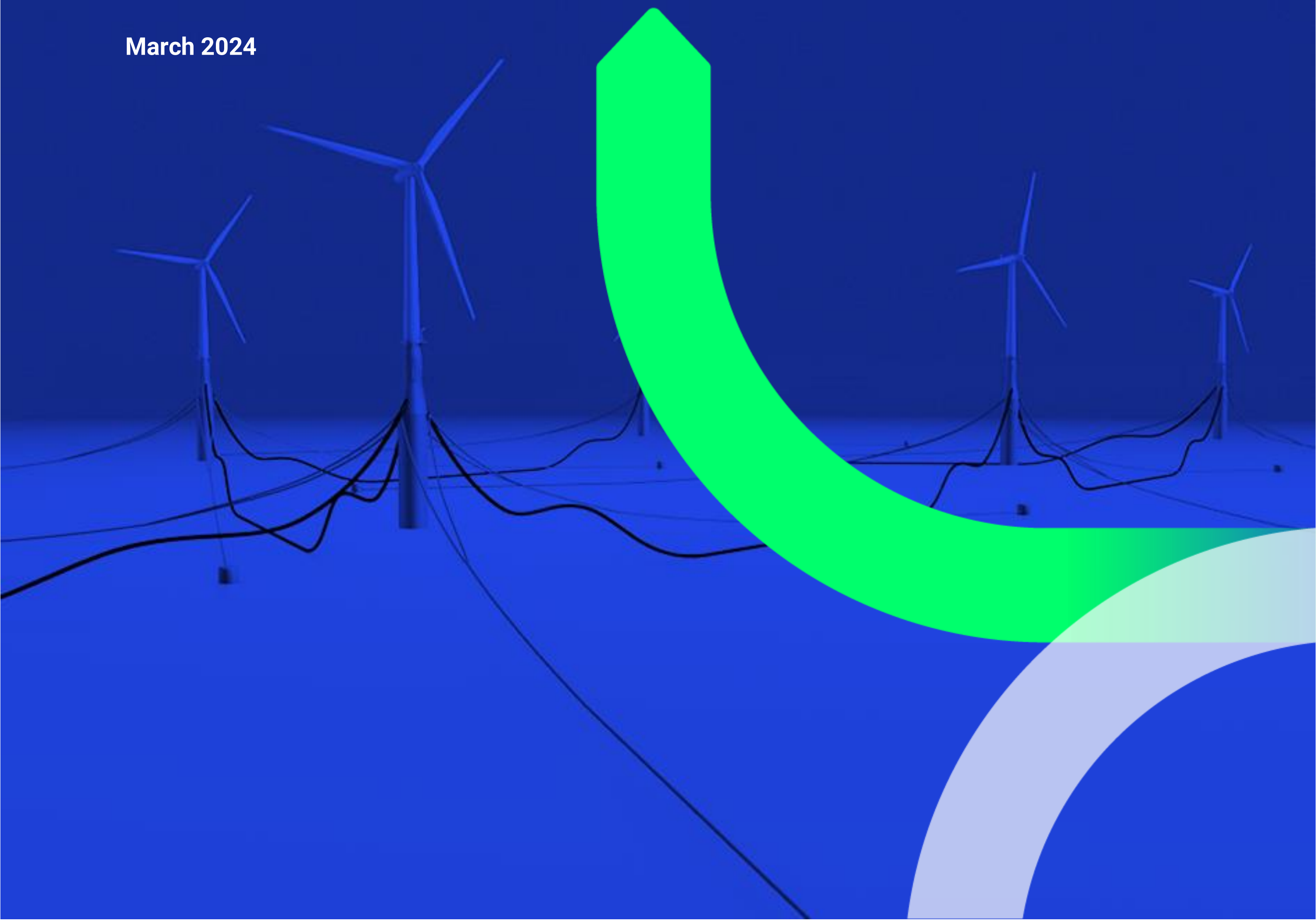
FLOATING WIND JOINT INDUSTRY PROGRAMME (JIP)

Floating Wind JIP Phase V Summary report

March 2024



INTRODUCTION

About the report

The Floating Wind JIP is the Carbon Trust's collaborative R&D programme, dedicated to overcoming technological challenges and advancing the commercialisation of floating offshore wind. The programme is a partnership between the Carbon Trust and 17 offshore wind developers. This summary report provides a high level overview of the six key research projects that have been carried out between 2022 and 2023.

Acknowledgments

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

- Fabrication, infrastructure and logistics: **Arup**
- Major component exchange with self-hoisting cranes: **Offshore Wind Consultants, WavEC Offshore Renewables**
- Stick building wind turbine generators on-site: **Heerema Engineering Solutions**
- Fatigue analysis of high voltage electrical equipment: **Petrofac**
- Dynamic cable failure rates and standards: **Offshore Wind Consultants, University of Exeter**
- Mooring system redundancy, reliability and integrity: **AMOG Consulting, sowento, Peak Wind, Offspring International**

Project findings are based on an impartial analysis of primary and secondary sources, including expert interviews. The Carbon Trust would like to thank everyone who has contributed their time and expertise during the preparation and completion of this report.

Special thanks go to: BAM Nuttall, Bouygues, Glosten, Gusto MSC, Ideol, JMU, Navantia Windar, Olav Olsen, Port of Brest, Port of Humboldt Bay, Port of Hueneme, Port of Morro Bay, Principle Power, Saipem, Siemens Gamesa and Stiesdal.

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The Carbon Trust's mission is to accelerate the move to a decarbonised future.

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Abbreviations

AHT	Anchor handling tug (vessel)
AI	Artificial intelligence
ALS	Accidental limit state
CAPEX	Capital expenditure
COG	Centre of gravity
DEL	Damage equivalent load
EUT	Equipment under test
F2F	Floating-to-floating
FLS	Fatigue limit state
FOW	Floating offshore wind
FOWT	Floating offshore wind turbine
FPSO	Floating production, storage and offloading unit
GW	Gigawatt
HSE	Health, safety and environment
HTV	Heavy transport vessel
HV	High voltage
IMO	International Maritime Organisation
JIP	Joint Industry Programme
KPI	Key performance indicator
LCOE	Levelised cost of energy
MIM	Mooring integrity management
MOSS	Maximum operating sea-states
MW	Megawatt
NREL	National Renewable Energy Laboratory
O&G	Oil and gas

O&M	Operations and maintenance
OEM	Original equipment manufacturer
OPEX	Operational expenditure
PSD	Power spectral density
R&D	Research and development
RBI	Risk-based inspection
SHC	Self-hoisting cranes
SSCV	Semi-submersible crane vessel
T&I	Transport and installation
TLP	Tension leg platform
TRL	Technology readiness level
TTP	Tow-to-port
ULS	Ultimate limit state
WTG	Wind turbine generator

FOREWORD

Sam Strivens

Head of Floating Offshore Wind and Maritime Decarbonisation

2023 saw the floating wind industry continue to make significant milestones towards full scale commercialisation, with the commissioning of a number of floating wind farms and new lease areas being announced.

Having a nameplate capacity of 88 MW, commissioning of Hywind Tampen in August made it the largest operational floating offshore wind farm in the world. Provence Grand Large in France, with a capacity of 24 MW, sees the world's first deployment of tension leg platforms for floating offshore wind.

Following on from the successful results of the Californian floating specific leasing round at the end of 2022, this past year saw floating specific auctions being conducted in France (AO5 in the south Brittany coast) and development of the Crown Estate's 4 GW Celtic Sea leasing round , due to undergo the pre-qualification process in spring 2024. With 2030 floating wind targets nearing for a number of countries, including 5 GW by 2030 for the UK, there are significant challenges to overcome to achieve commercial operation of floating offshore wind farm projects:

Operational maintenance solutions for major component repair or replacement

Iin May 2023 the second Kincardine turbine arrived at the port of Maasvlakte, Rotterdam for corrective maintenance. All five of the Hywind Scotland turbines are scheduled to be towed to Gulen Port in Norway in the summer of 2024, as no Scottish port has sufficient water depth for the drafts of these spar foundations. These instances highlight the need for globally sufficient port infrastructure capable of servicing floating wind, and the value of overcoming the challenges associated with in situ turbine maintenance, especially for larger scale commercial farms.

Turbine installation in deeper waters

The move towards commercial scale projects will also require development of installation solutions capable of undertaking multiple turbine installations in deeper waters. Existing operational floating wind farms have demonstrated a crucial proof of concept for several floating wind aspects, but when considering commercial scale installations, demonstration of innovative methods and technologies will be required to progress to the next level.

