Floating Wind Joint Industry Project

Phase I Summary Report

Key Findings from Electrical Systems, Mooring Systems, and Infrastructure & Logistics studies

May 2018

Acknowledgments

The Carbon Trust has produced this summary report based on studies delivered by the following external technical contractors:

- Electrical Systems: Petrofac and TNEI
- Mooring Systems: Rambøll
- Infrastructure & Logistics: London Offshore Consultants (LOC) and WavEC

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

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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, including market projections, 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 the past 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

Offshore wind power is on the cusp of global expansion, as the industry matures, prices fall, and deployment increases across several international markets. Having been pioneered in shallow European waters (<60m depth) using conventional fixed foundations, bathymetric constraints mean that much of the future potential exists in deeper waters (>60m depth) where floating foundations will be required. The added flexibility in the siting of floating offshore wind power will also facilitate exploitation of areas with the strongest wind resource, boosting yields and delivering a consistent supply of low carbon electricity to meet energy demand.

Market Growth

Despite only 50 MW of floating wind power being installed globally, a series of pilot wind farms are set to demonstrate the technical and commercial viability of the technology, ahead of the large-scale deployment expected within the next decade. Given the relative immaturity of this nascent technology, the pace and scale of deployment will be contingent on policy support to bridge the gap between pilot and commercial projects. Carbon Trust analysis of potential future deployment indicates a wide range of projections to 2030, characterised by 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 (GW) pipeline of opportunities, with considerable value to be captured by local and regional economies.

Technology Challenges

In addition to political barriers, large-scale deployment of floating offshore wind presents several technical challenges that will require innovation from suppliers and wider industry. Many of these challenges are common to multiple floating wind concepts, making them suitable for collaborative research and development efforts between industry players. The Floating Wind Joint Industry Project ('JIP') is a collaboration between the Carbon Trust, Scottish Government, and twelve leading international offshore wind developers with a strategic interest in floating wind technology. The JIP focusses on de-risking technology challenges and identifying innovations that can deliver cost reduction in large-scale floating offshore wind farms. This report presents key findings from three studies delivered in 2017, each addressing critical areas for future commercial projects. The report aims to make the challenges faced more transparent to enable the supply chain and wider industry to engage and develop the necessary solutions to de-risk the technology and accelerate cost reduction.

Electrical Systems

Floating wind farms will introduce several novel elements, largely in relation to dynamic power cables and floating substations. While no insurmountable issues are envisaged, a handful of potentially critical bottlenecks were identified. Most significant is the current lack of high voltage dynamic cables for export purposes, which require alternative designs compared to the static cables used in fixed-bottom offshore wind farms. The export cable is vital for transmitting power back to shore efficiently and represents a single point of failure in commercial wind farms. Given the potentially lengthy timescales to develop and qualify suitable cable designs, this is an immediate priority for the sector.

In response to this challenge, the Floating Wind JIP has launched a new project to accelerate the development of high voltage dynamic power cables.

An assessment of commercial-scale floating substations found that these would be feasible without significant technology development, but testing and qualification of electrical equipment is a current gap. Technology development is most relevant to auxiliary components that can limit cable fatigue, particularly cable bend stiffeners, for which larger and stiffer modules may be required.

Mooring Systems

The mooring and anchoring system is a critical component of floating wind devices that represents a unique differentiator compared to conventional fixed offshore wind foundations. While considerable experience and expertise exists from the oil and gas sector, the coupled behaviour of floating offshore wind turbines introduces new load characteristics that require further research in order to reduce fatigue and failure probabilities. Indeed, statistics from oil and gas suggest that mooring line failures are not just possible, but likely to occur across a fleet of floating wind assets. However, their occurrence and impact can be reduced with adequate design redundancy and appropriate planning.

The volume of mooring and anchor components deployed across a large-scale floating wind farm also creates complexities for installation and maintenance logistics. While there are well-established approaches and technologies from oil and gas, there are opportunities for innovation and optimisation to reduce costs, particularly in top connectors, anchors, and monitoring and inspection technologies. Considerable cost reduction potential is also evident in synthetic mooring line materials, relative to conventional steel chain and wire moorings, but further research and development is required in order to demonstrate their application in floating offshore wind over 25-30 year periods.

Infrastructure & Logistics

Infrastructure and logistics will be a key factor in making floating wind technologies cost competitive. Floating wind structures will need to be amenable to serial production methods that can ensure delivery of 50-100 units within a single summer installation campaign. As project sizes grow, with ever larger turbines and foundation structures, the constraints imposed on the port facilities will increase significantly. Port draught, crane capacity, onshore area, and wet storage area were all seen to limit the suitability of existing European ports. Port availability improves when considering the ability to import cranes from elsewhere, but the logistics of importing very large crawler cranes can add logistical challenges and costs. Re-purposing jack-up vessels at the quayside could be an alternative option that adds flexibility and improved efficiency for turbine assembly and integration.

Analysis of major repair procedures identified challenges with both portside and offshore maintenance strategies. The complexity of disconnect and tow-to-port operations, as well as infrastructure constraints, suggests that this approach may be challenging to implement in practice, particularly for large repair campaigns across multiple turbines. Undertaking in-situ repairs offshore could be preferable, if the feasibility and cost-benefit of floating-to-floating heavy lift operations can be demonstrated.

Given the constraints identified, it is considered that floating wind farms near good port infrastructure will be more competitive in the near-term and will be important to prove the cost competitiveness of floating wind technology. However, in the long-term, improved vessel technology has the potential to make floating offshore wind farms cost competitive in a much broader range of sites regardless of local port infrastructure, enabling a global implementation of the technology.

List of Key Findings and Priority Innovation Needs

Electrical Systems

Key Findings:

01 Commercial scale floating substations are feasible, with hulls capable of providing relatively low extreme motions and adequate fatigue life

02 Existing electrical equipment should be feasible with only minor modifications, but testing and qualification is a key requirement and current gap

03 Adequate fatigue lives can be achieved by optimising cable configurations, particularly through the use of bend stiffeners

04 Marine growth (biofouling) can have a material impact on dynamic cable configurations

05 High voltage dynamic cables for export purposes are a current and significant technology gap

06 Larger and more rigid bend stiffeners than current standard may be needed to improve cable fatigue life

07 Mid-depth cable configurations are feasible for deep-water sites, but further investigation of cable fatigue is needed

08 Cable connectors are readily available and viable, but the feasibility and logistics of out-of-service arrangements require further investigation

09 The business case for connectors is driven by the wind farm O&M strategy and assumption on the number of major repair procedures during the operational lifetime

10 No variance is expected to conventional circuitry and burial arrangements in fixed-bottom offshore wind

Priority Innovation Needs:

01 Qualification of high voltage dynamic cables for export purposes

02 Qualification of electrical equipment for large capacity floating substations

03 Larger and more rigid bend stiffeners

04 Out-of-service arrangements for turbine disconnect procedures

Mooring Systems

Key Findings:

01 A lack of understanding and focus exists regarding the relevance of mooring systems for floating wind turbines, both technically and economically

02 Shallow water (<100m) is more challenging than deep water for mooring and tendon design

03 Oil and gas statistics suggest that mooring line failures are likely to occur in floating wind farms, but many failure causes are avoidable with appropriate planning

04 Fatigue of moorings is not well understood for floating offshore wind – there is scope for further research to improve design standards and methodologies

05 Synthetic mooring lines have the potential to reduce costs, but need further development and qualification for long-term application in floating wind

06 Mooring installation is a major cost contributor. Closer collaboration is needed between mooring designers, substructure developers, and installation contractors

07 Top connectors and anchors have a major impact on installation – simple, low cost, but effective solutions are needed

08 Monitoring & inspection techniques from oil and gas are readily available, but expensive – there is considerable scope for more cost efficient approaches and technologies

09 Anchor mutualisation offers potential benefits for cost reduction, but is challenging to implement in practice

10 Soil liquefaction is a challenge, but can be mitigated through deeper penetration of anchor piles

11 There is a need for bespoke mooring system standards for floating offshore wind

12 Lessons learned from (full scale) demonstrator experience is very valuable and should be shared across industry

Priority Innovation Needs:

01 Understanding of fatigue mechanisms in floating wind mooring systems

02 Qualification of synthetic mooring line materials for floating offshore wind

03 Low cost installation methods and enabling technologies

04 Monitoring and inspection procedures and technologies

Infrastructure & Logistics

Key Findings:

01 The construction and maintenance of floating wind farms has significant infrastructure and logistical challenges that are different from fixed offshore wind

02 Infrastructure and logistics will be a key factor in making floating wind technologies cost competitive, but requirements will vary by concept

03 There are limited ports that can accommodate all requirements for the construction of large-scale floating wind farms

04 Re-purposing of low cost jack-up vessels could alleviate onshore crane capacity constraints

05 Substructure fabrication represents the critical path in construction logistics - substructure design and port infrastructure must be suitable for serial production methods

06 Current methods for dry dock substructure assembly are unlikely to be economically viable in large floating wind farms - quay side serial fabrication methods will be required

07 Turbine assembly and integration is a key challenge and cost driver

08 Long distance from assembly port to site may imply complex, lengthy and cost wet tow operations

09 Disconnection complexity and port infrastructure requirements are major challenges for tow-to-port maintenance strategies

10 Heavy lift offshore operations will be a requirement for several, if not all, concepts. Developing cost-effective methods is a priority for the sector.

Priority Innovation Needs:

01 Feasibility and cost-benefit of heavy lift offshore operations

02 Feasibility and cost-benefit of tow-to-port maintenance strategies

03 Efficient and cost-effective turbine integration procedures

04 Serial production methods for floating wind structures

Abbreviations

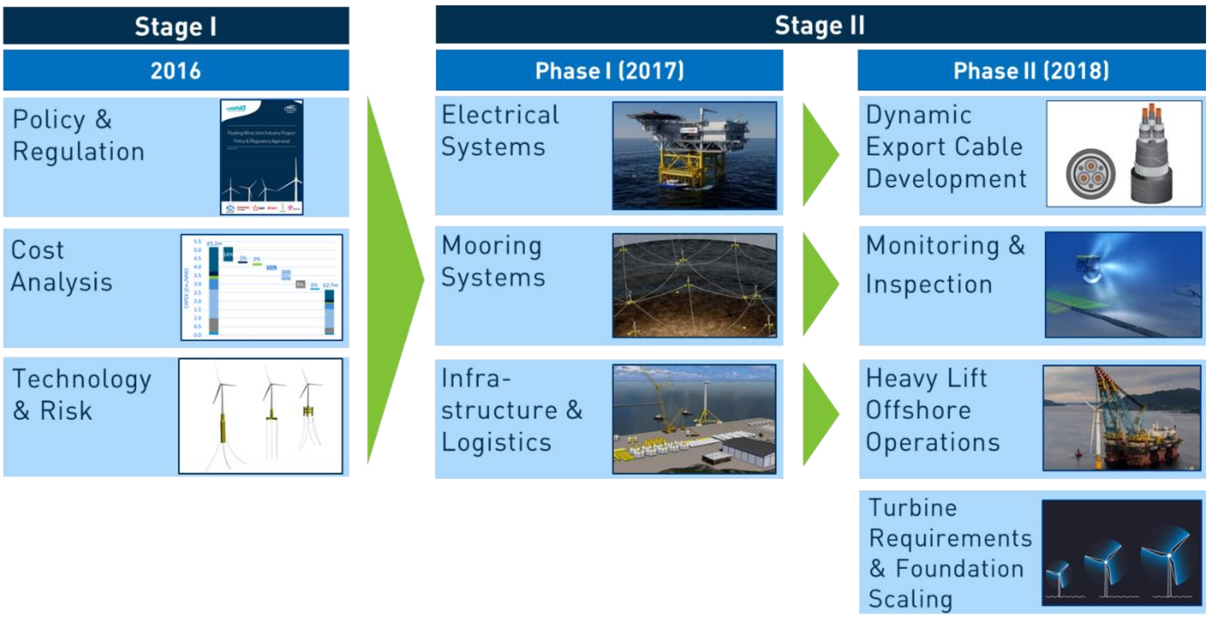
AC	Alternating current
AHV	Anchor handling vessel
CfD	Contract for difference
DC	Direct current
EPCI	Engineering, procurement, construction and installation
GW	Gigawatt
HMPE	High-modulus polyethylene
HV	High voltage
JIP	Joint industry project
LCOE	Levelised cost of electricity
MW	Megawatt
NREL	National 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
ROC	Renewable obligation certificate
TBC	To be confirmed
TLP	Tension leg platform
TRL	Technology readiness level
WTG	Wind turbine generator
UXO	Unexploded ordnance

Introduction

Background on the Floating Wind Joint Industry Project

The Floating Wind Joint Industry Project ("Floating Wind JIP") is a collaborative initiative between the Carbon Trust, Scottish Government, and twelve leading international offshore wind developers: EnBW, ENGIE, Eolfi, E.ON, Iberdrola, innogy, Kyuden Mirai Energy, Ørsted, Shell, Statoil, Vattenfall, and Wpd Offshore. The JIP aims to investigate the challenges and opportunities of developing large-scale commercial floating wind farms.

Since its formation in 2016, the JIP has been delivered through two stages, each consisting of studies to outline the critical needs for the sector to reach cost parity with other energy technologies. An initial broad review of policy needs, cost trends, and technology status in Stage I resulted in the prioritisation of several key technical challenges for further investigation in Stage II. Key findings from the first phase of projects are presented in this report (see chapters 2-4). A series of follow-on projects will be delivered in 2018 (see chapter 5).



Objectives & 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-focussed, 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. For the Phase I studies presented in this report, a 500 MW wind farm (50 x 10 MW units) was used as the basis for evaluating technology challenges.
- **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.

