitch and roll motions. The spar will face challenges due to its large draft requirements for the operational site, but also in terms of assembly sites and transportation routes.
- **Tension-leg platform (TLP):** The tension leg platform is a tension-stabilised structure with relatively shallow structural draft and limited motions during operation. The tension leg enables low structural weight of the substructure, and thus lower material costs. However, mooring tendons can present higher operational risk in case of mooring failure and add requirements with regard to soil conditions at site.
- **Barge:** Barges are the shallowest draft of all the floating foundation types. This is an advantage for installing the turbine alongside a quay at a shallow draft location. However, the design will therefore have greater motions due to waves, which can demand more robust mooring systems. Some barge designs include a moonpool to suppress wave-induced loading.



Source: WindEurope

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