Supply chain efficiency

Whilst the fixed bottom offshore wind industry has been able to grow organically, to reflect demand and showcase the benefit of economies of scale, the floating wind sector doesn't have the luxury of this organic growth. Commercial scale projects are being planned much earlier and with larger turbines, which bring a unique set of associated challenges that need to be overcome. It is obvious that for the next few years at least, the focus needs to remain on commercialisation and industrialisation of the technology. An important element of floating winds' success will be driving down the costs to a level where is considered as economically viable as fixed bottom offshore and other forms of energy generation. This is likely to come hand in hand with increased supply chain efficiency. Consequently, the industry may soon have to address the enduring challenge of rationalising the number of floating solutions and applying the most appropriate to a given development.

Collaboration

Collaboration is key to overcoming these technical challenges, and therefore achieving commercialisation whilst also ensuring timelines are met. Current pilot and pre-commercial projects alone show the number of key stakeholders who are required to achieve this feat.

As we reflect back on Stage 2 of the Floating Wind JIP, which ran from 2017 to 2023, it is evident how the research focus has evolved from early feasibility studies to complex R&D projects that focus on the technical challenges of commercialising floating offshore wind. Initial projects in 2017 considered the feasibility of floating offshore wind with 10 MW turbines, including the general potential of undertaking heavy lift operations offshore. Recent projects, however, are looking to address practical challenges associated with 15 MW and 22 MW turbines, including the detailed investigation of undertaking major component exchange offshore.

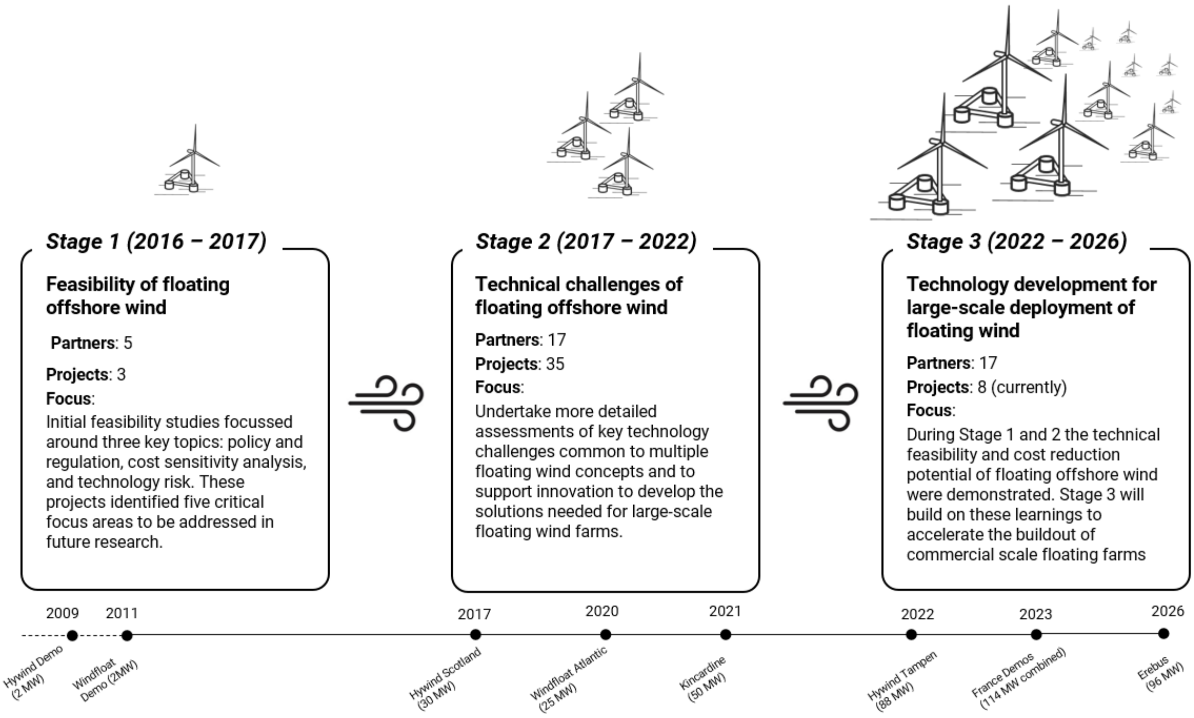
Whilst it is easy to become overwhelmed with the challenges required to commercialise floating offshore wind, it is also important to acknowledge the successes that have been achieved in this dynamic and fast paced industry. Moving into deeper, more demanding waters is a significant challenge and the industry is moving into a realm of known unknowns and unknown unknowns, however the route to commercialisation is becoming clearer for developers, governments and suppliers alike. As we move into Stage 3 of the Floating Wind JIP, projects will focus on unlocking the industrialisation of floating offshore wind projects globally.

Figure 1: Hywind Scotland floating offshore wind farm. Courtesy of Alistair Morris.

1.1. About the Floating Wind JIP

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

1.2. Evolution of the Floating Wind JIP



Since its formation in 2016, the programme has been delivered in three distinct stages, each consisting of studies to overcome the challenges and investigate the opportunities of developing commercial scale floating wind farms. An initial review of policy needs, cost trends, and technology status for floating wind in Stage 1 resulted in the prioritisation of several key technical challenges which have been investigated throughout Stage 2. This report summarises projects delivered during the final phase Stage 2 (Phase 5). Summary reports for previous phases of Stage 2 can be found here: Phase I, Phase II, Phase III and Phase IV. To reflect the evolution of floating offshore wind from technology demonstration to industrialisation, Stage 3 of the Floating Wind JIP officially launched in 2022, with an objective to advance technology development for the large-scale deployment of floating offshore wind.

1.3. Objectives of the Floating Wind JIP

The primary objectives for Stage 2 of the Floating Wind JIP were to overcome technical challenges and investigate opportunities for the deployment of large scale commercial floating offshore wind farms. The programme is technology focused, with a particular emphasis on:

- **Large scale deployment:** Floating offshore wind technology has been proven at prototype and pilot scale, through single or a small number of multi-MW units. However, commercial wind farms will bring new technological and logistical challenges due to the increased scale of turbines and units deployed.
- **Derisking technology challenges:** Limited commercial deployment of floating offshore wind to date means that several perceived risks exist. It is expected that many of these challenges can be overcome using existing solutions from other sectors, but there is a need for further investigation to establish the true level of risk presented and undertake research that can reduce risk throughout the project lifecycle.
- **Identifying innovative solutions:** Several technology challenges will require the development of novel solutions. Innovation will be central to delivering optimised and cost effective solutions for the industry, which is expected to present considerable opportunities for suppliers, innovators, research bodies, and academia.
- **Cost reduction:** All activity within the programme is guided by the need to deliver cost reductions ensuring that floating wind becomes a competitive energy technology in all major global markets. Cost assessments are included within the scope of most projects in order to build a robust estimate of the cost projections and cost drivers for programme partners to use when developing future commercial projects.

1.4. Stage 2: Summary of activity

Stage 2 of the Floating Wind JIP ran from 2017 to 2022, with some projects finishing in 2023. The primary objective of Stage 2 was to undertake detailed assessments of the key technology challenges common to multiple floating wind concepts and to support innovation to develop the solutions needed for large scale floating wind arrays. The programme underwent significant expansion with developer members evolving from five during Stage 1 to seventeen during Stage 2. A summary of Stage 2 activity is provided below:

Common R&D projects:

Over the five years of Stage 2, the programme has delivered 20 common R&D projects, addressing numerous topics such as major component replacement offshore, floating wind yield assessment, mooring redundancy, asset monitoring & inspection, dynamic cable development and assessing floating wind specific turbine requirements.

Industry competitions:

- **The Dynamic Export Cable competition** (2018): was launched to address the lack of availability of high voltage dynamic export cables for the transmission of power from wind farms to shore, which has been identified by the industry as a potential bottleneck for the commercial deployment of floating wind technology. The objective of the competition is to ensure that this necessary technology is a viable option for developers for commercial floating wind projects within the next

5 to10 years. The competition funded five cable manufacturers to develop and test their designs for future dynamic cable qualification

- **The Floating Wind Technology Acceleration Competition** (2021): was funded by the Scottish Government and successfully supported the development of eight applicants on their course to commercial availability. The individual project summaries can be found on the Carbon Trust website.[1] One successful applicant was the Dublin Offshore Load Reduction Device (LRD) concept, which is planned for full scale demonstration as part of the 100 MW floating offshore Malin Sea Wind project, in collaboration with ESB and CATAGEN.[2]

The Floating Wind Advisory Group:

In 2020, the Floating Wind JIP Advisory Group was formed. The advisory group creates a technical dialogue between relevant technology suppliers and the Floating Wind JIP projects. The advisory group was initially formed of turbine OEMs and floating substructure developers. The advisory group has recently been expanded (in Stage 3) to include cable suppliers, to support the increasing number of cable projects which are being delivered under the programme. The advisory group is currently formed of 15 members, below.