Image: Hywind Scotland (Statoil)

1. Floating Wind Market Status

Market analysis produced by:

1.1 Market Growth

1.1.1 Floating wind deployment to date

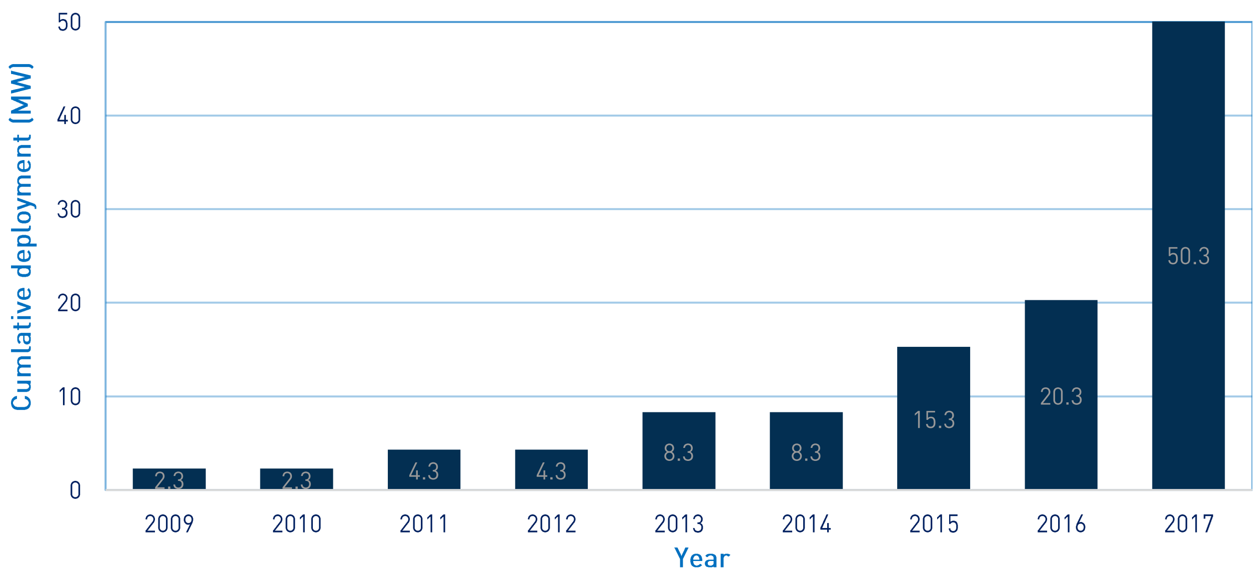
As of the end of 2017, total cumulative capacity of 50 MW of floating offshore wind power had been installed globally, distributed in countries located in Asia and Europe (Table 1 and Figure 1). A series of individual prototypes installed between 2009 and 2016 have demonstrated the viability of the technology 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 this next phase of technology development, proving that the technology can perform in array formation and with larger turbines (see Box 1). Early indications suggest that performance has exceeded expectations, with high yields confirming the technical and commercial viability of the technology.

Table 1: Commissioned offshore wind projects

First power	Country	Project	Total capacity	Turbine rating	Project developer	Technology developer	Concept	Turbine supplier
2009	Norway	Hywind I	2.3 MW	2.3 MW	Statoil	Statoil	Hywind	Siemens
2011	Portugal	WindFloat Atlantic Phase 1*	2 MW	2 MW	EDPR, Repsol, Chiyoda, Mitsubishi	Principle Power	WindFloat	Vestas
2013	Japan	Kabashima	2 MW	2 MW	Toda Corporation	Toda Corporation	Hybrid spar	Hitachi
2013	Japan	Fukushima FORWARD	2 MW	2 MW	Marubeni	Mitsui Engineering & Shipbuilding	Semi-Sub	Hitachi
2015	Japan	Fukushima FORWARD	7 MW	7 MW	Marubeni	Mitsubishi Heavy Industries	V-Shape Semi-Sub	MHI
2016	Japan	Fukushima FORWARD	5 MW	5 MW	Marubeni	Japan Marine United	Advanced Spar	Hitachi
2017	UK	Hywind Pilot Park	30 MW	6 MW	Statoil	Statoil	Hywind	Siemens
2018	France	FloatGen	2 MW	2 MW	IDEOL	IDEOL	Damping Pool	Vestas

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

Figure 1: Cumulative global deployment of floating offshore wind (2009-2017)



Box 1: Case Study - Hywind Scotland

Hywind Scotland, the world's first floating offshore wind farm, began commercial operations in October 2017. The 30 MW project, developed by Statoil in collaboration with Masdar, is comprised of five SWT-6.0-154 Siemens turbines supported by Hywind spar-buoy floaters, generating enough power for 20,000 homes.

The project marks a world-first in several features. In addition to being the first pre-commercial array deployment, the turbines will utilise an advanced control system to maximise yield and optimise structural stability. The spar floater also represents an evolution from the first Hywind 2.3 MW demonstration, with draft reduced from 100m to 85m despite a near tripling in power output, partly in order to comply with the available water depth in the Buchan Deep. Further optimisation and learnings have contributed to a 60-70% cost reduction from the original prototype. Statoil are confident of a similar rate of cost reduction to commercial scale projects, with LCOE of €40-60 /MWh targeted by 2030.

The pan-European approach to procurement and construction saw the spar foundations fabricated in Navantia, Spain, before being towed to the deep fjords of Leirvik, Norway, for upending and turbine assembly. Here, the world's largest floating-to-floating heavy lift operation of a wind turbine was completed by the Saipem 7000 vessel. The fully assembled structures were then towed to site off the coast of Peterhead in Aberdeenshire, Scotland, for hook-up and final commissioning. Average wind speeds in this area of the North Sea exceed 10 metres per second. Recently reported capacity factors for the first 3 months of operation averaged ~65%, proving the technical and commercial viability of the project.

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 Stated and Japan. By 2021, installed capacity is expected to reach ~200-260 MW, with ~5-6 concept designs suitably de-risked for deployment in larger commercial projects.

Table 2: List of upcoming floating wind projects

First power	Country	Project	Total capacity	Turbine rating	Project developer	Technology developer	Concept	Turbine supplier
2018	Japan	IDEOL Kitakyushu Demo	3 MW	3 MW	IDEOL & Hitachi Zosen	IDEOL	Damping Pool (Steel)	Aerodyn
2019	Portugal	WindFloat Atlantic: Phase 2	25 MW	8.3 MW	EDPR, Repsol, Engie, Chiyoda, Mitsubishi	Principle Power	WindFloat	MHI-Vestas
2018-2020	UK	Kincardine*	50 MW	2 MW x1 8 MW x6	Pilot Offshore, Cobra	Principle Power	WindFloat, plus other TBC	TBC
2020	USA (Maine)	Aqua Ventus I	12 MW	6 MW	University of Maine	University of Maine	VolturnUS	TBC
2020/ 2021	France	Groix Pilot Farm	24 MW	6 MW	Eolfi, China Guangdong Nuclear (CGN)	Naval Energies	Sea Reed	GE
2020/ 2021	France	Leucate Pilot Farm	24 MW	6 MW	Engie, EDPR, Caisse des Depots	Principle Power	WindFloat	GE
2020/ 2021	France	EolMed (Gruissan) Pilot Farm	24 MW	6 MW	Quadran	IDEOL	Damping Pool	Senvion
2020/ 2021	France	Provence Grand Large	24 MW	8 MW	EDF EN	SBM Offshore	TLP	Siemens
2021	Japan	Goto City	22 MW	2-5 MW	Toda Corporation	Toda Corporation	Hybrid Spar	TBC

** From a recently filed variation order with the Scottish government, the Kincardine project will now consist of a total of seven turbines installed over two phases. A single 2MW turbine is expected to be installed in the first phase in 2018. Kincardine Offshore Wind Limited (KOWL) has stated that the second phase installation period will be "up to 2020".*

1.1.3 Commercial projects and market growth to 2030

Following pilot array projects, floating offshore wind will need to be deployed at larger scale in fully commercial projects. Reaching high volumes of scale will be vital to further validating the technology and delivering cost reduction. The timescale and rate of deployment for commercial projects is still uncertain, but current market conditions suggest that the first large scale projects could be installed by 2025.

Table 3 outlines industry ambitions for floating wind deployment across a number of key markets. Collectively, there are aspirations for up to ~8 GW by 2025 and up to ~30 GW by 2030. However, crucially, these targets are not backed by official government policy and must be treated with low certainty. Given typical development timescales of 6-8 years, projects for commissioning by 2025 would need to already be under active development and a pipeline of projects for 2030 would need to be established within the next 5 years. Such pipelines would need to be of sufficient magnitude to account for project delays and attrition, particularly in uncertain regulatory regimes and competitive auction systems.

The aspirational targets outlined in Table 3 are therefore unlikely to be realised within the indicated timeframes. However, the degree of interest and appetite from industry highlights the medium- to long-term potential for floating wind power in these and other markets.

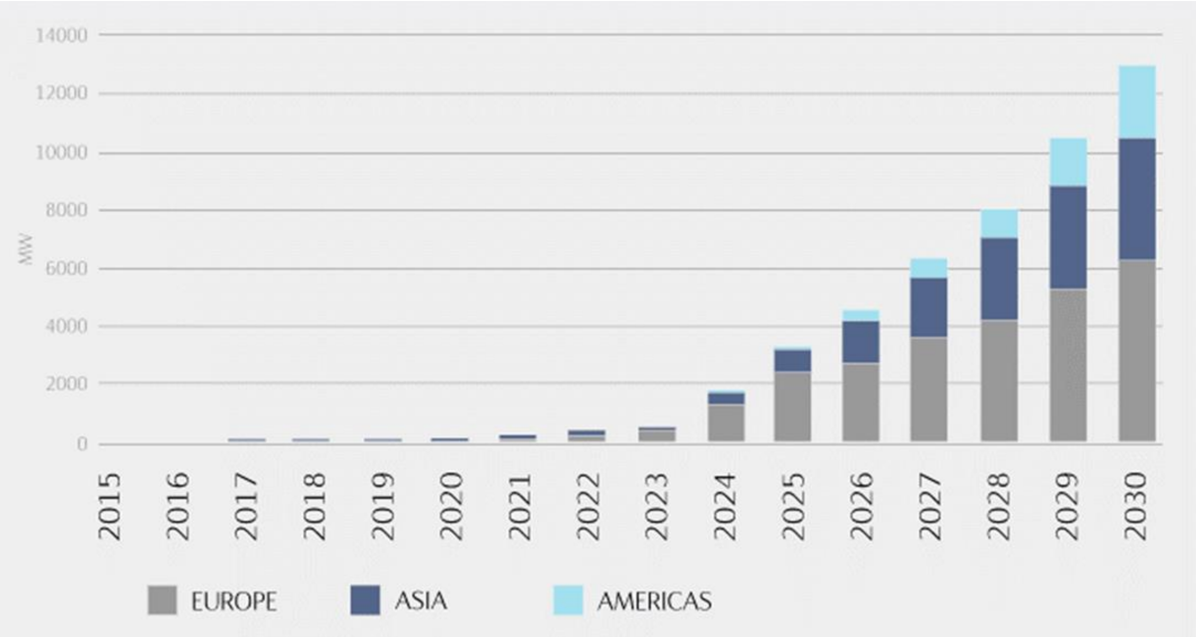
Table 3: Industry deployment ambitions to 2025 and 2030

Country	Installed (MW) 2018	Expected (MW) 2021	Industry Ambition (MW) 2025	Industry Ambition (MW) 2030	Industry Ambition (MW) Certainty
EUROPE					
UK	30	80	1,000	5,000	Low
France	2	98	2,000	6,000	Med
Norway	2	6	30	250	Low
Portugal	0	25	25	260	Med
Europe (Max)	**34**	**209**	**3,055**	**11,510**	
ASIA					
Japan	16	41	1,400	4,000	Med
China	0	0	1,000	3,000	Med
Taiwan	0	0	1,000	2,000	Low
Asia (Max)	**16**	**41**	**3,400**	**9,000**	
UNITED STATES					
California	0	0	1,000	2,500	Med
Hawaii	0	0	400	1,200	Low
Maine	0	12	500	5,000	Low
United States (Max)	**0**	**12**	**1,900**	**8,700**	
GLOBAL					
Global (Max)	**50**	**262**	**8,355**	**29,210**	

N.B. Excludes several potential markets which have yet to outline long term ambitions for floating offshore wind power. Information sources can be found in Appendix 2.

The expected level and location of future deployment to be realised by 2030 will be largely dependent on conducive government policies, supportive regulatory frameworks, and the pace of technology innovation in the industry. Carbon Trust expect up to ~12 GW to be feasible by 2030, which is supported by other industry sources, including Statoil (Figure 2). There is potential upside if policy support and technology commercialisation is accelerated across several markets, as part of increased build out of both fixed and floating offshore wind power globally. However, there is also potential downside to these projections if countries do not offer a route to market for floating wind projects and deployment of both fixed and floating offshore wind power is constrained.

Figure 2: Statoil market outlook to 2030



N.B. Market outlook produced in 2017. Phasing of future deployment likely to vary according to latest market conditions, with first commercial projects from ~2025.

Technology commercialisation and deployment is expected to be led from Europe, reflecting its current leading position and ability to leverage existing skills, knowledge, expertise, and supply chain capabilities from the established offshore wind and oil and gas sectors. However, long-term growth is expected to result in a greater weighting to markets in East Asia and North America.

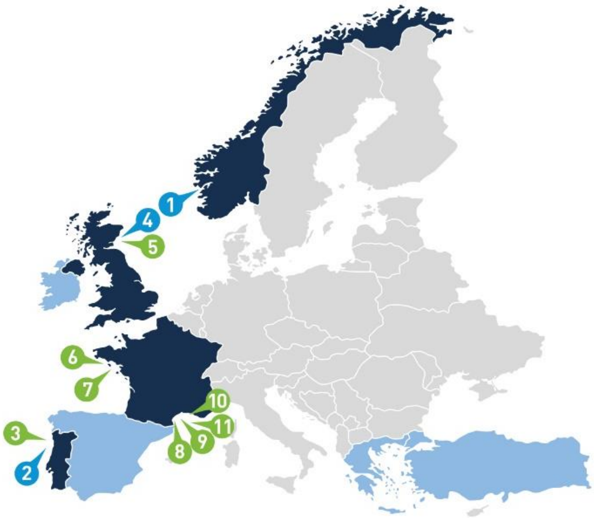
A map and list of installed and pipeline floating offshore wind projects in the three key regional markets can be seen in Figure 3.

Figure 3: Regional floating wind deployment

Key

Lead markets | Follower markets

● Installed projects ● Pipeline projects



Europe

Project	MW
Norway	
1. Hywind I	2.3
Portugal	
2. WindFloat Atlantic 1	2
3. WindFloat Atlantic 2	25
United Kingdom	
4. Hywind Pilot Park	30
5. Kincardine	50
France	
6. FloatGen	2
7. EolMed (Gruissan) Pilot Farm	24
8. Leucate Pilot Farm	24
9. Groix Pilot Farm	24
10. Provence Grand Large	24
11. France commercial tender	500-2000

Asia

Project	MW
Japan	
12. Kabashima demo	2
13. Fukushima FORWARD: Phase 1	2
14. Fukushima FORWARD: Phase 2	12
15. IDEOL Kitakyushu demo	3
16. Goto City	22
Taiwan	
17. Eolfi Taiwan	500-2000
China	
18. CGN Jieyang	500-3000

United States

Project	MW
Maine	
19. Aqua Ventus I	12
20. Aqua Ventus II	480
California	
21. Humbolt Coast	120-150
22. Morro Bay	700-1000
Hawaii	
23. Oahu Northwest	400
24. Oahu South	400
25. Oahu Progression	400

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.

Although the UK is blessed with considerable wind resource in shallow water depths, it is possible that an offshore wind-heavy UK energy strategy could necessitate deployment in deeper waters using floating technology. Floating wind could also support the UK's industrial strategy by benefitting 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 boasts the world's first and, currently, only floating wind farm, Hywind Scotland. The 30 MW project has achieved higher-than-expected capacity factors and survived several harsh winter storms in its first months of operation. The most noteworthy upcoming floating project is the 50 MW Kincardine wind farm, which will be constructed in two phases, with a 2 MW semi-submersible unit in 2018 followed by up to six 8 MW units in 2019-2020. A further two projects – Dounreay Tri (10 MW) and Forthwind (60 MW) – are struggling to meet the closure of the enhanced ROC subsidy regime and are unlikely to proceed. No commercial projects are currently under development, although potential sites are being explored by several prospective developers.