[1] Floating wind technology acceleration competition: Project summaries | The Carbon Trust, 2021

[2] Malin Sea Wind Project - Dublin Offshore, 2023

2. Fabrication, infrastructure and logistics

ARUP

2.1. Project overview

To date, floating offshore wind (FOW) projects have been deployed at small demonstration and pre-commercial scale capacity, much smaller than current bottom fixed offshore wind farms, which have now exceeded 1 GW in project capacity. The current FOW pipeline shows that commercial sized floating farms will be in development over the next decade, bringing challenges to fabrication, infrastructure, and logistics. Constraints to effective deployment may include facilities for steel and concrete fabrication; port facilities for assembly and storage; launching facilities; transport of large equipment; and local content requirements.

This Fabrication, Infrastructure and Logistics (FIL) project delivered by Arup for the Floating Wind JIP built upon previous projects to further understand the key fabrication, infrastructure, and logistical constraints towards building large scale floating wind farms and to ensure that these infrastructure constraints do not prevent FOW deployment. The project objective was to understand the common infrastructure requirements for FOW projects in order that port authorities can understand investment requirements, and developers and fabricators have a framework for port selection.

Project objectives

1. Understand common infrastructure, fabrication and logistical constraints towards building large scale floating wind projects;
2. To provide port authorities with a clearer view of investment requirements;
3. To provide developers and fabricators with a framework for port selection;
4. Understand the restrictions infrastructure requirements may have on realising floating wind potential.

Figure 2: FloatHOME project, courtesy of Principle Power.

Methodology

The project methodology sought to build up an impression of logistics, infrastructure and supply chain needs for commercial scale deployment options for FOW across the regions of Asia, America and Europe.

Six key scenarios were defined to cover a broad range of substructure types, mooring systems and logistical options that factored in the availability and cost of materials, marshalling and integration infrastructure, and offshore site constraints. The 6 scenarios were defined as:

1. International substructure fabrication
2. Localised steel semi-submersible/ suspended weight spar
3. Localised concrete semi-submersible
4. Regional steel spar-buoy offshore
5. Localised concrete barge
6. Localised steel tension leg platform (TLP) nearshore integration

The project concluded that in order to support the 6 different scenarios and various permutations, there would likely be differing infrastructure requirements for the fabrication and critical marshalling integration roles, resulting in 27 different facility functions being considered; 19 for fabrication (across substructures, anchors, moorings, cables and wind turbine generator (WTG) and 8 for the marshalling roles.

Some of the key assumptions made whilst investigating these six scenarios were:

- Anchors and mooring chains were transported (from fabrication to marshalling) on general cargo vessels and barges.
- For steel manufacturing, both international steel component manufacture and localised assembly, as well as local fabrication, scenarios were assessed.
- Concrete fabrication, focused on localised markets, with both pre-cast fabrication and slip forming.
- Option of both WTG integration at the quay, as well as away from the quay with a jack-up vessel considered.

Crucially, the project also engaged a selection of key stakeholders across the industry and wider supply chain around the themes of capital expenditure (CAPEX) reduction, local content and fabrication programme.

2.2. Key findings

1 **Collaborative action is required to ensure effective investment in national port infrastructure.**

- There are multiple infrastructure facilities required to successfully deliver commercial scale FOW projects across the mooring, anchoring, cabling, and substructure installations. This offers opportunities for smaller ports located in prime windfarm development zones.
- National strategic investment plans for port infrastructure could help overcome demand for port facilities.
- Collaboration across the industry, with governments, port authorities, supply chains, and developers is required to highlight bottlenecks and explore new opportunities such as clusters and hubs.
- There may be limitations around the available in country infrastructure for larger scale fabrication, WTG marshalling and WTG integration activities. These limitations could be mitigated with the development of national and regional support schemes.

2 **Substructure assembly areas require critical infrastructure investment including significant capabilities and capacity.**

- There is currently limited land area at most port facilities to carry out serial component production and final assembly of substructures, with access to necessary heavy lift quay space for both steel and concrete.
- Modelling of scenarios determined that at least 2 final assembly locations are required in key geographies to be able to meet a typical demand of 50 units within 2 years.
- These facilities will likely need an area of 18-24 Ha and require significant component storage space to maintain continuous mass production.
- Past 45 units, the land area of the marshalling port stops being the limiting factor, which instead becomes weather windows for transport and installation (T&I).
- To unlock increased capacity, there will need to be either an expansion of multiple existing facilities in geographical locations, or the development of bespoke port facilities to enable efficient delivery of commercial scale FOW projects.

3 **Significant investment is required for wet storage areas to aid commercial deployment of foundations.**

- Many installation scenarios require significant wet storage capacity. This could be split across fabrication or marshalling facilities, or nearby sheltered waters, either afloat (requiring a large anchorage area) or grounded (may require permitting) depending on suitable draft seabed conditions.
- Wet storage requires sufficient water depth to allow the flexible movement of substructures in and out of position. The area required could be reduced when deploying substructures capable of ballasting and grounding.

- Variety in substructure design and the relative temporary nature of wet storage makes investment decisions challenging.
- Ports without any suitable wet storage may be required to create offshore anchoring, utilise existing structures or work with neighbouring ports of harbours.

4 **Selection of the installation campaign strategy will be dependent on scenario fabrication, launching and integration rates.**

- FOW integration can be carried out within the port but is exposed to a discord between the fabrication, launching, and installation rate.
- This discord, coupled with the high costs of integration equipment, means that maintaining the utilisation of equipment could be challenging.
- Effective wet storage of units could maintain a continued utilisation of onshore ringer cranes or near shore jack-up vessels for integration, where wet storage capacity then becomes the limiting factor. The key will be to balance the total number of foundations stored versus the installation rate.
- Multiple integration deployment campaigns split across projects into the northern and southern hemispheres could ensure consistent mobilisation, though with additional transport costs.
- Integration of spar-buoy floaters is more analogous to fixed offshore wind, where a single campaign of continuous deployment is feasible, and metocean conditions will instead be the limiting factor.

5 **Demand for FOW substructure fabrication rates outweighs current capabilities in certain markets. An international roadmap could help manage demand, utilizing multiple fabricators both nationally and internationally.**

- Reaching the required maturity and rate of fabrication is likely to take several years through multiple projects. There is a significant discrepancy between the market ambitions and the existing fabrication capability of the industry, as shown in Figure 3.

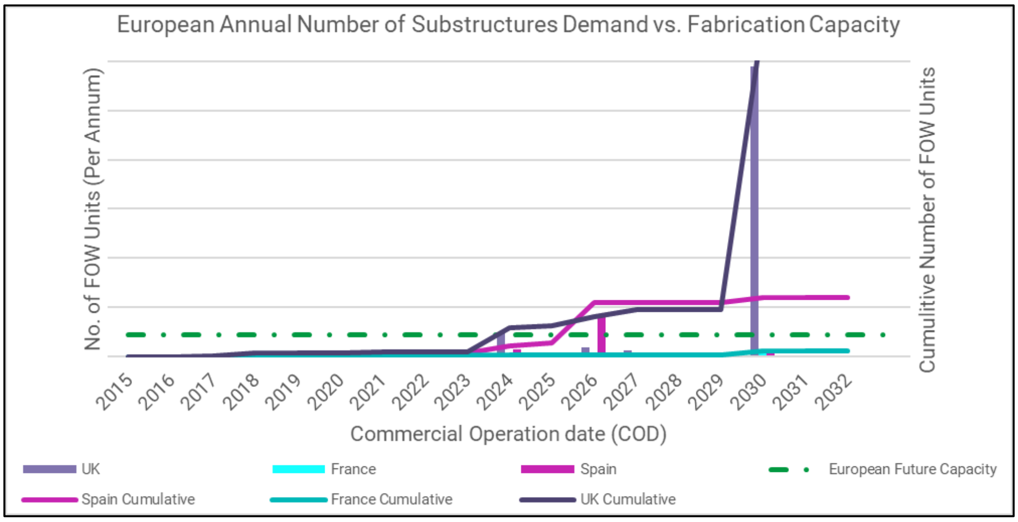


Figure 3: The European potential fabrication capacity vs demand. 2 fabrication facilities were assessed as part of this project.

- Splitting fabrication contracts into two or more manageable substructure procurement packages would reduce the risk of delays. Formalised alliances or joint ventures may ease the demand.
- The demand for steel fabrication will outstrip the trained skilled workforce. Concrete requires a lower skilled workforce, making it a better option in some scenarios. There is little incentive for steel ship building facilities, with a reliable revenue stream, to pivot towards substructure fabrication.

2.3. Industry needs and innovations

1 Developing specialist semi-submersible barges that can increase launch efficiency.

- There are currently a limited number of semi-submersible heavy load carriers suited for the launching of substructures.
- The challenge with semi-submersible heavy load carriers is that they were designed for transportation of other vessels, caissons and are not suited to wider more symmetrical structures such as FOW barges, or semi-submersibles. This current method of transportation is reaching its limits, with the large overhang makes transporting these structures difficult. Figure 4 shows the semi-sub structure for a 9.5 MW rated turbine, and as footprints will increase for larger turbines, this shows the current transport restrictions.

Figure 4: Kincardine semi-submersible foundation transport overhand, courtesy of Boskalis.

2 Initiating whole life carbon considerations of floating offshore wind substructures.

In order to improve the whole life carbon of the FOW substructures the following 3 areas were identified as areas for further development:

- **Low carbon solutions:** The quality of recycled steel, green steel and lower carbon concrete is currently limited. Substructure designers will rely on scientific research developments to implement alternative materials in the future.

- **Carbon intensive transportation:** The nature of the vessels used, and the high impact of their emissions will continue to be closely considered by bodies such as the IMO and there will be a future modal shift to cleaner fuels. There needs to be development of low carbon fuel solutions from these key vessels to enable the industry to minimise the impact in the near and longer term.
- **Substructure towing efficiencies:** There are likely to be challenges with the lack of larger anchor handling tug vessel (AHT) availability, a potential bottleneck as demand for tow-out of substructures increases; investment in larger AHTs will be required for more efficient installation.

3 Further development of technology and tools to improve the mooring and hook-up operation offshore.

- Reducing the operational time for hook-up could significantly impact the overall assembly schedule, both by reducing the process time, but also by reducing risk factors for the required weather window to carry out hook-up operations.
- Areas of development where the manufacturing schedule could be improved are:
    - Alternative connection points such as pinned connections.
    - Partial pre-assembly of the mooring elements with the substructure.
    - Use of a mixture of permanent and temporary mooring elements.

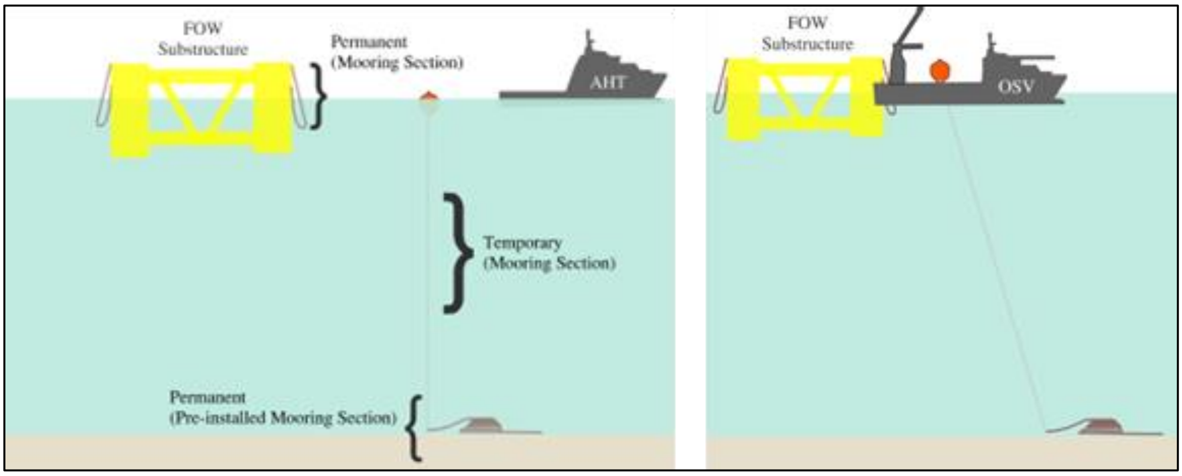


Figure 5: Potential temporary and permanent mooring interfacing, delivered for the FIL project by Arup.

3. Major component exchange with self-hoisting cranes

3.1. Project overview

Major component exchange for floating offshore wind (FOW) turbines is considered an expensive and challenging operation. A large proportion of FOW site locations will be located in deep waters, where conventional jack-up vessels cannot be used.

One viable solution to undertake a major component exchange is to tow the FOW substructure to the port (TTP), to undertake the exchange in sheltered conditions. There are many challenges associated with a successful TTP operation, including the large towing distances to FOW arrays, costs associated with onshore cranes and downtime losses due to weather constraints. Another solution is to mobilise semi-submersible heavy lift vessels, however, the expensive charter costs and potentially limiting crane lift capabilities, mean this is unlikely to be a long term competitive solution.

An alternative offshore maintenance strategy is to use self-hoisting, turbine mounted cranes. The benefit of using a self-hoisting crane is that the crane follows the relative motions of the turbine. The final crane height is provided by the turbine structure, rather than a heavy lift vessel, meaning less expensive vessels (with lower crane lifting capabilities) can be used. However, there are still some challenges associated with using self-hoisting cranes, including:

- The logistical challenge of transferring the crane between the service vessel and the turbine;
- The need to assemble and disassemble the crane system on each turbine requiring maintenance;
- The need for design modifications or retrofits to the turbine, tower, and/or substructure, which may involve the need for system recertification.

The Floating Wind JIP previously assessed technology options surrounding major component exchange including self-hoisting cranes or climbing cranes. This Major Component Exchange with Self-Hoisting Cranes project (SHC), delivered by OWC and WavEC, built on this previous research.

Project objectives

1. Identify solutions to conduct onsite major component exchange of WTG nacelle components without relying on large heavy lift vessels or towing a substructure to port.
2. Examine different technology concepts for major component exchange and assess feasibility considering technology, risk, cost and operational requirements.
3. Detail the steps needed to achieve commercial deployment of these technology concepts.

Methodology

The Major Component Exchange with Self-Hoisting Cranes (SHC) project was undertaken to further understand self-hoisting crane technology options, their feasibility, barriers to commercial deployment and industry innovation needs.

Eighteen separate self-hoisting crane concepts were identified and assessed against a series of technology, maturity and FOW suitability criteria. A number of these concepts were subsequently shortlisted, and an in depth assessment was carried out including:

1. Assessment of technology scalability.
2. Development of detailed method statements.
3. Development of storyboards to illustrate key operational steps.
4. Identification of main hazards and risk mitigation approaches.
5. Definition of the main Infrastructural requirements to carry out operations.
6. Weather window assessment for a generic replacement operation utilising self-hoisting cranes.
7. Numerical simulation of critical operations.
8. Comparison of total exchange duration.

Several assumptions were made during the in depth assessment, including:

- 10 MW and 15 MW reference turbines provided by the Floating Wind JIP were used as a baseline.
- All four main floating substructure types; semi-submersible, barge, tension leg platform (TLP) and Spar were considered.
- A primary focus was made on the 15 MW semi-submersible substructure.
- Both permanent and temporary working decks were assumed.

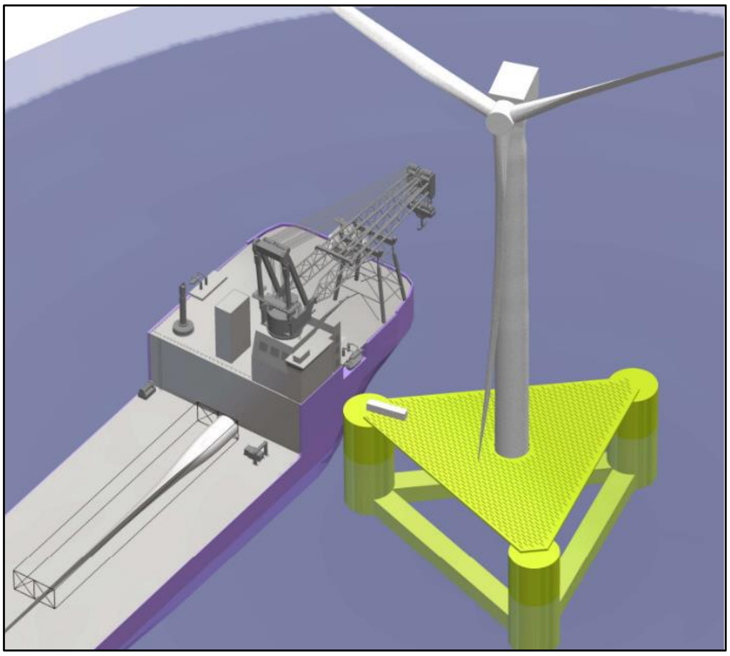


Figure 6: Storyboard development, OWC and WavEC.