POLICY SUPPORT

Policy support in the UK has been driven by the enhanced renewable obligation certificates (ROCs) available in Scotland for floating wind technology, reinforced by Scotland's goal to generate 100% of its electricity from renewables by 2020. However, the closure of the enhanced ROC regime at the end of September 2018 presents a risk for the sector, with no clear successor mechanism to provide a route to market for pilot or commercial projects. A range of alternatives, such as a ring-fenced budget for Contracts for Difference (CfDs) or Innovation Power Purchase Agreements (PPAs) have been suggested, but the UK Government has shown no immediate signs of introducing a new revenue support mechanism.

A more positive development could emerge from the Crown Estate Scotland's announcement of a new leasing round for offshore wind, which is expected to cater for deep-water sites suitable for floating technology. Identification and acquisition of suitable sites by developers is likely to attract interest and investment from developers, but the scale of projects and visibility of a route to market will be critical.

FRANCE

OPPORTUNITIES FOR FLOATING WIND

There are suitable sites for floating projects in both the Mediterranean and Atlantic waters off the 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 multi-MW offshore wind turbine – fixed or floating – is set to be installed in May 2018, a 2 MW Vestas turbine supported by IDEOL's concrete Damping Pool floating technology, including a novel synthetic rope mooring system. The 'FloatGen' project has leaped ahead of several fixed-bottom projects that have experienced delays due to permitting and supply chain issues.

Following this first full-scale prototype demonstration, France has provisionally awarded contracts to four pilot floating wind farms in the Mediterranean (x3) and Atlantic (x1) (see Table 2). The projects will receive a feed-in tariff set at €240/MWh, with commissioning expected in 2020/21. A tender for up to 2 GW of commercial projects could be announced before 2020, with potential sites already under investigation and a 'competitive dialogue' underway. Projects would be commissioned by 2025/26. Wind industry group France Energie Eolienne (FEE) has outlined a target of up to 6 GW floating offshore wind capacity by 2030, but realisation will be contingent on government support.

POLICY SUPPORT

France's current multi-annual energy program *(Plan de programmation pluriannuelle de l'Energie (PPE))* has proposed the development of 3 GW of offshore wind capacity by 2023, with a further 3 GW to be included in its pipeline beyond 2023. This capacity is expected to be dominated by fixed-bottom offshore wind project. However, the program has also called for the approval of up to 2 GW of floating wind and tidal projects, in addition to the 96 MW of pre-commercial projects being supported. Tenders could be launched before 2020 with commissioning slated for 2025/26.

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.

PORTUGAL

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 ~40 GW, which far exceeds the ~3.5 GW suitable for fixed-bottom offshore wind. 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 2 MW WindFloat semi-submersible unit installed 5km off the coast of Aguçadoura in 2011. Following 5 years of strong performance, including surviving harsh Atlantic storm conditions and registering high load factors, the unit was decommissioned in 2016.

Building on the prototype demonstration, a 25 MW second phase, consisting of three 8.3 MW turbines, is under development and expected to achieve final commissioning in 2019.

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. The Industrial Strategy for Ocean Renewable Energies (EI-ERO) was approved in 2017, with the aim of developing the country's offshore wind potential. This currently includes plans for up to 260 MW of offshore wind by 2030.

UNITED STATES

OPPORTUNITIES FOR FLOATING WIND

The United States is a potentially major market for floating offshore wind, particularly on the West Coast and Hawaii, due to the rapid drop-off of the continental shelf. In states with high solar penetration, such as California, 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.

Fixed-bottom 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 power.

PROJECTS

The United States installed its first offshore wind turbine in 2013, a part-scale prototype of University of Maine's VolturnUS concrete semi-submersible concept. This is due to be followed by the first full-scale floating wind turbine, through the 12 MW Aqua Ventus I project, consisting of two 6 MW turbines. The project, whose partners include Naval Energies and Cianbro, is slated for installation in 2020. There are aspirations for large-scale commercial deployment beyond 2020, but no firm timeline or government support has been established.

The first commercial projects are more likely to emerge on the West Coast. Several commercial projects are being explored for development, including the up to 1 GW project in Morro Bay, up to 150 MW project off the Humboldt Coast (both California), and three 400 MW projects in Hawaii.

POLICY SUPPORT

The Aqua Ventus I demonstration project will receive up to $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.

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 parallel, the California Energy Commission has identified six potential zones for floating offshore wind power, concentrated off the central and southern coast of California.

JAPAN

OPPORTUNITIES FOR FLOATING WIND

Japan has vast potential for floating technologies due to significant depth constraints for fixed-bottom 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 and acceleration of deployment, with floating wind set to play a major role in a growing offshore wind industry.

PROJECTS

Japan has 16 MW 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), is expected to be installed off the coast of Kitakyushu in 2018/19, a 3 MW steel edition of IDEOL's Damping Pool technology. Toda Corporation are also planning an up to 22 MW 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.

POLICY SUPPORT

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. Revenue support for commercial projects exists through a feed-in tariff of 36 JPY/kWh for all offshore wind projects. However, the main obstacle has been the lack of clarity and arduous nature of current consenting and permitting policy. New legislation is expected to introduce a streamlined development process and identify ocean zones suitable for offshore wind, which could provide the catalyst for commercial floating wind projects.

TAIWAN

OPPORTUNITIES FOR FLOATING WIND

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 fixed-bottom 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.

Strongest wind speeds and demand centres are located off the west coast, in the Taiwan Strait. Like Japan, it faces challenges from earthquakes, extreme waves and tsunamis. Taiwan also possess relatively strong manufacturing and maritime industries.

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 ~500 MW 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.

POLICY SUPPORT

Taiwan has introduced a supportive policy and regulatory framework to enable to the pursuit of aggressive offshore wind expansion. Near-term targets to 2025 have recently been upgraded from 3 GW to 5.5 GW, with longer term ambitions of 10-17 GW. While near-term targets are expected to be achievable using fixed foundations, long-term build out is likely to require floating technology.

Attractive fixed revenue support has been allocated to ~3.8 GW of fixed-bottom offshore wind projects due to be installed from 2020 to 2024. 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.

OTHER

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

IRELAND:

New legislation introduced later in 2018 could re-start offshore wind development in Ireland. While fixed-bottom offshore is expected to dominate early development, floating wind is also of interest. The Galway Bay test site has been extended to include floating wind technologies and a partnership between Gaelectric and IDEOL had previously targeted an initial 30 MW pilot farm to be followed by multi-GW commercial projects, prior to Gaelectric entering liquidation.

NORWAY:

Despite pioneering the world's first full-scale prototype demonstration in 2009, Norway has not extended its offshore wind fleet due to an abundance of cheap hydroelectric power. However, several potential demonstration sites are being explored in order to enable domestic suppliers to showcase the considerable industrial expertise and capabilities that exist in Norwegian firms. Funding for such demonstration projects remains a gap. Alternatively, single unit installations are a likely possibility in providing power to supporting enhanced oil recovery in Norwegian oil fields. Large-scale deployment is likely to be contingent on an expansion of electricity export to an integrated European market.

SPAIN:

Having been a leading market for onshore wind generation, with over 23 GW 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 25 MW FLOCAN 5 pilot project led by ACS Cobra, which would consist of 3-5 concrete semi-sub/spar hybrid devices supporting 5-8 MW turbines. However, considerable delays and limited development activity has created uncertainty that the project will be realised. 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 20 MW 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.

AEGEAN SEA (TURKEY & 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 32 GW of offshore wind potential lies in deeper waters better suited to floating technology. This potential also extends into other Aegean countries, including Greece, where Seawind and Olav Olsen had been earmarked for pilot demonstration projects under the Clean Energy for EU Islands Initiative.

CHINA:

China is set to become the largest offshore wind market within the next decade, predominantly using conventional fixed foundations due to an abundance of shallow water conditions. However, floating wind is attracting interest, particularly in Guangdong, where state utility China Guangdong Nuclear Power Group (CGN) are looking to develop up to 3 GW of floating wind power. CGN have also invested in Eolfi's 24 MW pilot farm in Groix, France.

SOUTH KOREA:

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. Dutch company GustoMSC have secured partnerships with Halla Wind Energy and Korean Maritime Consultants to design floating foundations for the 100 MW Dongbu wind project at Jeju Island in South Korea. Similarly, Hexicon has formed a joint venture with Coens Co to develop projects in the Korean market. However, government support for commercial projects remains uncertain.

1.2.2 Policy needs for the floating wind industry

Despite the potential that exists for floating offshore wind power in the markets identified, this will only be realised if supportive policy and regulatory frameworks are introduced to bridge the gap from current pilot projects to large scale commercial developments. While policy and regulatory needs are country-specific and therefore vary by market, the following are considered key requirements to unlock commercial projects and accelerate the development of floating wind power:

- MARKET VISIBILITY: The industry will need a **pipeline of commercial projects** in order to attract investment and reach the volumes of scale necessary to bring down costs. Governments can provide visibility through target setting; site identification, leasing and tendering; and the introduction of suitable support mechanisms. Given that typical development timelines for commercial projects can span 6-8 years, site identification and acquisition must begin imminently if large-scale floating wind farms are to be commissioned by 2025. Confidence of market scale is also key to enabling the supply chain to invest in new products and facilities for the sector.

- SUPPORT MECHANISMS: Floating offshore wind will require appropriate **financial support in order to bridge the gap between current pilot projects and large-scale commercial developments**. Commercial projects will principally require stable revenue support, but additional mechanisms such as low-interest loans, guarantees, and public-private partnerships can also improve project bankability. It should be noted that enhanced support should only be a temporary measure before fully commercial projects can compete with other more mature energy technologies. Ring-fenced competition can also facilitate cost reduction and control government spending in the near-term, provided suitable safeguards and penalties are in place to detract speculative bids.

- PROJECT DE-RISKING: Minimising risk for investors will be key to reducing capital costs and ensuring that prospective commercial projects are realised on time and on budget. Markets will benefit from a **transparent and robust site leasing process** and a **clear regulatory framework for project consenting**. Countries can also adopt **centralised development models** whereby the government takes on the responsibility and cost of site surveying and permitting, as well as potentially the provision of offshore transmission assets. In some markets, securing long-term power purchase agreements will be critical to reducing investor risk.

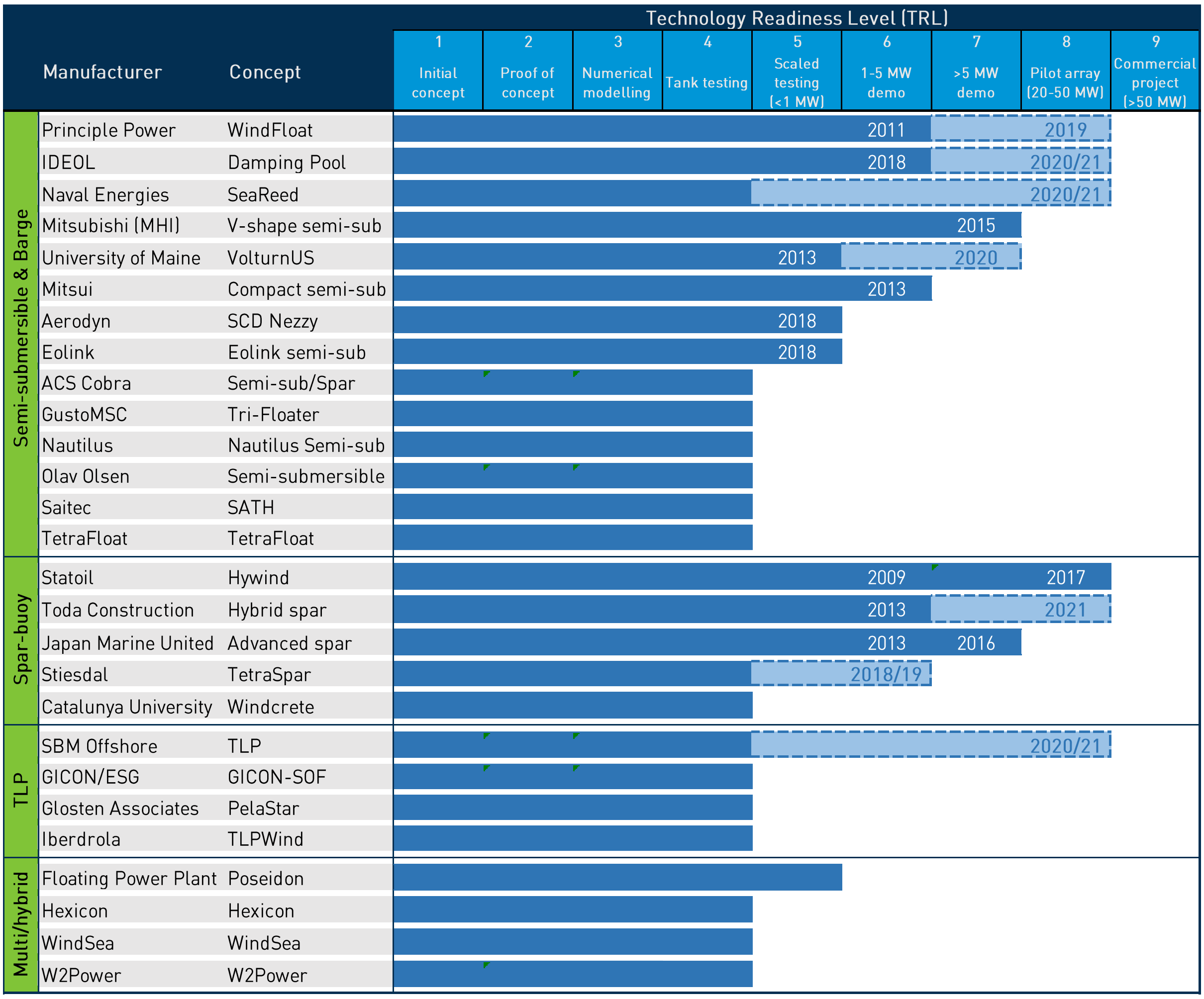
- TECHNOLOGY INNOVATION & SUPPLY CHAIN DEVELOPMENT: Technology innovation and the development of a robust and competitive supply chain have been integral to delivering cost reduction in fixed-bottom offshore wind. Floating wind power will require similar **targeted investment to de-risk technology challenges and catalyse innovation that can unlock cost reduction**. In addition to providing visibility of market scale, **investment in enabling infrastructure**, such as ports and manufacturing facilities, can improve supply chain competitiveness and maximise local capture of economic value.

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 4 includes a list of 27 concepts considered to be the most active and advanced. While a large number have successfully completed tank testing, the progression to full-scale demonstration has proved more elusive, largely given 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, it is believed that 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. The market consolidation anticipated will also manifest in commercial and industrial partnerships, as evident in two recent industry collaborations for Principle Power and IDEOL (Box 2).

Figure 4: 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/permitted, 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

Principle Power & Aker Solutions

In February 2018, Norwegian offshore oil and gas contractor Aker Solutions purchased a stake in floating wind concept developer Principle Power Inc. (PPI). An initial 5% stake is set to increase to 10% by the end of 2018, with option to increase further. It is expected that the capital injection will support the pursuit of commercial projects in several global markets.