3.2. Key findings

1 **The inclusion of working decks on the floating substructure is strongly recommended to facilitate self-hoisting crane use.**

- The use of a working deck as an intermediate lifting point simplifies floating-to-floating lifting operations. This also minimises the self-hoisting crane boom requirements and potential bending moments on the tower.
- The temporary working deck should have connection points to attach and secure blade cassettes and/or drive train components.
- One benefit of self-hoisting crane concepts is that smaller vessels can be utilised. Additional weight from the self-hoisting crane and components will require in depth numerical assessments to determine the hydro-dynamic stability of the substructure. Self-ballasting capabilities will be beneficial to compensate for this.
- The use of self-hoisting cranes also introduces a new level of operational complexity and consequently, new health, safety and environmental (HSE) challenges, which need to be minimised. Measures such as twist-lock sockets to enable the securement of larger components are recommended.

2 **On-site preparations play a significant role in the overall duration of offshore work activities and consequently, overall cost.**

- For most technologies, the offshore work associated with installing the self-hoisting crane on the turbine is the primary factor contributing to the total operation duration.
- Demobilisation of the self-hoisting crane from the turbine to the vessel was found to be the second largest contributor to total operation duration.
- Simplifying assembly procedures could substantially reduce the on-site preparation work required, thereby reducing the downtime losses and associated costs caused by WTGs having to remain offline during operation and maintenance work.
- Each self-hoisting crane technology was assessed using detailed method statements, as indicated in Figure 7. This described the sequence of tasks, durations and related limiting weather conditions.

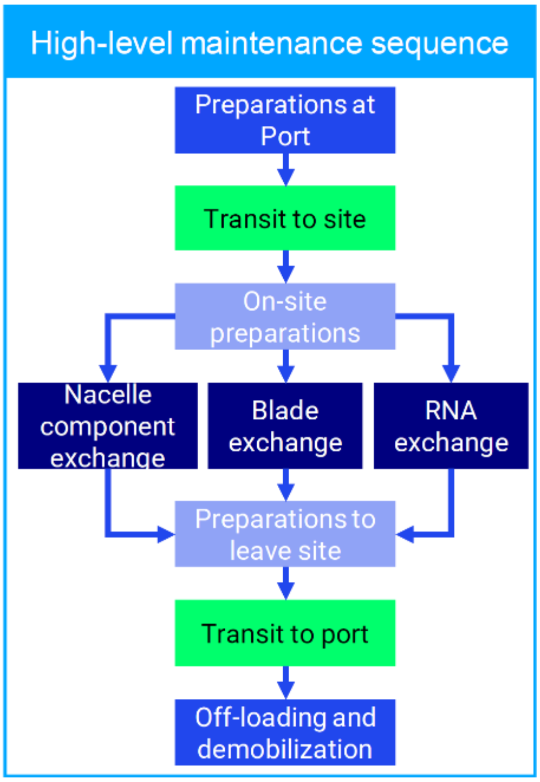


Figure 7: Generic sequence of on-site maintenance of large offshore wind components, delivered by OWC and WavEC.

3 **Both geared and direct drive turbines will present challenges in relation to using self-hoisting cranes for major component exchange.**

- Self-hoisting cranes could be used across both direct drive and geared wind turbines, to replace major components such as blades, generators and bearings as well as drivetrain components on gearbox turbines.
- However, for direct drive wind turbines, replacement of the generator and main bearing would be more challenging to undertake offshore.
- For direct drive turbines, consideration should be given to modular construction (e.g., generator segments) to facilitate fewer challenging lifts in the offshore environment.
- Furthermore, self-hoisting crane concepts that interface with the top of the turbine mainframe may necessitate additional interface considerations when used with a direct drive turbine.

4 **Integrating different types of substructures is a key consideration in using self-hoisting crane technology for major component exchange.**

- The typology of the FOW turbine substructure plays a fundamental role in the feasibility of the major component exchange whilst using self-hoisting crane technologies. Deck space attached to the turbine or floating substructure has the potential to be a limiting factor. As many substructures are not typically designed with suitable working decks, temporary working decks could be a solution.
- Self-hoisting crane developers have not expressed any compatibility concerns with specific substructures, though have stated their technologies may be better suited to specific substructure types. Substructures with larger surface areas and ballasting capabilities, to accommodate additional weights, could be at an advantage.
- Interface standardisation could support the advancement of self-hoisting crane technology in the market.

Figure 8: Reference substructure designs for the Floating Wind JIP.

3.3. Industry needs and innovations

1 **Demonstration programmes are a crucial next step to bring self-hoisting cranes to market.**

- Commercial scale FOW farms are forecast to be in operation by the 2030s and will require significant global capabilities to carry out the required operations and maintenance (O&M) procedures. So far, few concepts have undertaken offshore testing, which will be fundamental for understanding the restrictions of O&M capabilities at a commercial scale.
- While successful onshore tests are important for self-hoisting crane development, offshore testing is necessary to increase industry confidence and refine O&M strategies. Offshore testing and validation steps are likely to look different for the varying self-hoisting crane technologies, as their maturity levels rise, though overall steps could include a demonstration of bottom-fixed offshore wind turbines followed by a demonstration of FOW turbines.
- Key performance indicators (KPIs) could include total operation durations, operational success rates, limiting environmental conditions, feedback from operators, and self-hoisting crane kinematics.

2 **Enhancing crane reach and lifting capacity must be upgraded to accommodate next generation wind turbine generators.**

- Existing self-hoisting crane technologies were historically designed for onshore wind operations, with smaller turbines and consequently a lower lifting capacity requirement. The next generation of FOW turbines will be 15 MW+ and in turn, will require larger lifting capacity and crane reach.
- The commercialisation of self-hoisting crane technologies for major component exchange on 15 MW wind turbines will largely depend on the ability to increase crane lifting capacity. To facilitate O&M operations and major component exchange for turbines up to 15 MW, upgrades are required to the lifting capacity and crane reach of existing solutions.

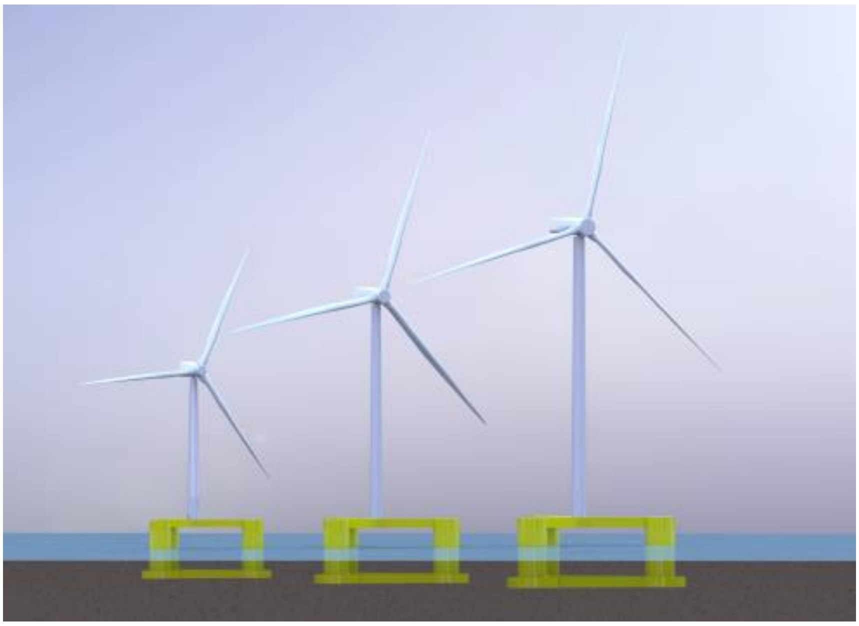


Figure 9: Turbine scaling, provided for the Floating Wind JIP by Ramboll.