PPI will also benefit from Aker Solutions' technical capabilities and global presence. Aker Solutions bring a wealth of knowledge and experience as a leading designer of semi-submersible platforms for the oil and gas sector, as well as experience in managing large and complex projects in harsh offshore environments. These capabilities mean that Aker Solutions could provide full engineering, procurement, construction, installation (EPCI) services to commercial projects, removing the added cost and risk of procuring services externally.

IDEOL & Kvaerner

IDEOL has secured a collaboration agreement with Norwegian oil and gas contractor Kvaerner. Similar to the PPI-Aker Solutions alliance, the partnership will unlock a more comprehensive one-stop-shop offering for EPCI services, combining IDEOL's experience and expertise of floating wind concept design with Kvaerner's experience in designing, constructing, and operating floating concrete structures for the oil and gas sector.

IDEOL has also recently secured a €15m investment from private equity firm Kerogen Capital and has entered into a memorandum of understanding with Acacia Renewables, a subsidiary of Macquarie Capital, to develop commercial-scale floating offshore wind projects in Japan from 2023.

1.4 Technology Challenges

1.4.1 Common technology challenges for large-scale commercial deployment

Despite its promise, floating wind technology is still nascent and has yet to be deployed at large-scale. The challenge for the industry is to reduce costs from today's expensive demonstrators to a commercial model where designs can be optimised and standardised and the industry can benefit from the economies of scale needed to drive costs down. A number of cost projections suggest that floating wind can reach cost parity with fixed-bottom during the 2020s, if deployed at scale. However, large-scale deployment of floating offshore wind will bring new technology challenges that will need to be overcome through technology innovation and de-risking from industry, academia, and the wider supply chain. An overview of the key challenges is highlighted in Figure 5.

1.4.2 Role of the Floating Wind Joint Industry Project (JIP)

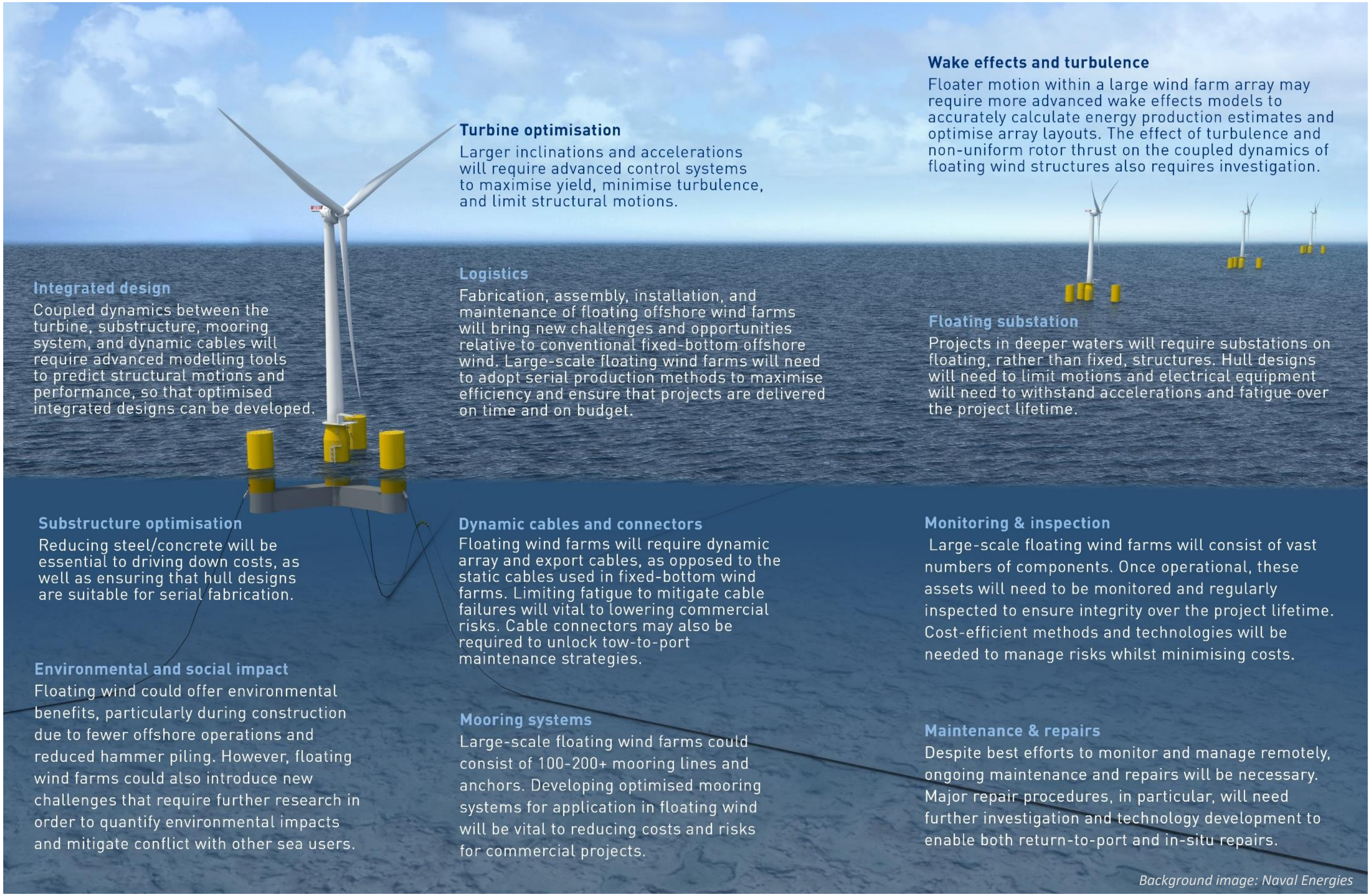
Many of the challenges identified are common to multiple floating wind concepts. Common challenges like these are often best addressed through collaborative initiatives in which the costs, risks, and benefits of research and development (R&D) can be shared between multiple parties. Collaboration can unlock public and private investment to undertake R&D that may otherwise not be possible for individual organisations, as well as help to stimulate activity in the supply chain.

This approach is central to the Floating Wind Joint Industry Project (JIP), by pooling funds and fostering knowledge sharing that can accelerate the development of floating wind technology. Managed by the Carbon Trust, the JIP is funded by the Scottish Government and twelve leading international offshore wind developers with a strategic interest in the emerging floating offshore wind sector. The following chapters present key findings from three studies delivered in 2017, each focussing on novel technology challenges for the industry:

- **Electrical Systems (Chapter 2):** Assessing the unique and novel electrical system challenges for commercial-scale floating wind farms
- **Mooring Systems (Chapter 3):** Evaluating challenges and opportunities for optimisation in mooring and anchoring systems
- **Infrastructure & Logistics (Chapter 4):** Infrastructure requirements and logistical challenges for the construction and maintenance of floating wind farms

It should be noted that the challenges identified are not insurmountable, but will require dedicated research and development activities and innovation from the supply chain. This report aims to make the challenges faced more transparent to enable suppliers and wider industry to engage and develop the necessary solutions to de-risk the technology and accelerate cost reduction.

Figure 5: Technology challenges in large scale floating wind farm



2. Key Findings: Electrical Systems

Study delivered by:

2.1 Study Overview

Floating wind deployments to date have largely consisted of single unit prototypes, connected directly to shore with a single low voltage electrical cable. However, as farm size increases and projects move in to deeper water further from shore the requirements and demands of the electrical infrastructure will increase, with a more complex configuration of inter-array cables, higher voltage export cables, deep-water (>50 metres depth) substations, and cable connectors. This study, delivered by Petrofac and TNEI, was commissioned to assess and evaluate the key technical challenges related to deep-water substations, dynamic cables, cable connectors, and wind farm circuitry and burial.

2.2 Key Findings

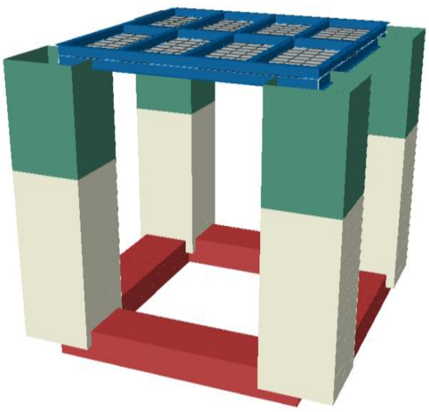
SUBSTATION

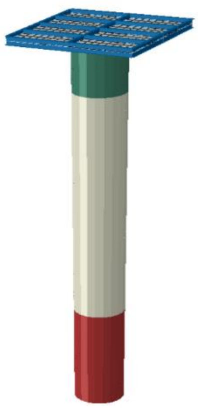
01 Commercial scale floating substations are feasible, with hulls capable of providing relatively low extreme motions and adequate fatigue life

Concept design and analysis of a 500 MW floating substation identified that there are no major barriers to feasibility. Existing technology is largely considered to be suitable, with only relatively minor modifications required.

Three concept hull designs were developed, reflecting three of the dominant floating structure types – semi-submersible, spar-buoy, and tension-leg platform (Figure 6). Hulls for the semi-submersible and TLP were identical, in order to facilitate port-side assembly and wet tow to site. Semi-submersible and spar adopted a four point catenary mooring system while the TLP adopted a steel wire tension-leg configuration.

Figure 6: Concept substation hull designs for semi-submersible and TLP (left) and spar (right)





Motion characteristics were modelled in four sites, reflecting environmental conditions representative of key markets for floating wind power.

	Water depth (m)	Wave height (Hs)	Wave period (Tp)
UK (North Sea)	100	12.1	10.7
France (Mediterranean)	100	7.5	7.4
Japan	250	13.9	9.6
United States (California)	800	10.7	8.4

Hydrodynamic analysis produced response amplitude operators (RAOs) for all structures, in order to understand the response and motion of the structures in different environmental conditions. These motions were used as the basis for evaluating the operating envelopes and sensitivity of the electrical equipment supported (see #2), as well as the cable fatigue analysis (see #3).

Motions for all three structures were seen to give suitable fatigue lives for both the hull and cables (provided cable configuration is optimised accordingly; see #3). Maximum accelerations were also seen to be relatively small. However, wave slam was identified as a potential issue, which can result in increased accelerations and excitations. Cylindrical hull forms and stiffer structures were seen to resist wave slam more than square hull designs with large surface areas.

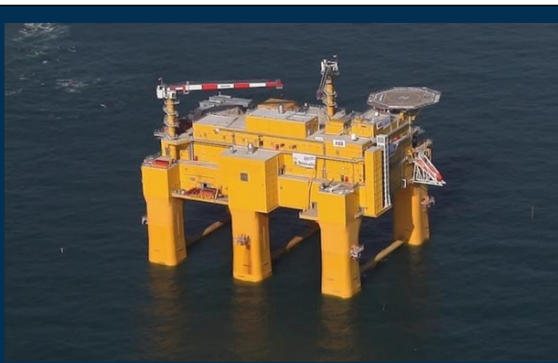
02 Existing electrical equipment should be feasible with only minor modifications, but testing and qualification is a key requirement and current gap

Electrical equipment will need to resist the motions of the hull, both in terms of extreme motions and fatigue over the lifetime of the project. Although the conceptual hull designs in this study were able to give relatively small maximum accelerations, currently, electrical equipment for substations is not designed for such conditions.

However, engagement with electrical equipment suppliers revealed that acceleration limits for such equipment is generally within the bounds of motion expected on floating substations. Namely, electrical equipment must be designed to withstand accelerations during assembly and transportation (including road, rail, and offshore wet tow). Indeed, there are examples of equipment being exposed to accelerations exceeding these limits without suffering a detrimental impact to performance.

Box 3: Case study - DolWin Beta

The DolWin Beta substation, a 900 MW DC transformer, was transited on a floating semi-submersible vessel, before being installed on a fixed jacket foundation. Equipment would have been designed to withstand motions on the floating structure during transit to site.



An assessment of similar equipment deployed in seismically active regions also identified equipment with acceleration limits suitable for floating structures, partly driven by seismic qualification standards to ensure that transformers in seismic areas continue to operate during seismic events.

Nevertheless, in addition to resisting loads for low frequency, high acceleration events, equipment will also need to withstand a larger number of fatigue cycles over its lifetime. Limited information was obtained on this impact within the scope of this study, but represents an area for further research.

Electrical equipment for application on floating structures requires further testing, development, and qualification. Namely, critical components of the transformer include the tank, internal supports, and accessories such as Buchholz relays and bushings. Bushings, in particular, represent a potential weak link and require further development and qualify cation to ensure adequate performance over the project lifetime.

Box 4: Case study - Fukushima Kizuna

The transformer for the world's first floating substation at Fukushima (pictured: 50te, 25 MVA transformer) was tested on a tilt table and the 66kV switchgear was tested on a vibrating table. Testing and qualification of higher capacity equipment will be needed for commercial floating wind farms.

DYNAMIC CABLES

03 Adequate fatigue lives can be achieved by optimising cable configurations, particularly through the use of bend stiffeners

Analysis of cable fatigue was undertaken for all substation hull types and site conditions reference above. Both lazy wave and catenary configurations were assessed.

The steel armour of the cables were seen to be the most critical component for fatigue, dominated by bending. As such, fatigue was found to be mostly concentrated in the upper sections of the cable, near to the floater hang-off, where maximum bending is most common. In some instances, fatigue was also pronounced at the touchdown point at the seabed.

While considered a key challenge, it is believed that adequate fatigue lives can be achieved by optimising cable configurations. Cable configurations must be optimised on a project-by-project basis, accounting for the cable properties, configuration (e.g. lazy wave, S-wave, catenary), structural motions of the floater, water depth, and environmental conditions (including wave loading and marine growth – see #4).

Optimisation is supported by the use of auxiliary components such as bend stiffeners and buoyancy modules. In particular, given the dominance of fatigue bending near the floater, an increase in stiffness using bend stiffeners was seen to improve fatigue life significantly. There is scope to develop larger and stiffer bend stiffeners than currently available to further improve fatigue lives (see #6).

04 Marine growth (biofouling) can have a material impact on dynamic cable configurations

Once installed, dynamic cables are susceptible to biofouling over the lifetime of the project. The addition of marine growth can have a material impact on the cable configuration, adding mass that alters the buoyancy of the cables and shifts the distribution of fatigue loads. The extent of marine growth must therefore be carefully considered and factored into cable design, such that the configuration can limit fatigue loads throughout the project lifetime, as marine growth increases over time. It should be noted that marine growth is expected to be most prevalent near the surface of the ocean, where the water is oxygenated and warmer.

05 High voltage dynamic cables for export purposes are a current and significant technology gap

Medium voltage dynamic cables for inter-array purposes have been developed by several suppliers. Due to the nature of cable construction, "wet" cable designs are generally employed for 22-66kV dynamic cables. Although there is limited track record with dynamic cables at this voltage, these are considered to be available and only a small step from the market.

However, a potentially significant gap exists in the availability of high voltage dynamic cables for export purposes, which represents both a technical and commercial risk for large-scale floating wind farms. Because of the higher voltage of 130-250kV cables, these need to be "dry" designs and the larger cross-sectional area creates challenges for maintaining a radial water barrier whilst limiting fatigue.