3 An increase industry collaboration is required to standardise and optimise self-hoisting crane designs.

- Industry collaboration will be essential to accelerate the commercial deployment of self-hoisting cranes for floating wind turbines.
- It is well understood that in most cases, a collaboration between self-hoisting crane developers and turbine manufacturers is critical to their development including collaboration with substructure designers. The continued support of turbine manufacturers could facilitate design optimisation, broader adoption and market entry for self-hoisting cranes.
- Engaging multiple stakeholders to advance self-hoisting crane design standardisation could prevent early commitment to a particular self-hoisting crane technology, thus ensuring open market competition between self-hoisting crane technologies. It may also help to avoid higher manufacturing costs due to the necessary turbine modifications when using a particular self-hoisting crane technology.
- Clarity is required on the business strategy for SHC utilisation in the O&M strategy. It is unknown if self-hoisting cranes will be sold or rented through contracts and how this could affect the commercial O&M strategies of wind farm operators. This would enable much of the industry to develop their required investment roadmaps.

4. Stick building wind turbine generators on-site

4.1. Project overview

The fixed-bottom offshore wind market has experienced steady growth over the last two decades, but the floating offshore wind (FOW) market is anticipated to develop much faster, to match the global demand for renewable energy. To date, FOW projects have been deployed as small demonstration scale and pre-commercial scale projects, where the wind turbine generator (WTG) assembly process has taken place at the quayside. The WTG is integrated into the floating substructure, before being towed to the offshore site, and subsequently anchored to the seabed and connected to the subsea cables.

As the FOW industry grows and larger floating turbines are installed in deeper waters, attention must be placed on finding practical solutions for their installation. Quayside assembly may not be suitable or cost effective for larger commercial floating wind projects due to factors such as weather restrictions for tow-outs, quayside capacity and length, harbour water depth restrictions and onshore crane capacity at port.

This Stick Building Wind Turbine Generators On-Site (SBOS) project, delivered by Heerema Engineering Solutions (HES) for the Floating Wind JIP built upon previous projects to further identify and assess innovative methods and technologies that permit WTG assembly at FOW farm sites.

Project objectives

1. Assess and evaluate different innovations and enabling technologies that permit WTG assembly at FOW project sites;
2. Outline and define the operational procedures for stick-building on site;
3. Determine the limitations for on-site assembly and identify potential major showstoppers;
4. Encourage versatility in installation methods for floating WTGs and enable significant cost reductions.

Figure 10: Kincardine Wind Farm, courtesy of Arturo Anderson.

Methodology

A review of technologies to assist with stick building on-site was undertaken and technologies assessed against their ability to address floating-to-floating (F2F) challenges and their respective technology readiness level (TRL). These technologies need to enable F2F installation to occur whilst addressing the challenges of relative motions between the floating substructure and vessel, large lifting height and capacity, and the impact of lifting off-centre of gravity (COG) components. The available technologies were categorised as:

- Installation assets;
- Soft landing systems;
- Quick connection systems;
- Complete installation solutions.

Installation scenarios were developed for a shortlist of technologies to identity the critical parameters for SBOS. Four floating substructure types were modelled to assess the WTG installation process considering onshore preparation, transport and offshore installation. The following geographical locations and lifting asset scenarios were used:

- Narbonne, France, reflecting a 'benign' weather environment with a monohull lifting asset, shuttling to port;
- The Straight of Taiwan, reflecting a 'moderate' weather environment with a semi-submersible crane vessel (SSCV) installation with one critical lift and shuttling to port;
- Morro Bay, USA, reflecting a 'harsh' weather environment with a wind farm installation vessel and feeding with a heavy transport vessel (HTV).

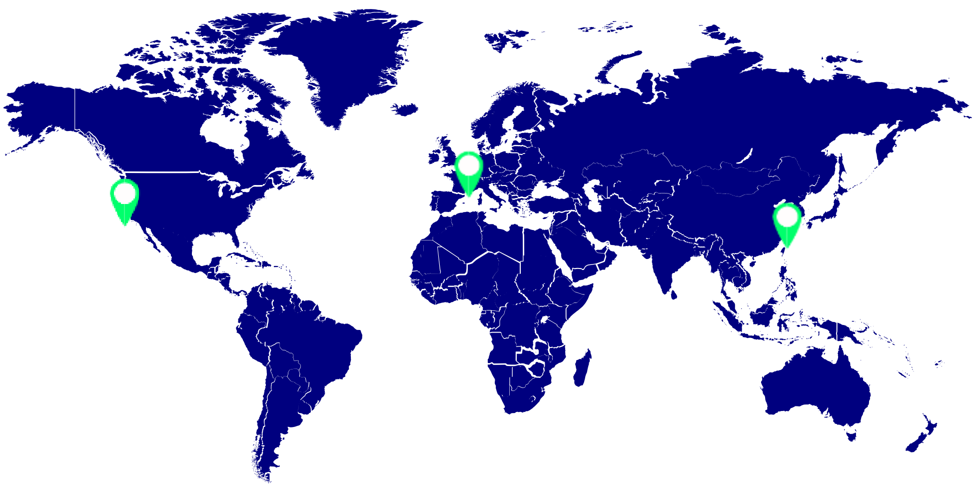


Figure 11: Selected geographic locations for reference environmental conditions.

Hydrodynamic modelling was undertaken to determine the workability and analyse the free hanging installation stage before set down. Workability is defined as the amount of time an operation can be performed within predefined weather conditions. Wind loads were not considered as part of this modelling scenario, therefore advanced hydro-aerodynamic simulations in the time domain will be required to capture the dynamic behaviour affected by varying wind and wave loads.

4.2. Key findings

1 **The current fleet of installation vessels is not designed for large floating WTG installations. Certain new vessel concepts are better equipped for dealing with relative motions between floating structures.**

- For assembly and installation of a 15 MW floating offshore wind turbine (FOWT), a large lift height is required, meaning that few vessels can undertake the installation and those that can are required to utilise their maximum lift height. Consequently, this results in lifts with very short rigging lengths and tight clearances between the payload and the crane.
- To avoid collisions between delicate WTG items and any other objects, minimal allowable clearances between the items should be investigated. In general, smaller clearances result in a lower operability and as such a lower workability.
- Limited space is available on the crane for the connection of tugger systems working in the horizontal direction. With relative motions between the floating bodies offshore, this makes the SBOS operations in general, weather sensitive.
- A tower, nacelle and blade installation were modelled between a monohull vessel and a tension leg platform (TLP) in the benign condition. The tower installation was found to have the highest workability and the blade installation was found to have the lowest workability. The required lift height of the components compared to the crane size leaves short rigging lengths, which results in short pendulum periods. Active compensation tuggers are available on the market, which can actively control the applied damping force on the blades in order to maintain position.
- Certain novel vessel concepts are better equipped to solve the challenge of relative motions, though many of these concepts have low technology readiness levels.

Figure 12: Monohull vessel tower installation (aft view), delivered for the SBOS project by HES.

2 **Mechanical motion compensation grippers allow for a significant relative motion reduction, and avoid unfavourable pendulum behaviour of payloads suspended in slings.**

- A fully assembled WTG installation was modelled in two scenarios: on a TLP with a semi-submersible vessel in moderate conditions and on a spar platform using a wind installation vessel in harsh conditions.

- The lowering of the WTG onto the foundation is a weather sensitive process. In moderate conditions, the workability was found to be extremely poor (47%) during the winter, but manageable during the summer months. The limiting factor in this scenario is the restricted crane boom clearance due to WTG motions. In the harsh conditions, due to natural periods mainly outside the wave domain, the limiting factor was found to be the force of the gripper holding the spar and the vessel motion.
- Mechanical motion compensation grippers are currently entering the market, which allow for significant relative motion reduction, and avoid unfavourable pendulum behaviour of payloads suspended in slings. The limitations of these systems are that they are fairly complex and have a high energy consumption. They also need to overcome a lot of internal friction forces, which limits their ability to quickly respond to motions.

3 **Novel connection systems can improve the workability of the mating operation by reducing the time required to be connected to the floater.**

- Due to the dynamic nature of floating to-floating installation, weather windows can be a bottleneck for the operation. For this reason, quick connection of the WTG components onto the floater is essential for effective installation. Examples of novel connection systems which allow for a quick connection are:
  - Slip Joints;
  - Wedge Connections;
  - Flange Clamp Tools.
- These systems are operated remotely, removing the need for personnel at the instance of mating; thereby reducing the risk of injury during an operation. These example systems are applied in various pilot projects, however, there is yet to be a demonstration in large commercial projects.
- By reducing the duration of the critical stage of connection between the crane vessel and the floater, smaller weather windows can be utilized to increase the overall installation speed.