The traditional water barrier for a dry design is a lead sheath, which has poor fatigue life properties that make it unsuitable for a dynamic design. As such, alternative approaches to cable design may be required for dynamic export cables. For example, the only known example of a dynamic cable exceeding 120kV used a corrugated copper sheath design.

The development and qualification of high voltage dynamic cables for export purposes is considered a key priority for the sector.

06 Larger and more rigid bend stiffeners than current standard may be needed to improve cable fatigue life

In addition to the cable itself, there are also gaps in the supporting components needed to optimise the configuration of high voltage dynamic cables. Namely, the size of bend stiffeners required is at the upper end of what is currently available and may exceed the limit of available polyurethane designs, particularly at the higher stiffness that may be required in order to limit cable fatigue (as highlighted in #3). It is also considered that manufacturability could be a challenge for this larger size of bend stiffener and further development is required by both suppliers and scientific research bodies.

07 Mid-depth cable configurations are feasible for deep-water sites, but further investigation of cable fatigue is needed

Some key markets for floating offshore wind power, such as California and Hawaii, have sites with water depths up to ~800 metres. In such locations, running array cables to the seabed could increase costs due to the additional length of cabling required. An alternative mid-depth configuration, in which buoyancy modules are used to create a mid-water arch, was investigated and considered to be feasible, based on previous track record in the oil and gas industry. However, further analysis of cable fatigue in such configurations is required, particularly at higher voltages than commonly used in oil and gas.

CABLE CONNECTORS

08 Cable connectors are readily available and viable, but the feasibility and logistics of out-of-service arrangements require further investigation

Dry-mate cable connectors suitable for medium voltage inter-array cables have been developed by a handful of suppliers and are considered market-ready up to 72.5kV. Such connectors can enable floating wind turbines to be disconnected and returned to shore for maintenance activities, but further investigation is needed to validate the feasibility of this approach in practice.

Connector performance and reliability will need to be maintained over the full project lifetime (up to 25-30 years), including an ability to remain operable despite marine growth, corrosion, and splash zone fatigue. Demonstrating this capability will be important for suppliers of such equipment.

The need to maintain electrical connection and minimise loss of power production also requires consideration of the out-of-service arrangement when a turbine unit is removed from the field. Possible options include:

1. **Spool length of cable** – cable with two female connectors replaces the turbine unit, with the cable laid to rest on the seabed
2. **Surrogate turbine structure** – small temporary structure to which the turbine moorings and connectors could be attached
3. **Electrical buoy** – small buoy permanently on station with cables terminated inside. Separate connection to the turbine structure enables the turbine to be disconnected without disrupting the primary electrical connection

09 The business case for connectors is driven by the wind farm O&M strategy and assumption on the number of major repair procedures during the operational lifetime

Dry-mate cable connectors are more expensive than standard cable terminations. However, the increased up-front capital expenditure could offer a cost benefit if it can unlock a lower cost operations and maintenance (O&M) strategy for floating wind turbines by enabling units to be disconnected and towed to port for major repair procedures.

The cost benefit is highly sensitive to the number of assumed disconnect operations expected over the lifetime to undertake major turbine repairs. If only very few major repairs are assumed, a standard cable termination could be considered more cost effective. Use of a connector, rather than a continuous cable, also inherently increases the failure risk of the system. Standard terminations therefore have the advantage of eliminating capital cost and a point of failure from the system.

However, the ultimate cost benefit is intricately tied to the proposed O&M strategy for the wind farm. There are arguments to suggest that the added flexibility offered by the ability to disconnect turbines for port-side maintenance could provide a benefit to wind farm operators by limiting exposure to heavy lift vessel charter rates. See key findings from the Infrastructure & Logistics study for more.

CIRCUITRY & BURIAL

10 No variance is expected to conventional circuitry and burial arrangements in fixed-bottom offshore wind

There are no fundamental differences between the circuitry requirements for floating offshore wind compared to those for fixed-bottom offshore wind. The desired circuitry arrangement will be determined on a project-specific basis in order to maximise transmission efficiency in the wind farm. It should be noted that for plug-and-play maintenance strategies, a ring configuration will be advantageious in minimising downtime from other turbines in the string when turbines are removed for maintenance.

Burial requirements will depend on the level of expected third party interaction (e.g. fishing/shipping activity), seabed type, and cost benefit analysis determined by the project developer. It should be noted that very deep locations may adopt mid-water cable configurations, which would mitigate the need for burial of inter-array cables (see #7).

2.3 Innovation Needs

Based on the key findings above, the following high priority innovation needs have been extracted. It is considered that these innovation needs can be met through a combination of supply chain innovation, joint industry initiatives, and applied research from academic research institutions.

01 Qualification of high voltage dynamic cables for export purposes

There is a need to develop, test, and qualify high voltage dynamic cable to export power from the floating substation back to shore. As with electrical substation equipment, this requires a two-step process:

A: Standard development

- Joint industry: Initiatives involving standards bodies and industry working groups to develop suitable standards and guidelines for the testing and qualification of dynamic power cables.

  Note: A recently-formed Cigre working group is actively developing standards for dynamic power cable qualification.

B: Development, testing, and qualification of high voltage dynamic power cables

- Suppliers and technology developers: Opportunity for equipment suppliers to develop suitable products for the industry. Early movers stand to benefit from securing orders for the first commercial projects.
- Joint industry: It is possible that manufacturers will be reluctant to develop and qualify equipment without a commercial project, yet the lack of a qualified export cable represents a risk to projects and presents a timeline issue if no qualified cable can be made available within the development timeframe. Stimulating the qualification of such equipment may therefore require external intervention to accelerate development, possibly in the form of joint industry initiatives.

  Note: The Floating Wind JIP has recently kicked-off a project that aims to stimulate the development of high voltage dynamic power cables (see Chapter 5 on Phase II project for further information).
- Academic research: Opportunity for research bodies and academia to undertake further analysis and testing of power cables, including the development of advanced materials with improved fatigue properties.

02 Qualification of electrical equipment for large capacity floating substations

There is a need to test and qualify electrical equipment for floating substations in commercial projects. This requires a two-step process:

A: Standard development

- **Joint industry:** Initiatives involving standards bodies and industry working groups to develop suitable standards and guidelines for the testing and qualification of electrical equipment.

B: Testing and qualification of electrical equipment

- **Suppliers and technology developers:** Opportunity for equipment suppliers to develop suitable products for the industry. Early movers stand to benefit from securing orders for the first commercial projects.

- **Joint industry:** It is possible that manufacturers will not qualify equipment without a commercial project, yet the lack of qualified equipment represents a risk to projects and presents a timeline issue if no qualified equipment can be made available within the development timeframe. Stimulating the qualification of such equipment may therefore require external intervention to accelerate development, possibly in the form of joint industry initiatives.

- **Academic research:** Opportunity for research bodies and academia to undertake further analysis and testing of equipment, including the development of advanced technologies, materials, and components.

03 Larger and more rigid bend stiffeners

There is a need to develop larger and more rigid bend stiffeners to reduce fatigue in dynamic power cables, particularly those at higher voltages than commonly used in the oil and gas industry. Developing new products may also require novel manufacturing approaches.

- **Suppliers and technology developers:** Opportunity for suppliers and manufacturers to develop larger and stiffer bend stiffeners.

- **Academic research:** Opportunity for research bodies and academia to develop advanced materials and manufacturing techniques for large polyurethane components.

04 Out-of-service arrangements for turbine disconnect procedures

There is a need to develop cost-effective methods and technologies for 'plug-and-play' functionality of floating offshore wind turbines.

- **Suppliers and technology developers:** Suppliers of cable connectors and technology developers advocating a plug-and-play operations and maintenance strategy should demonstrate the viability of such an approach, including the out-of-service arrangements when a turbine is removed from the field. This should include demonstrating the performance of the connector technology over the full project lifetime.

- **Joint industry:** As a challenge common to several floating wind concepts, collaborative efforts may be effective in further investigating barriers and developing solutions for the industry.

05 Other

Below is a longer list of areas that require further development to reduce technology risk and costs for commercial floating wind farms:

- Development of optimised, low cost hull forms for floating substations
- Investigation of multiple modular substations (offshore transformer module (OTM) approach) on floating structures
- Investigation of feasibility of subsea substations
- Fatigue analysis of electrical equipment on a floating substation
- Analysis of dynamic loading and response of cables in a mid-depth configuration
- Development of fatigue-resistant radial water barrier for dynamic cables
- Development of high strength armour wires for increased fatigue resistance
- Investigation of novel cable installation methods
- Development of flexible cable attachment to reduce cable bending fatigue loads
- Investigation of autonomous marine growth cleaning systems

3. Key Findings: Mooring Systems

Study delivered by:

3.1 Study Overview

The mooring and anchoring system is a critical component of floating wind devices that represents a unique differentiator relative to conventional fixed offshore wind foundations. Despite considerable track record and experience from the oil and gas sector, the mooring and anchoring systems used for floating wind turbines have yet to be fully optimised. A number of different mooring and anchoring solutions are available to technology developers, but there is a limited level of technology convergence, with a wide variety of systems being implemented. Restrictive industry standards are also thought to be contributing to overly conservative and more expensive mooring and anchoring systems. This study, delivered by Rambøll, was commissioned to undertake a review of current state of the art solutions available, identify more innovative solutions and opportunities for optimisation, and assess the barriers to implementation.

3.2 Key Findings

GENERAL

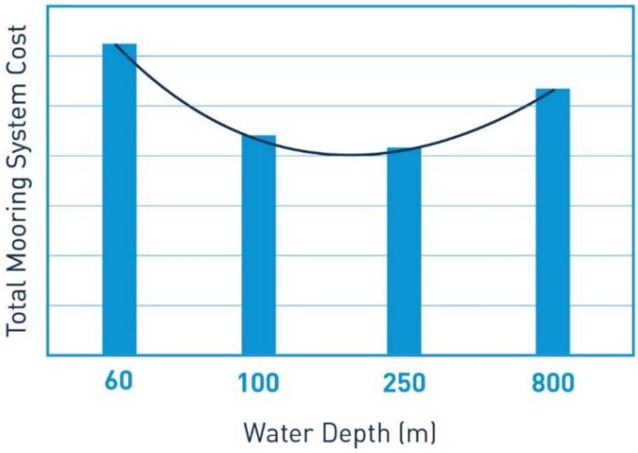
01 A lack of understanding and focus exists regarding the relevance of mooring systems for floating wind turbines, both technically and economically

Current mooring system designs deployed in early demonstration projects are based on traditional oil & gas steel chain designs, which are typically high cost solutions. In general, it is seen that the full mooring system costs – including design, installation, and operations and maintenance – are often underestimated by floating wind technology developers.

While considerable learnings can be gained from the offshore oil and gas industry, the coupled behaviour of floating wind turbines and large volume of units deployed means that alternative solutions may be required. It is believed that there is considerable scope for cost reduction through improved understanding of fatigue mechanisms (see #3), alternative mooring line materials (see #5), and improved installation methods (see #6), among others.

02 Shallow water (<100m) is more challenging than deep water for mooring and tendon design

Floating offshore wind turbines are expected to be technically viable from ~40 metres water depth and upwards, particularly beyond the 50-60 metre limit anticipated for conventional fixed foundations. However, the mechanical properties and dynamic loading on the mooring system mean that these shallow water sites (<100m) can increase fatigue loads, resulting in larger and more expensive mooring systems, particularly in conventional steel chain catenary systems. Furthermore, for catenary systems, the general physical principles



N.B. Chart depicts costs for a conventinal steel chain catenary mooring system (non-optimised). Note that the x-axis is non-linear.

of achieving the required restoring forces in shallow water lead to increased footprints and more expensive systems.

The optimal depth range for catenary systems is considered between 100-250 metres, in which favourable load characteristics and mooring line dimensions lead to lowest costs. Beyond 250 metres, the added length of mooring lines adds to cost. However, even mooring systems up to 800 metre depth remain cheaper than shallow 60m depths when conventional steel chain catenary systems are used. It should be noted that taut or semi-taut synthetic mooring systems were seen to be lower cost and considerably less sensitive to water depth than catenary steel chains, but still face challenges in shallower depths (see #5).

For TLPs, tendon costs increase more linearly with water depth as tendon length increases. Synthetic HMPE ropes were seen to be lower cost than steel wires, most notably in deeper water depths.

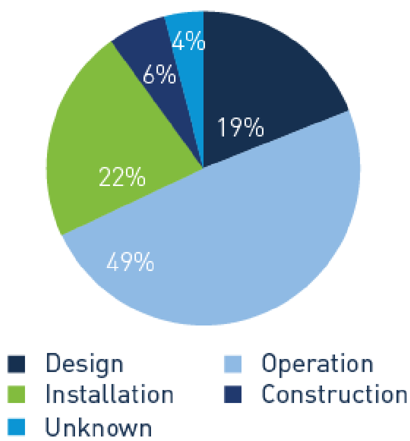
Environmental conditions also have a sizeable impact on mooring system design and costs, particularly the sensitivity to wave height. Harsh environments will drive cost up, particularly when combined with shallow water depths.

FATIGUE & RELIABILITY

03 Oil and gas statistics suggest that mooring line failures are likely to occur in floating wind farms, but many failure causes are avoidable with appropriate planning

Analysis statistics from oil and gas suggests that mooring line failures are not just possible, but are quite likely to occur in large scale floating wind farms. Indeed, the failure rates observed are above target levels prescribed by industry standards. This suggests that floating wind units will need to factor in acceptable levels of redundancy or utilise advanced reliable designs, accounting for the floating-wind-specific load characteristics, to mitigate the probability of failure. Contingency plans will also be needed to manage the risk of such events.

Despite these statistics, it was identified that failures in oil and gas are mostly caused by avoidable problems and errors, for example due to installation damage, manufacturing defects, wear, abrasion, design errors, corrosion, and synthetic material degradation. Indeed, over half of failures have occurred outside of operation. Implementation of mooring & risk management plans (e.g. Mooring Integrity Management and Mooring Risk Management Plans) could also reduce failure risk, if adapted from oil and gas and adjusted for floating wind application.



04 Fatigue of moorings is not well understood for floating offshore wind – there is scope for further research to improve design standards and methodologies

Despite considerable track record of deployment from offshore oil and gas, the application of moorings in floating wind power is a fairly recent development that introduces new challenges for design and reliability. Namely, the coupled behaviour of floating wind turbines introduces new fatigue load characteristics (e.g. additional fatigue load cycles from transferred wind turbine loads or increased out-of-plane-bending by increased yaw motions) that can have a material impact on the performance and reliability of the mooring system. These load characteristics are currently not sufficiently covered by design standards, including those specific to floating wind.

In addition to high frequency fatigue loads, it was found that snap and shock loads in extreme conditions can have a significant influence on fatigue life. Improving the accuracy of forecasting extreme environmental conditions and the accuracy of the modelling tools to assess their influence could support greater design optimisation. As these extreme loads typically govern the design of the floating wind system, either over or under-estimating them can have a material impact on the cost and reliability of the system.

MOORING LINE MATERIALS

05 Synthetic mooring lines have the potential to reduce costs, but need further development and qualification for long-term application in floating wind

Synthetic mooring lines have a long-term track record in oil and gas, particularly in deep and ultra-deep water, but also utilised for shallow depths. Synthetic mooring lines are highly attractive for application in floating offshore wind, with potential to deliver significant cost savings compared to conventional steel and wire moorings due to lower mass, high fatigue performance, smaller footprint, shorter lines, lower vessel requirements during installation, and lower structural mass for TLPs. A range of synthetic materials are available for different configurations and site conditions, but the most promising applications include:

- Shallow locations and semi-sub/spar/barge: Polyester and Nylon
- Deep water locations and TLP: HMPE, Aramid, and other stiff materials

All synthetic mooring systems are most effective when deployed in taut and semi-taut configurations. Polyester ropes have an oil and gas long track record and proven suitability in offshore environments for more than 30 years, thus no issues are expected for application in floating offshore wind. HMPE ropes have been deployed in ultra deep oil and gas applications but are less common in long-term shallow and intermediate depth mooring applications. High stiffness makes them attractive for floating wind TLP designs.

Nylon, which due to its high elasticity is attractive for shallow water floating wind mooring systems, has traditionally only been deployed for short duration in oil and gas due to concerns over fatigue. However, recent advances indicate that new nylon mooring line constructions may provide adequate fatigue performance over longer lifetimes suitable for floating wind farms.

Nevertheless, there are challenges and limitations with synthetic mooring systems that will need to be considered and addressed for commercial deployment. As with conventional mooring configurations, fatigue in shallow water depths could lead to problems or result in higher cost systems. More specific to synthetic lines is the added complexity and cost of installation, due to the need for pre-stretching for some materials and the sensitivity of the synthetic lines to damage during handling and load-out. Quality control and inspection during operation could also bring challenges due to the prevalence of protecting jackets that preclude visual inspections. However, if these challenges can be overcome, there are strong indications that synthetic taut or semi-taut mooring systems could enable considerable cost savings.

INSTALLATION, TRANSPORT, AND LOGISTICS

06 Mooring installation is a major cost contributor. Closer collaboration is needed between mooring designers, substructure developers, and installation contractors

Mooring system installation is a technically well-known procedure from oil and gas with several established and experienced contractors active in the market. However, mooring system installation is an important cost contributor, particularly given the large volume of mooring lines and anchors that must be installed in a floating wind farm, often in challenging offshore environments. Factors influencing the installation of the mooring system include:

- **Top connectors:** Ease of connection, including required bollard pull, connection time, and met-ocean limitations
- **Anchors:** Installation time; placement precision; piling requirements
- **Mooring line material:** Steel chain versus synthetic rope; complexity of multiple materials and components; tensioning requirements
- **Mooring line dimensions:** Chain/tendon diameter, mass, and length influencing handling and vessel requirements
- **Floater type and design:** Platform stability; mooring connection point
- **Site location and environmental conditions:** Distance from port; met-ocean conditions
- **Vessel availability:** Handling capacity; bollard pull; charter rate
- **Port facilities:** Onshore set-down area; load-out; proximity to site
- **Project size:** Volume of mooring lines and anchors; installation timeline

Given the complexity of installation, it is considered that early focus in projects on mooring system design in combination with installation methods will be key for delivering cost reduction.

It is noted that installation cost and complexity is a greater contributor and challenge for semi-taut and tension leg mooring configurations, though this is generally countered by lower procurement costs.

07 Top connectors and anchors have a major impact on installation – simple, low cost, but effective solutions are needed

Hook-up is considered the most critical operation during installation, particularly for TLPs but also relevant for catenary mooring configurations. As such, the top connection can have major implications on the installation process, as well as disconnect procedures that might be considered during operation and maintenance. Current top connectors from oil and gas are typically large and costly solutions. There is scope to develop simpler, lower cost, but effective connectors that can facilitate rapid connection with minimal impact on the floater design and vessel requirements.

Anchor designs are fairly well established from oil and gas, but there is again scope for solutions that are optimised for application in floating offshore wind, particularly those that can facilitate rapid installation in challenging conditions. Anchors for challenging seabed conditions is also an area for development.

OPERATIONS & MAINTENANCE

08 Monitoring & inspection techniques from oil and gas are readily available, but expensive – there is considerable scope for more cost efficient approaches and technologies

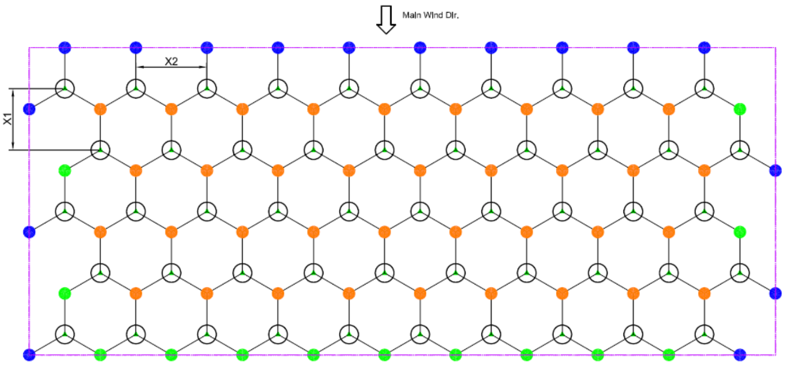
Most standards, adopted from oil and gas, require short inspection intervals for mooring lines. Given the large number of mooring lines and other assets to monitor and inspect across a floating wind farm (minimum 150 mooring lines in the 500 MW baseline wind farm for this study), there will be a need to develop appropriate risk-based approaches to monitoring and inspection regimes. This is likely to require a relaxation in standards and guidelines specific to floating wind.

Floating offshore wind farms will also require the development of more cost-efficient methods for monitoring and inspection. Although suitable technologies exist from oil and gas, these are typically high cost and may not be economical for large-scale floating wind farms. There is therefore a need to identify and develop technologies and sampling methods that can enable wind farm operators to cost effectively manage the assets in their wind farms. This includes software to streamline the post-processing and analytics of the vast quantities of data from sensors and inspection technologies.

ARRAY LAYOUTS

09 Anchor mutualisation offers potential benefits for cost reduction, but is challenging to implement in practice

Mooring layouts in large arrays are not considered a major challenge for the industry, with sufficient flexibility in layouts able to mitigate risks of mooring clashing, even with overlapping mooring lines.



Anchor mutualisation, whereby individual anchors are connected to more than one mooring line, could present opportunities for cost reduction, through reduced anchor and installation costs, as well as fewer geotechnical surveys and inspection requirements. However, the impact of these benefits is expected to be marginal in a large floating wind farm and may also be challenging to implement in practice. Drawbacks include:

- Strict requirements related to the position of anchors
- Less optimised mooring systems and array layouts due to distance constraints
- May be unfeasible for complex bathymetry of site, difficult seabed conditions, or complex existing seabed infrastructure (e.g. pipelines, UXO, shipwrecks, etc.)

SEISMIC LOADING

10 Soil liquefaction is a challenge, but can be mitigated through deeper penetration of anchor piles

A number of attractive markets for floating wind technology, such as Japan, Taiwan, and the US West Coast, are situated in seismically active locations that could impact the integrity of the mooring system. The primary challenge is related to soil liquefaction that could disrupt anchor holding capacity and result in a loss of station-keeping. However, this is not considered to be a major showstopper, provided appropriate design codes are adhered to. Namely, extending anchor penetration into deeper soil layers that will not be affected by liquefaction should provide sufficient holding capacity during seismic events. The additional anchor size and use of piled anchors could increase costs, particularly for TLP tendon designs, for which there are larger vertical forces.

STANDARDS

11 There is a need for bespoke mooring system standards for floating offshore wind

Current standards applied to floating offshore wind mooring designs are largely based on and directly reference existing standards from offshore oil and gas and fixed-bottom offshore wind. Although floating wind-specific standards and guidelines exist, they have not yet been sufficiently development to fully account for the novel characteristics of floating wind devices.

Some notable variances to oil and gas include different safety levels and requirements for load calculations (50yr loads instead of 100yr, dynamic coupled calculations required) and different mooring and TLP tendon requirements. However, there are also some notable gaps, including uncertainties in the standards that need to be solved in the future, including the application of TLP tendon ropes, the definition of redundancy, and requirements to submit a mooring integrity management (MIM) plan. Industry engagement suggests that further work is required in order to reach a consensus on appropriate redundancy, and safety levels for floating wind mooring standards, in order achieve an acceptable risk and cost trade-off.

LEARNING FROM DEMONSTRATORS & INFORMATION SHARING

12 Lessons learned from (full scale) demonstrator experience is very valuable and should be shared across industry

The building-up of long-term experience cannot be artificially accelerated. In this context it is very important that for the early projects of early commercial scale systems, an emphasis is put on monitoring of the mooring system behaviour and a detailed analysis and learning from the lessons accumulated in these early projects in order to understand better the key challenges.

3.3 Innovation Needs

Based on the key findings above, the following high priority innovation needs have been extracted. It is considered that these innovation needs can be met through a combination of supply chain innovation, joint industry initiatives, and applied research from academic research institutions.

01 Understanding of fatigue mechanisms in floating wind mooring systems

There is a need to develop an improved understanding of fatigue mechanisms for mooring systems in floating offshore wind application to improve design optimisation, reliability, and cost.

- **Suppliers and technology developers:** Interpreting and sharing information from early demonstration projects to foster learnings that can inform future mooring system designs.
- **Academic research:** Research studies, component testing, and development of advanced coupled analysis modelling tools to advance industry understanding of fatigue mechanisms and failure modes.
- **Joint industry:** Initiatives involving technology developers, suppliers, academia, standards bodies and industry working groups to develop suitable standards and guidelines for fatigue analysis of mooring systems in floating offshore wind.

02 Qualification of synthetic mooring line materials for floating offshore wind

There is a need to develop and qualify synthetic mooring line materials for long-term application in floating offshore wind farms. Research and development initiatives should assess the suitability of a variety of mooring line materials in taut and semi-taut configurations, including advanced nylon, polyester, HMPE, and aramid relevant to shallow, intermediate, and deep water application.

- **Suppliers and technology developers:** Internal R&D to develop suitable solutions and accelerate the route to market, including low cost installation methods and approaches to monitoring and inspection.
- **Academic research:** Research studies and component testing to develop novel mooring line materials with strong fatigue properties over long-term application.
- **Joint industry:** Initiatives involving suppliers, academia, standards bodies and industry working groups to develop suitable standards and guidelines for the qualification of the most promising synthetic mooring line materials.

03 Low cost installation methods and enabling technologies

There is a need to develop low cost installation methods for large-scale floating wind farms, which are expected to consist of hundreds of mooring lines and anchors. A key enabler will be the development of simple, low cost, but effective top connectors, as well as anchors with improved installability.

- **Suppliers and technology developers:** Internal R&D and product development to develop suitable solutions and accelerate the route to market. Cooperation between equipment suppliers, installers, and technology developers.
- **Academic research:** Research studies and component testing to develop innovative top connectors, including spin-out ventures.
- **Joint industry:** Initiatives involving suppliers, academia, equipment suppliers and technology developers.

04 Monitoring and inspection procedures and technologies

There is a need to develop cost effective monitoring and inspection procedures and technologies that can enable wind farm operators to manage asset integrity at low cost, without compromising risk exposure. This will include a combination of: (1) standard development, to adopt less conservative risk-based approaches to monitoring and inspection regimes; (2) technology development to support improved performance, reliability, and cost reduction (incl. robust and accurate sensor technologies, artificial intelligence, autonomous underwater vehicles); and (3) advanced post-processing, data management, and analytics tools (incl. machine learning, big data).

- **Suppliers and technology developers:** Internal R&D to develop innovative technology solutions and software for wind farm asset integrity.
- **Academic research:** Research studies to develop advanced monitoring and inspection technologies and management systems.
- **Joint industry:** Initiatives involving standards bodies and industry working groups to develop dedicated standards and guidelines for monitoring and inspection regimes in floating wind farms.

  Note: The Floating Wind JIP has recently kicked-off a project that aims to investigate monitoring and inspection requirements in floating offshore wind farms, including recommendations for standard development and technology innovation needs (see Chapter 5 on Phase II project for further information).

05 Other

Below is a longer list of areas that require further development to reduce technology risk and costs for commercial floating wind farms:

- General standard development to develop dedicated standards for the floating wind industry
- Greater focus on mooring system design early in the substructure design process, including closer engagement with installation contractors
- Anchor designs for challenging seabed conditions

- Large diameter mooring lines and high strength components for high loads and 10+ MW turbines
- Increased anchor handling vessel (AHV) carrying and installation capabilities for large diameter mooring lines and anchors
- Shallow/intermediate water depth mooring systems to unlock economically viable sites in 60-100m depth ranges
- Component standardisation to unlock economies of scale, including greater design consolidation in the industry
- Improved product quality assurance and quality control
- Advanced numerical simulation and load calculation tools
- High accuracy environmental load calculations
- Seismic impact analysis on TLP tendons and anchors
- Anchor mutualisation strategies
- Inter-array mooring configurations (lines connecting all individual turbines, with only a small number of mooring lines anchoring the wind farm to the seabed)
- Cross-industry data and information sharing

4. Key Findings: Infrastructure & Logistics

Study delivered by:

4.1 Study Overview

Deployment of floating offshore wind to date has primarily consisted of single unit prototype demonstrations, with the largest project consisting of five turbine units in a pre-commercial pilot installation. These small-scale deployments, typically using lower capacity turbines, impose minimal logistical constraints given the long time periods for construction and the ability to use readily available infrastructure, including dry docks.

However, future commercial floating wind farms will require tens to hundreds of units to be deployed, at larger turbine ratings and with larger associated structural dimensions. Construction and installation of all turbine units, moorings, and electrical cabling will need to be completed within a restrictive time period and within available weather windows.

Likewise, operation and maintenance of such a large fleet of assets in a commercial wind farm will require novel maintenance strategies, which may require disconnect and tow-to-port methods and/or complex floating-to-floating heavy lift operations.

This study, delivered by London Offshore Consultants (LOC) and WavEC, was commissioned to assess the requirements and procedures for the construction and maintenance of large scale floating wind farms, and highlight the key challenges envisaged for commercial deployment. This consisted of evaluating the phasing of operations in fabrication, assembly, installation and maintenance campaigns, including the infrastructural requirements to undertake these operations.

4.2 Key Findings

GENERAL

01 The construction and maintenance of floating wind farms has significant infrastructure and logistical challenges that are different from fixed offshore wind

Conventional fixed-bottom offshore wind power has established efficient and effective methods and procedures for the construction and maintenance of large-scale wind farms, including a number of complex operations undertaken offshore at the project site. Floating offshore wind presents the opportunity to shift a number of these operations to the port-side, bringing a number of significant benefits that include reduced construction risk, reduced weather downtime, reduced health and safety risk, and the use of lower cost infrastructure.