4.3. Industry needs and innovations

1 **Further analysis of motion compensation systems is required to define their limitations in terms of motion and velocity.**

- The level of motion compensation these systems can provide is governed by the velocity and stroke that the system can achieve. Further investigation is required to obtain a more thorough understanding of the limits of the systems.
- Other effects which determine the efficiency of the compensation system are the interaction between the compensation system and the dynamic positioning system, the effect of friction and sensor delays, and the control strategy.
- Further research and in field tests are required to increase understanding of these aspects of motion control during the FOWT installation scenarios. Validation of results with data from commercial projects in the future is also recommended.

2 Investigate opportunities to optimise floating offshore wind turbine installation strategies by decoupling blade and nacelle installations from the tower installation.

- Several solutions were identified which install WTG components with a separate lift system on the foundation, removing the need for an expensive installation vessel and reducing relative motions. These solutions would also allow installation optimization by decoupling the installation of the wind prone components (blades/nacelle) from the heavier components (towers) which could be installed with the current fleet of installation vessels.
- The potential of such an installation strategy is expected to be large, however, the TRL of these systems is currently low, and more detailed studies and investments are required.

Figure 13: Assembly of tower section, assembly of nacelle on tower section, blade installation, delivered for the SBOS project by HES.

3 Apply structural adjustments to WTG components to aid floating installation from a floating vessel.

The road to industry acceptance includes changes to the current WTG design to aid floating to floating installation. These changes will need to be developed with and supported by turbine OEMs to ensure full industry acceptance. The following modifications are recommended:

- Modifying WTG towers to enable the upending of tower sections, which would result in more efficient deck layouts and reduced installation durations.
- Incorporating strong points in the tower design to withstand external loading during installation. For example, increasing the tower's structural capacity in the radial direction would allow for the application of guiding frames during blade installation, reducing weather sensitivity.
- In the case of direct-drive turbines, the centre of gravity (COG) of the nacelle and WTG assembly is shifted towards the hub. This complicates the installation operation, as the crane hook ends up in an awkward position relative to the COG. It also makes the WTG structure inherently unstable, requiring large and expensive frames to hold the WTG during assembly on deck. Therefore, it is recommended to investigate possibilities for bringing the COG of the WTG assembly closer to the centre of the tower structure.
- It would be beneficial to develop industry accepted installation guidelines for floating-to-floating WTG installation, which can be implemented and reviewed by contractors, developers and marine warranty surveyors. The objective is to guarantee the secure and safe installation of WTGs with consistent and reliable outcomes.

5. Fatigue analysis of high voltage electrical equipment in floating structures

5.1. Project overview

Deployment of floating wind turbines and floating substations creates various challenges, including how electrical equipment is designed for fatigue, and how test procedures will be developed to provide an adequate representation of the fatigue damage experienced over the design life of the equipment while operational on floating structures. This is complicated by the accelerations electrical equipment will endure in floating structures being dependent not only on the local metocean characteristics but also the different motion characteristics of varying types of floating structures.

To date, only pre-commercial designs for floating wind turbines have been developed. An example of this is the 50 MW Kincardine Offshore Floating Wind Farm, which consists of five 9.5 MW and two 2 MW turbines based on semi-submersible substructures. The only floating substation deployed to date was in support of the Fukushima FORWARD programme, which supported a pilot scale floating wind demonstrator farm. The substation was positioned on an advanced spar substructure, with a helipad and met mast installed.[3]

This Fatigue Analysis of High Voltage Electrical Equipment in Floating Structures (HVEF) project, delivered by Petrofac for the Floating Wind JIP, set out to better understand high voltage electrical equipment design and its suitability for operation in offshore floating structures.

Figure 14. 66kV substation "Fukushima Kizuna", Courtesy of Fukushima Offshore Wind Consortium.[3]

Project objectives

1. Obtain a greater understanding of fatigue analysis of electrical equipment in floating structures through the identification of relevant forces and weak points of electrical equipment sensitive to acceleration stress;
2. Advise on potential design changes required and a type-test program for floating wind applications;
3. Determine a basis of feasibility for the application of electrical components in floating wind, identifying the associated risks and costs incurred.

[3] (PDF) Construction of Phase 1, Fukushima FORWARD, available at http://www.fukushima-forward.jp/

Methodology

A combination of simulations was conducted with varying motion characteristics and floating foundation solutions for both WTGs and offshore substations. This enabled a better understanding of the accelerations electrical equipment would have to endure under the specified conditions and parameters outlined below. It is important to highlight that the high voltage elements in the offshore substation operate at significantly higher voltages compared to those found in the offshore wind turbine.

This analysis was performed in the time domain using the mooring analysis programme OrcaFlex. The simulations were modelled considering the following designs and environments:

Wind turbine generators (WTGs)

- 15 MW turbine on a spar hull;
- 15 MW turbine on a semi-submersible hull.

Substations

- 250 MW substation on a semi-submersible hull;
- 800 MW substation on a semi-submersible hull;
- 250 MW substation on a TLP hull;
- 250 MW substation on a barge hull.

Environments

- 'Benign' similar to a Mediterranean Sea deployment;
- 'Moderate' similar to offshore California or Japan;
- 'Harsh' similar to that found in the North Sea.

Damage equivalent load (DEL) calculation & comparison

1. Acceleration parameters for each design and mooring system were obtained and simplified to a damage equivalent load (DEL), which enabled comparison between different fatigue environments via a common metric which can be quantified;
    - Electrical components of the wind turbine are concentrated in the nacelle, and so a single set of acceleration data was extracted for this location.
    - Within the substation, the electrical equipment is more distributed and therefore the acceleration data was extracted for the centre of the transformer, reactor, HV switchgear and auxiliary transformer.
2. The frequency content of each simulation was calculated by performing a Fourier transform and used to produce a combined power spectral density (PSD) plot to determine where the energy was concentrated in the frequency spectrum;
3. Vibration test standards were investigated for qualifying electrical equipment and DELs were calculated from the defined parameters in DNV-CG-0339;
4. The test standard DELs were then compared with the simulated and calculated acceleration levels from the varying designs and environments;
5. A more applicable test specification methodology was developed, and the practical considerations were discussed.

5.2. Key findings

1 **Fatigue accelerations are higher in wind turbine nacelles than in all substation vessel types, however the extent is dependent on floating structure type, environment and mooring design.**

- It was found that the DELs in the wind turbine nacelle for both the assessed spar and semi-submersible designs were generally higher than those anywhere on any of the substations, as the motions generated in the nacelle due to pitch and roll of the floating WTG structure were amplified by the tower height. In general, the DELs for components in the wind turbine nacelle were approximately three times those seen in the substations.
- The exception to this was the substation TLP design, where high frequency vertical accelerations were seen to result in a significantly higher DEL compared to the other substation hull designs. This was most noticeable in the benign environment, where interaction between the wave frequency and the vertical natural frequency was responsible for an amplified response. This was not the case for the harsh environment, where the DEL was comparable to the other three substations. Tuning of the hull form and tendon stiffness specifically to the deployment location would be an effective way to reduce this effect.
- The semi-submersible substations demonstrated the lowest DELs across all sites due to their resistance to wave-induced motion and the separation between the wave frequency loading and the hydrodynamic natural periods.

2 **Existing vibration test standards are not designed to perform as fatigue tests for floating offshore substation environments.**

- The review of DNV-CG-0339 and similar standards found that these existing standards are designed to identify problematic areas of resonance at the types of forcing frequencies seen in shipping environments. The fatigue environment that the reviewed standards are intended for is not representative of a substation environment due to the absence of significant sources of vibration including marine diesel engines, rotating machinery or compressors, therefore making the existing standards unsuitable. The wind turbine nacelle will see high frequency vibration from the rotor and gearbox, but the mechanical vibration is a similar environment to that experienced in existing fixed-bottom turbines and hence does not represent a new feature of a floating structure.
- Adopting the test methodology of the existing standards, which focus on identifying resonance, has the potential to create misleading test results. This is due to the floating structure vibration environment relating to wave frequencies, and the test frequency would be higher than experienced in the real world environment.
- The DELs calculated from the test accelerations were compared to the DELs obtained from the wind turbine and substation designs, assuming a 20 year design life. It was determined that the DEL for the test acceleration defined in the standards was not certain to exceed 20 years of life as per the simulations conducted in this project and therefore the test specification was not suitable for use without modification.