However, this approach in undertaking more operations at port will impose greater pressure on the onshore infrastructure required, particularly in relation to the available draft, crane capacity, onshore set-down area, and wet storage. There are also additional installation procedures that must be accounted for, such as the mooring and anchoring system and dynamic array and export cables. The key novel challenges for floating offshore wind farms include:

- Port infrastructure requirements (see #3 & #4)
- Serial substructure fabrication (see #5 & #6)
- Turbine assembly and integration – port-side and offshore (see #7)
- Challenging and weather-constrained wet tow operations (see #8)
- Feasibility of disconnect and tow-to-port maintenance strategies (see #9)
- Feasibility of floating-to-floating heavy lift operations (see #10)

02 Infrastructure and logistics will be a key factor in making floating wind technologies cost competitive, but requirements will vary by concept

It should be noted that the requirements, challenges, and limitations vary by floating wind concept, particularly the extent of port-side vs offshore operations. This, in turn, has implications for the construction and maintenance methods adopted, and the associated infrastructure requirements.

Table 4: Summary of construction methods for each of the main floating wind typologies

Key Features	Semi-sub	TLP	Spar
Substructure Fabrication	Multiple Site(s)	Multiple Site(s)	Multiple Site(s)
Substructure Assembly & Loadout	Quay + Trailer	Quay + Trailer	Quay + Trailer
Turbine Assembly & Integration			
Lower Tower Integration	Quay	Quay	Inshore/offshore
Turbine Assembly	Pre-assembled rotor	Pre-assembled rotor	Pre-assembled rotor
Turbine Integration	Quay/Inshore/Offshore	Offshore	Inshore/Offshore
Transit			
Substructure	Wet tow/On-deck	Wet tow/On-deck	Wet tow/On-deck
Substructure-Turbine Integrated	Wet tow/On-deck	Not Possible	Wet tow
Specific Operations	None	Tendon Tensioning	Upending
Mooring System	Pre-Installed	Pre or Post	Pre-Installed

Notes: *Subject to vary by project, particularly in relation to concept design, site location, environmental conditions, and available infrastructure. TLP based on designs lacking sufficient stability for towing operations. Inherently stable TLP designs will adopt methods more similar to semi-submersible concepts. Barge concepts assumed to follow same logistical approach to semi-submersibles.*

The construction of a 500 MW floating wind farm (50 x 10 MW units) can be summarised as follows:

1. Fabrication and assembly of substructures or its components in countries with low personnel cost, including Europe and Asia. Simultaneous transport of several units by semi-submersible barges or self-propelled vessels. Vessel transport to port or site for float-off. Possibility to integrate the lower part of the tower with the substructure.
2. One of three options for turbine integration and hook-up:
   A. Transport of multiple substructures to a local port for turbine integration, undertaken with a large crawler crane, followed by tow to site and connection to pre-assembled moorings *(most common for semi-subs)*

   B. Transport of substructures to a sheltered location for turbine integration, done with a jack-up (for semi-subs and TLPs) or a large crane vessel (for spars) and then tow to site and connection to moorings *(most common for spars)*

   C. Transport of multiple substructures to site, connection to pre-assembled moorings, followed by integration of the turbine and substructure using a large crane vessel *(most common for TLP)*
3. Connection of the cable array strings between the floating wind turbines.

PORT INFRASTRUCTURE

03 There are limited ports that can accommodate all requirements for the construction of large-scale floating wind farms

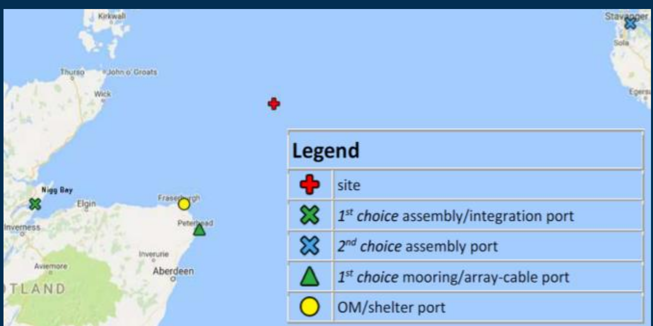
Despite its many advantages, undertaking more operations at the quay-side adds constraints to the port requirements. Namely, draught, quayside area, onshore set-down area, wet storage, and crane capacity all become important factors. Analysis of 96 European ports[1] revealed that very few ports in Europe are able to accommodate all of these requirements. In particular, draught and crane capacity are significant constraints for large floating wind structures.

These constraints are reduced if a large crawler crane can be brought to the port, but this is not without considerable logistical challenges (see #4). Draft also remains an important limitation, particularly when considering the evolution to larger turbines and substructures. Thus minimising draft becomes an important consideration for concept designers.

Despite the constraints and limitations observed, it is seen that several suitable ports are located in Scotland and Norway, in close proximity to a potential key market for floating wind in the Northern North Sea.

Box 5: Case study - Nigg Bay, Scotland

Located in the Cromarty Firth in the north of Scotland, Nigg Bay is well placed to service floating wind offshore projects. Attributes suitable for large scale serial production include: a large on-shore area for component set-down and serial production lines; a large quay-side with sufficient draft for large structures; a large dry dock for wet storage of assembled units; and close proximity to other nearby ports that can handle parallel operations. For example, analysis of a hypothetical North Sea project identified Invergordon for turbine integration and Peterhead for mooring and cable installation.



While Nigg can potentially accommodate two parallel serial production lines to ensure timely delivery of assembled substructures, North Sea projects could also be spread production over two yards, with Stavanger identified as a likely candidate.

[1] Based on the DTOcean ports database, which includes 96 ports and 195 terminals in 12 countries.

04 Re-purposing of low cost jack-up vessels could alleviate onshore crane capacity constraints

Installed craning capacity in most ports is not sufficient for the height and weight of lifts required to assemble large next generation turbines (10+ MW). As such, very large crawler cranes will need to be hired during construction and are unlikely to be in place for maintenance during wind farm operation. Given that only a small handful of suitable cranes exist globally at present, importing such crawler cranes will require complex logistical operations and long lead-times, including transportation to site, assembly of the crane (using other secondary crawler cranes), importing and mobilising its ballast, and chartering for a full construction season. The time and cost of mobilisation becomes even more significant for major repair operations.

An alternative solution could be to re-purpose jack-up vessels at the quay-side. Jacking the vessel deck above quay-side elevation would gain the hook-height required, enabling its existing crane to be used. This would present a potential market opportunity for current vessels in the fixed-bottom industry which may soon be redundant for future wind farms using larger turbines. These jack-up vessels are likely to be mobilised quicker and available at lower charter rates, given the expected dominance of larger next generation vessels within the next decade (first commercial wind farms expected by ~2025).

SUBSTRUCTURE FABRICATION, ASSEMBLY, & LOAD-OUT

05 Substructure fabrication represents the critical path in construction logistics - substructure design and port infrastructure must be suitable for serial production methods

Analysis of the ability to construct and install 50 units in a single summer campaign identified substructure assembly as the key bottleneck and critical path. Delivery of 50 units in 200 days necessitates a fully assembled substructure to be produced every 4 days. Given expectations of ~7-15 days per substructure, continuous serial production is required. This would involve continuous production of at least 4 substructures at a time at different stations in the production line. Establishing two parallel assembly lines can reduce throughput time to 2.5 days.

Meeting such demanding construction schedules requires floating wind substructure designs to be compatible with serial fabrication methods. There is also a need for port infrastructure and construction yards to be able to facilitate production lines of multiple units. Where timely delivery from a single facility is not possible, substructure fabrication may be spread across two or more facilities to ensure that delivery timelines are not compromised (see Nigg Bay case study).

06 Current methods for dry dock substructure assembly are unlikely to be economically viable in large floating wind farms - quay side serial fabrication methods will be required

Although dry docks are a feasible option for substructure fabrication and assembly, there are severe limitations on the number of dry docks worldwide that are compatible with large substructures, particularly in draught and width. Using a dry dock also limits the productivity gains of mass production, since the units must be assembled simultaneously. An alternative method, assembly at dockside on a submersible barge, is feasible, since individual components fall within the lifting capacities of dock cranes, but this approach is again less amenable with serial production methods.

The most practical and economical approach would be to assemble structures on the quay-side, with load-out by trailer. At a quay it is possible to develop a serial assembly line (or multiple lines) that optimises the throughput time, with several units constructed in parallel. The use of trailer systems also mitigates the need for heavy lifts and associated crane capacity requirements.

Nevertheless, very large dry docks are still likely to be valuable assets during construction when utilised for wet storage of completed structures (see #3 and Nigg Bay case study). Wet storing structures provides a production buffer, particularly when weather downtime prevents towing to site.

TURBINE ASSEMBLY & INTEGRATION

07 Turbine assembly and integration is a key challenge and cost driver

Turbine assembly and integration will vary by floating wind concept:

Typology	Preferred location	Comments
Semi-submersible	Port-side	Shallower draught and greater stability favours integration of the turbine to the foundation at the quayside. Integration in a sheltered location would be required if the water depth is limited at the quayside.
Spar	Offshore (sheltered area)	Deep draught precludes the possibility of WTG integration at quayside. Integration can take place at an inshore deep-water location or at the offshore site subject to weather.
TLP	Port-side / Offshore (at site)	Variable by design – inherently stable designs will favour port-side integration, but stability requirements for some designs may dictate that integration is done offshore at the project site, once the substructure has been stabilised with mooring tendons.

Each method will bring different challenges. For port-side integration, even though there are cranes that can perform this operation from the dock, they are not available at most ports and only a small handful exist globally. Width and draught requirements at the port and in the dry dock may also constrain the feasibility of the operation. However, the ability to lift between a fixed structure (the crawler crane or jack-up) and an almost fixed structure (the substructure afloat at the sheltered quay) is favourable. Furthermore, weather downtime would be minimal and the re-purposing of low cost jack-ups at quay-side or in sheltered areas could alleviate crane capacity constraints (see #4).

Offshore integration is a less established and more challenging lifting procedure, given the added dynamic motions of a floating-to-fixed (TLP at site) or floating-to-floating (spar and semi-submersible in sheltered area or at site) heavy lift operation, particularly given added met-ocean limitations (see #10). High charter rates of suitable dynamic positioning vessels are a barrier to cost reduction, but if low cost solutions can be developed this would alleviate several port constraints. Doing so could potentially open new markets for floating offshore wind, where port infrastructure is a barrier.

INSTALLATION (TRANSIT & HOOK-UP)

08 Long distance from assembly port to site may imply complex, lengthy and cost wet tow operations

The port infrastructure requirements highlighted in #3 may mandate long distance towing operations from port to the project site. These operations will be weather restricted and limited to slow towing speeds of significantly less than 5 knots. Transit over such long distances may involve several legs between sheltered ports and anchorages, as well as the identification of ports of refuge for periods of extreme weather.

This is especially important for transits times longer than the available forecast period (72 hours; equivalent to ~360 miles), for which the operation must be designed to withstand 10-year return storm events. This could impact the overall cost of the substructures, transit operations and towing vessel selection, ultimately influencing the overall cost of the project. These restrictions will also have implications for port-side O&M strategies.

This again highlights the importance of adequate port infrastructure close to project sites. It should be noted that towing procedures for short transit to site are generally well established operations that can be undertaken by suitable anchor handling vessels (AHV) and tug boats. This should include at least one relatively large AHV with high bollard pull to ease mooring hook-up procedures. As identified in the Mooring Systems study (see Chapter X), mooring hook-up is a critical operation that requires further technology innovation to develop cost-effective solutions for improved installation efficiency.

OPERATIONS & MAINTENANCE

Major repair operations involving heavy and high lifts of a turbine component were analysed, differentiated by:

- **Operation location:** (1) Port-side; (2) Offshore (sheltered location); (3) Offshore (in-situ)
- **Operation type:** (1) Gearbox / direct drive replacement; (2) Blade replacement

In summary, the decision to perform onshore versus offshore heavy lift operations will depend on the technology, individual project characteristics, expected turbine downtime, and market pressures influencing vessel and crawler crane charter rates. The flexibility of suitable floating wind concepts to respond to market dynamics and adopt the lowest cost approaches according to need presents an advantage for the technology. Both strategies bring challenges (outlined below) and require further analysis and technology innovation to de-risk heavy lift maintenance procedures in floating wind farms.

09 Disconnection complexity and port infrastructure requirements are major challenges for tow-to-port maintenance strategies

There is considerable interest in the potential to disconnect floating wind turbines and tow to port for maintenance at the quayside, mitigating the need for expensive heavy lift vessels. While this approach may be valid in certain project and market conditions, there are several challenges that must be considered and will need to be addressed, particularly when considering the size of future floating wind structures and the logistics of large maintenance campaigns involving multiple component exchanges.

Disconnect complexity: While cable and mooring connectors exist, the practicality of undertaking disconnect and reconnect procedures is a challenge:

- *Time & weather windows:* Disconnect operations could take several hours and be limited by available weather windows.
- *Out-of-service arrangements:* As identified in the Electrical Systems study, out of service arrangements for the electrical connection requires further investigation, in both single and multi-unit disconnect procedures.
- *Connector cost benefit:* The time advantage gained from an optimised quick-connection and release system, which may only be used a few times in the project lifetime, will likely be limited. Performance and reliability over a 25-30 year lifetime for expensive connectors is another potential concern.

Port infrastructure: Tow-to-port maintenance strategies require excellent port infrastructure close to site, given the following challenges:

- *Towing operations:* Long wet tows will be slow and weather constrained. As highlighted in #8, tow duration over 72 hours may have costly design implications.
- *Port draught:* Ports will need sufficient draught to be able to accommodate the floater. This may require de-ballasting or additional buoyancy to reduce floater draft.
- *Crane capacity:* Onshore crawler cranes will need to be able to undertake heavy lifts at high hook heights. As highlighted in #4, there are very few suitable crawler cranes available globally at present. Importing cranes to port will incur high mobilisation costs and long lead times. Redeploying jack-up vessels at the quayside would be an alternative solution that adds flexibility.
- *Port availability:* Conflicts with other competing port activities could add constraints for reactive maintenance procedures, resulting in delays in securing a suitable terminal.

Turbine downtime is another important consideration when disconnecting turbines from an array, which will need to be minimised in order limit loss of revenue during turbine repair operations.

10 Heavy lift offshore operations will be a requirement for several, if not all, concepts. Developing cost-effective methods is a priority for the sector.

As highlighted in #7, floating-to-floating or floating-to-fixed lifting operations will be a necessity for several concepts (e.g. spar, TLP) and may be required for all concepts, depending on the installation and maintenance strategy adopted.

Offshore operations will always be heavily weather restricted and involve chartering large heavy lift crane vessels, often at high cost. However, it is believed that this method can be competitive with port-side operations as the vessels and technology become more commonly available, just as they are on a conventional offshore windfarm.

When performing lifts from a floating vessel to a floating substructure, the relative motions between the lift vessel and substructure will result in high demands on the vessel's dynamic positioning system and will impose restrictive met-ocean constraints. Most of the existing floating vessel fleet would be unable to lift to the hub height of a 10 MW wind turbine, but next generation floating heavy lift crane vessels could unlock opportunities for floating offshore wind (see case study). In addition to the vessel, there will be a critical need for innovation in the supporting technologies and components, such as bumpers and guiding systems, that can enable lifts in challenging met-ocean conditions. More mobile solutions, such as climbing cranes and nacelle cranes, could also undertake cost-effective component exchange, if developed and de-risked for application offshore.

Box 6: Case study - Next generation heavy lift crane vessels

Several offshore contractors are already developing next generation dynamic positioning heavy lift crane vessels that will be able to undertake major component exchanges on offshore windfarms (e.g. Boskalis 'Bokalift' and GeoSea 'Orion', pictured). It is quite possible that wind farm developers would be able to leverage the availability of these vessels to undertake operations across a fleet of assets, both fixed and floating, thereby limiting the impact of high mobilisation costs.

Boskalis 'Bokalift'

GeoSea 'Orion'

In contrast to port-side maintenance, weather restrictions will be relevant for the lifting operation only, as opposed to the disconnect and transit restrictions when towing to port. Provided weather limits for the heavy lifts can be extended, this could offer a more optimal solution for major repairs, particularly when repairs are required on multiple turbines.

Evaluating the feasibility for the use of heavy lift crane vessels in sufficiently large wave and wind conditions needs to be verified and is a key priority for the sector. The combination of these crane vessels and substructure transport vessels/barges opens the possibility to build wind farms in locations with very scarce local infrastructure, since none of the main operations need to be undertaken at nearby ports.

4.3 Innovation Needs

Based on the key findings above, the following high priority innovation needs have been extracted. It is considered that these innovation needs can be met through a combination of supply chain innovation, joint industry initiatives, and applied research from academic research institutions.

01 Feasibility and cost-benefit of heavy lift offshore operations

There is a need to investigate the feasibility and weather limitations for heavy lift offshore operations, together with the identification of relevant technology innovations that can enable major repair procedures to be undertake offshore.

- **Suppliers and technology developers:** Next generation dynamic positioning vessels are expected to unlock opportunities, but further innovation will be required from tier 2 and 3 suppliers to develop component technologies to enable heavy lifts. There is also a need for more mobile solutions that can undertake repair procedures, such as internal cranes and climbing cranes.

- **Academic research:** Research studies, component testing, and development of advanced modelling tools to assess the feasibility of complex lifting operations, as well as the development of more innovative technologies (low TRL).

- **Joint industry:** Initiatives involving marine contractors, vessel designers, component suppliers, academia and others to jointly investigate key challenges and outline innovation needs.

  Note: The Floating Wind JIP has recently kicked-off a project investigate the feasibility, challenges, and technology development needs for heavy lift offshore operations (see Chapter 5 on Phase II project for further information).

02 Feasibility and cost-benefit of tow-to-port maintenance strategies

There is a need to investigate the feasibility and cost benefit of tow-to-port maintenance strategies, including disconnect and reconnect procedures, out of service arrangements, towing operations, and port logistics.

- **Suppliers and technology developers:** Internal R&D to develop cost-effective and reliable cable and mooring connectors. Detailed studies into the practical feasibility of full tow-to-port operations, in both single and multi-units. Demonstration of port-side maintenance operations in pilot projects.

- **Academic research:** Research studies and component testing to develop advanced connectors, evaluate electrical configurations, and develop advanced modelling tools.

- **Joint industry:** Initiatives involving technology developers, suppliers, academia and others to jointly investigate key challenges and identify innovative solutions.

03 Efficient and cost-effective turbine integration procedures

Related to #1 and #2 above, there is a need to develop efficient and cost effective methods for turbine integration, both at the quay-side and offshore (including sheltered locations and at the project site).

- **Suppliers and technology developers:** Development of next generation crawler cranes to improve market availability and ensure rapid and cost-efficient mobilisation. Development of next generation crane vessels and component technologies (as above). Analysis of optimal turbine assembly and integration methods (i.e. component integration and size and sequencing of lifts).
- **Academic research:** Research studies, component testing, and development of advanced modelling tools.
- **Joint industry:** Initiatives involving marine contractors, suppliers, equipment suppliers, technology developers, academia and others to collectively investigate key challenges.

04 Serial production methods for floating wind structures

There is a need to adopt best practice from parallel industries and develop efficient and effective serial production methods for floating wind structures.

- **Suppliers and technology developers:** Floating substructures designed for serial production. Efficient and effective steel and concrete fabrication methods, targeting at least one substructure per week.
- **Academic research:** Research studies to develop advanced welding, robotics, and automated manufacturing technologies.
- **Joint industry:** Initiatives involving substructure designers, fabricators, equipment suppliers, academia and others to collectively develop optimised substructure designs and fabrication methods.

05 Other

Below is a longer list of areas that require further development to reduce technology risk and costs for commercial floating wind farms:

- Methods to reduce draught requirements at port (incl. buoyancy aids)
- Port infrastructure upgrades
- Hydrolift technologies for rapid quay-side load-out
- Rapid steel welding methods for modular components
- Quick setting concrete to accelerate throughput time
- Mooring and anchoring system installation logistics
- Dynamic cable installation and disconnection logistics
- Advanced anchor handling vessel technology
- Accessibility and workability on floating structures
- Advanced forecasting tools
- Advanced logistics modelling tools

5. Projects for Phase II

Phase II Overview

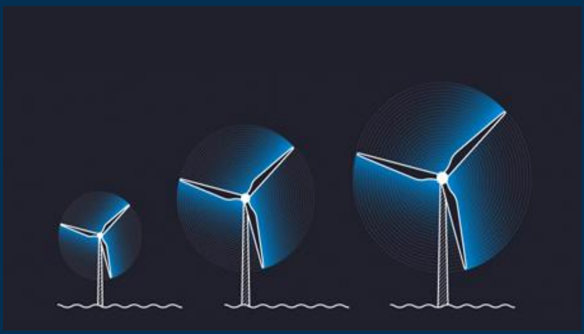
Four projects will be delivered in Phase II, building on the findings from Phase I, again seeking to address common technical challenges for large-scale commercial floating wind farms. Projects will run throughout 2018. Each study will again involve close engagement with wider industry in order to solicit opinion and expertise from experienced suppliers and to identify relevant technology innovations for the sector.

Turbine Requirements & Foundation Scaling

Contractor: Rambøll

Challenge:

Turbine size is increasing rapidly, with 13-15 MW WTGs set to be on the market by 2025, the same period by which the first commercial-scale floating wind farms are expected to be installed. The scaling of floating substructures could have an important impact on procurement costs, as well as logistics for fabrication and installation.



Some concept designers suggest that the scaling may be less sensitive than fixed foundations, presenting a potential advantage for floating wind in a future with larger turbines.

It is also considered that modifications will be required to conventional offshore wind turbine designs to ensure suitability for application on floating structures.

Project Overview:

This project will be delivered through two inter-related studies:

1. ***Turbine Requirements:*** Review of design requirements & 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 will use 6 MW, 10 MW and 15 MW 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 will help to increase confidence in less conservative design requirements and identify opportunities for lower cost integrated designs.

Heavy Lift Offshore Operations

Contractor: Seaway Heavy Lifting

Challenge:

The Phase I Infrastructure & 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 fixed-bottom 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.

Project Overview:

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

- 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

The study will assess the same 6 MW, 10 MW, and 15 MW turbine ratings analysed in the Turbine Requirements & Foundation Scaling project, but also extend its investigation to 20 MW turbines to future proof the study in light of the long lead-times and high investment costs required for such technologies.

The study will be supported by a peer review panel consisting of several leading heavy lift contractors.

Dynamic Export Cable Development

Contractor: BPP Cables

Challenge:

Early prototypes and first arrays of floating wind turbines have been connected to shore using low and medium voltage power cables (~22-66kV). However, large-scale commercial floating wind farms will require power to be transmitted using higher voltage cables (~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 be mechanically dynamic.

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 high voltage dynamic cables for export purposes. This represents a potentially significant challenge for future floating wind projects and adds considerable risk to prospective commercial projects. The timeline and uncertainty, in particular, present a risk and potential bottleneck for early commercial floating wind projects.

Project Overview:

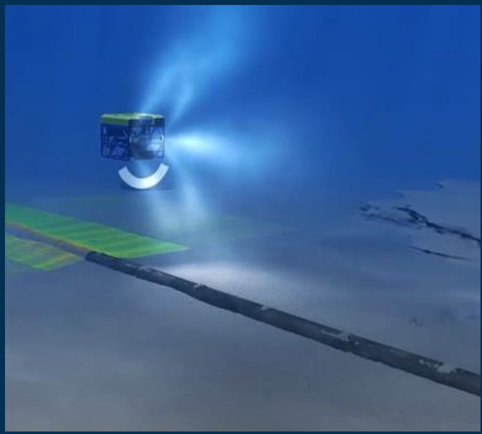
This project will investigate the challenges and assist the development of high voltage dynamic power cables for export purposes in floating offshore wind farms. BPP Cables will lead an initial review of the current status and analysis of the technical challenges for high voltage dynamic cables, before supporting the launch of a competition to cable manufacturers with suitable designs. A handful of cable manufacturers will be supported to develop detailed designs and the option to progress with further studies, testing and/or qualification will be evaluated at the end of the project.

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

Monitoring & Inspection

Contractor: Oceaneering

Challenge:



The Phase I studies identified that monitoring and inspection requirements for large-scale floating wind farms presents a potential cost challenge. Floating wind farms introduce novel elements, relative to fixed-bottom projects, that may require alternative approaches and new technologies. This includes monitoring, inspection, and maintenance of the hull, ballast systems, mooring and anchoring system, and dynamic cables. The total number of components and assets to maintain across a large-scale wind farm is considerable.

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 to monitor, inspect, and maintain a large number of assets across the wind farm. There are concerns that current monitoring and inspection requirements (as defined in industry standards and guidelines) are overly conservative, resulting in higher operation and maintenance costs across the wind farm.

Project Overview:

This study will investigate the requirements specific to monitoring and inspection of floating offshore wind assets in key geographic markets. This will include:

- A review of existing standards and guidelines
- Evaluation of state of the art and innovative technologies to monitor and inspect assets
- Development of a suitable monitoring and inspection protocol to cost-effectively mitigate operational risks in a commercial floating wind farm
- Assessment of how standards and guidelines might be updated to reflect the ability for novel technology innovations and/or maintenance strategies to mitigate integrity risk in floating wind farms
- Identification and prioritisation of research needs to de-risk monitoring, inspection, and maintenance requirements and develop technologies that can unlock less conservative requirements

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. The philosophy 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 philosophy 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 most shallow 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 design include a moonpool to suppress wave-induced loading.

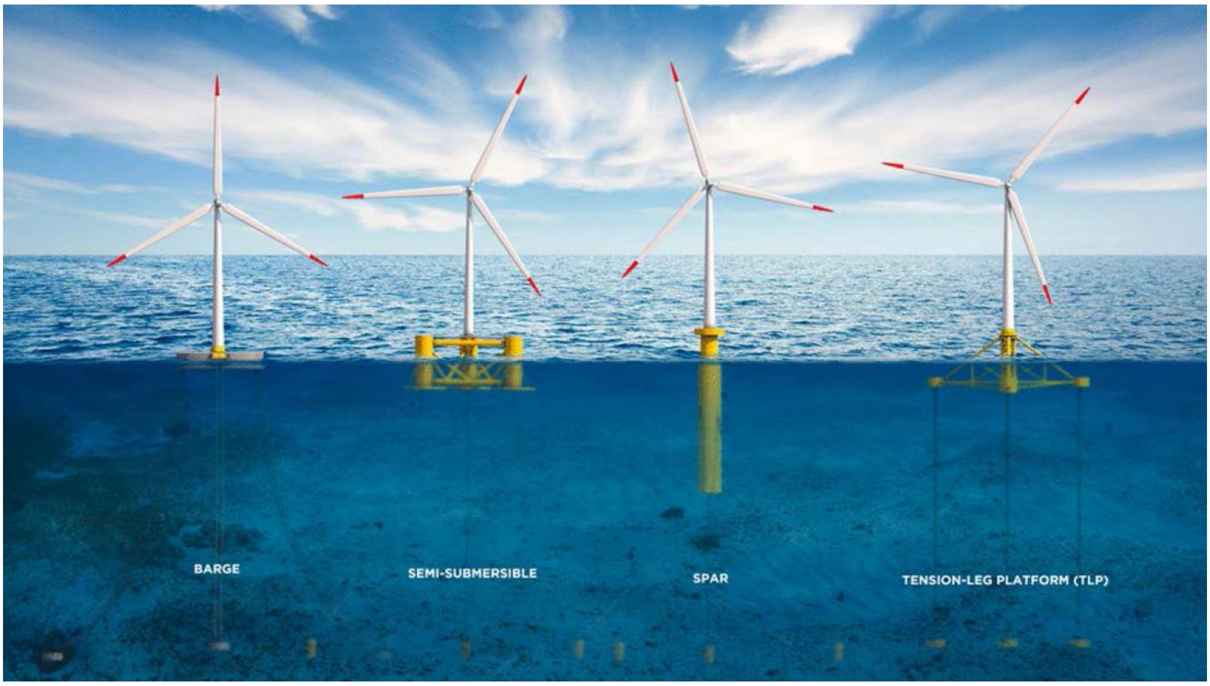


Image: WindEurope

Appendix 2: Industry deployment ambitions

Table based on publically stated industry ambitions and information sources.

Country	Installed (MW) 2018	Expected (MW) 2021	Industry Ambition (MW) 2025	2030	Certainty	Source (Industry Ambition)
EUROPE						
UK	30	80	1,000	5,000	Low	Aspiration from Friends of Floating Offshore Wind Position Paper.
France	2	98	2,000	6,000	Med	FEE/SER target, supported by regions of Bretagne, Occitanie and Provence-Alpes-Côtes d'Azur.
Norway	2	6	30	250	Low	2025: Single unit demonstrations, plus application in enhanced oil recovery; 2030: Large demonstration project(s).
Portugal	0	25	25	260	Med	Industrial Strategy for Ocean Renewable Energies (EI-ERO).
Europe (Max)	**34**	**209**	**3,055**	**11,510**		
ASIA						
Japan	16	19	1,400	4,000	Med	JWPA Wind Power Roadmap (2016); no governmental targets.
China	0	0	1,000	3,000	Med	Up to 3 GW CGN Jieyang project (no firm timeline); no governmental or industry association targets.
Taiwan	0	0	1,000	2,000	Low	4x Eolfi projects; no governmental or industry association targets.
Asia (Max)	**16**	**19**	**3,400**	**9,000**		
UNITED STATES						
California	0	0	1,000	2,500	Med	2025: 2x unsolicited lease requests - Morro Bay (700-1000 MW) & Humboldt (120-150 MW); 2030: NREL Floating Offshore Wind in California (Scenario A).
Hawaii	0	0	400	1,200	Low	3x unsolicited lease requests - Oahu N-W, Oahu S, Progression (no firm timeline).
Maine	0	12	500	5,000	Low	Aqua Ventus II and III projects. 5 GW by 2030 part of Maine's renewable ocean energy goals.
United States (Max)	**0**	**12**	**1,900**	**8,700**		
GLOBAL						
Global (Max)	**50**	**240**	**8,355**	**29,210**		

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