3 **The fatigue test specification should be developed to match the required DEL accelerations calculated through simulations.**

- A methodology was presented to determine a target test DEL from the DELs established within the simulations for each floating structure type and environment, including adjustments to be made to allow for design life and design fatigue factor. This enables various combinations of acceleration, frequency and duration to be assessed to determine if a feasible test programme can be developed.
- A constant sinusoidal test is considered to be the most appropriate method to apply for testing equipment in the offshore environment due to the dominance of the energy at the wave frequency and the absence of rotating machinery. Using this method, it can be demonstrated that the fatigue damage incurred during the test will be an acceptable match for the fatigue damage accumulated in service, provided various constraints are met.

4 **There are currently limited test facilities for equipment weighing over 20 tonnes; planning the fatigue strategy should account for further specific constraints.**

- When determining the test frequency, acceleration and duration for a given target DEL, further limitations should be considered which may arise from:
    - Structural resonance
    - Nonlinearity of response
    - The non-propagating stress limit
    - The test facility capabilities
- Satisfying all of these constraints becomes increasingly difficult as the equipment under test (EUT) mass and physical dimensions increase. An investigation into test facilities available in Europe showed that the choice was limited beyond an EUT mass of 20 tonnes. Beyond 50 tonnes, physical testing may not be feasible, depending on the acceleration level and test duration required.

5 **Design by analysis approach should be adopted for testing larger items of equipment.**

- Full physical testing offers the most clarity for validating design life and identification of failure points which may potentially lead to improved future design, however for larger items of equipment, the acceleration that a test facility is able to generate can become the limiting factor. Extending the test duration to accumulate a sufficient number of cycles is of limited use, as the nonlinear relationship between stress and damage means that the time required to complete the test rapidly increases with a reduced acceleration input. In addition, the high capital cost for large items of equipment produced in small quantities also reduces the attractiveness of performing a physical destructive test.
- In this case, a design by analysis method should be considered to demonstrate the fatigue performance of the electrical equipment via finite element analysis, or even via hand calculations if the structure is suitably uncomplicated. The potential of adopting a hybrid approach between

physical testing of subassemblies coupled with analysis of the complete equipment should be considered as a means by which the benefits of both methods can be obtained.

5.3. Industry needs and innovations

1 **Development of generalised acceleration bands corresponding to different floating structure types and environments.**

- For an electrical equipment manufacturer, designing or following test specifications for individual structures types and environments is expensive and time consuming.
- Minimising the number of tests required to qualify equipment would therefore reduce the cost of developing new designs. Development of electrical equipment suitable for use in multiple projects could be streamlined by testing to an acceleration level that bounds the required project accelerations.
- Setting criteria based on classes of environment (for instance similar to the IEC wind turbine classes) would enable qualification of equipment by manufacturers without having to requalify them for every project.[4]

2 **Standards for performing fatigue testing for use in floating offshore wind deployments.**

- Due to the differences between the fatigue environments considered in the existing vibration testing standards and those experienced by components installed on floating structures, a standard should be developed for performing fatigue testing specifically for use on FOW structures.

3 **Industry would benefit from more test facilities for equipment larger than 20 tonnes equipment.**

- A survey of testing facilities in Europe found that the number of facilities able to test equipment in excess of 20 tonnes is relatively limited, and testing equipment beyond 50 tonnes may not be feasible, depending on size and acceleration requirements. In this case, testing should be performed using a finite element model or a potential hybrid methodology which physically tests subassemblies of large equipment.

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[4] IEC 64100-1. Geneva, Switzerland: International Electrotechnical Commission; 2005.

6. Dynamic cable failure rates and standards

6.1. Project overview

The Dynamic Cable Failure Rates (DCFR) project was delivered by Offshore Wind Consultants in collaboration with the University of Exeter for the Floating Wind JIP.

With floating wind technology only approaching its early commercialisation phase, dynamic cable systems for floating wind are still under development. Since the dynamic nature of FOW structures presents unique challenges, and with large scale floating wind installations planned in the coming years (e.g., 4.5 GW in the Celtic Sea), the development of robust dynamic cable systems and solutions is essential.

Knowledge about both static and dynamic power cable technology, and their associated lifetimes, is a key limiting factor in the move towards the realisation of successful installation and operation of floating offshore farms. However, due to the immaturity of the technology and its short history in the industry, there is currently a limited understanding of the fatigue lifetime and expected failures of dynamic cable systems.

Improving the understanding of subsea cable failure rates and mechanisms is integral to the development of the FOW industry. To achieve this, the collection, classification and analysis of failure rate data is critical to determine and mitigate the highest risk failures. Furthermore, standardisation of rules and regulations for the design and testing of dynamic power cables could be seen as essential to mitigate risk and provide a good foundation for confidence in dynamic cable operation and longevity once installed in a FOW farm.

This aims of the project were to provide insight into the basis of feasibility for the application of dynamic cables in floating wind, as well as to advise on the potential changes required in dynamic cable design, qualification, and testing.

Project objectives

1. Obtain a better understanding of dynamic cable failure rates and standards, to inform the data collection requirements for future floating wind development and dynamic cable modelling and testing.
2. Provide insight into dynamic cable design considerations for preventing failure events.
3. Provide recommendations for the standardisation of testing and fatigue modelling methods for dynamic cables.
4. Provide recommendations on a standard process for working with dynamic cables, leading to reductions in overall costs.

Methodology

The project methodology sought to provide a better understanding of dynamic cable failure rates, modes, and root causes, as well as to evaluate existing cable testing and qualification standards through extensive literature and data review, and stakeholder engagement. In addition, a methodology was proposed to approach both the load modelling and fatigue assessment that could be used to understand the impact of a wide range of dynamic cable design decisions on its fatigue life.

The cable failure literature and data review covered both static and dynamic systems in offshore renewables and oil and gas contexts, and was conducted in the following stages:

i. mapping the relevant components and sub-assemblies of dynamic cable systems,

ii. reviewing failure data sources,

iii. analysing failure data,

iv. contextualizing failures with a view to lifetime phases and system configurations for floating wind.

Surveys and interviews with key industry stakeholders (including cable and ancillary manufacturers and research institutes) were undertaken to obtain industry views on the main risks involved in working with dynamic cable systems and to understand the main challenges that are anticipated in the future.

The review of standards related to submarine dynamic power cables was mainly focused on mechanical, electrical, and fatigue testing, and covered 62 publications from multiple regulatory bodies, including DNV, ISO, API, IEC, CIGRE, ABS, and BV. The standards were categorised based on three criteria:

- Type of cable (static/dynamic)
- Field of application (oil and gas/offshore renewable energy)
- Type of component (cable/ancillaries)

The identified standards were further screened regarding their direct applicability to subsea cables; the resulting shortlist of standards was used to assess and summarise best practices, and recommendations were made for future development and applications of standards for dynamic subsea cables.

Cable load modelling and fatigue assessment was carried out using OrcaFlex software and was focused on a single reference model – a semi-submersible floater, water depth of 150m and harsh environmental conditions. The dynamic cable parameters were varied in order to ascertain the impact on the resulting loads and cable fatigue. It is important to note that although different offshore sites and floater/cable configurations will have different absolute fatigue life's, the relative qualitative assessment performed identifies relations and trends which can be applied more widely.

6.2. Key findings

There is limited data focused on failure rates of dynamic power cables. This is due to the limited number of installations over a short time period and a lack of formal reporting framework for component failures of floating wind deployments. Therefore, there is a reliance on static cable failure information, which has been reflected in the findings of this report.

The review and analysis of the available failure rate data of static offshore wind subsea cables yielded an average failure rate envelope between 0.0019 failures/km/year and 0.0213 failures/km/year[5], with installation and manufacturing as the most common failure modes.

Understanding dynamic cable failures requires addressing the historically observed causes of cable failures, drawing from lessons learned in static power cable applications. However, the cyclical nature of wave, wind and current loads in FOW structures suggests that fatigue will assume a significantly more crucial role in dynamic cable systems.

1 There are no comprehensive standards for the testing and qualification of dynamic cables, with too much reliance on standards intended for the oil and gas industry.

- Dynamic subsea cable systems are still under development with no large scale commercial farms yet installed. The testing and qualification of dynamic cables and associated infrastructure is therefore also at a developmental stage.
- Of the 62 standards and guidelines reviewed, 16 were directly applicable to subsea power cables (11 indirectly applicable). Only 6 publications were directly applicable to dynamic subsea power cables, but all of them refer to previous standards.
- The main concerns relate to the over-reliance on oil and gas publications, implying that standards are not specific to offshore wind applications. For example, certain oil and gas standards imply high safety factors and installations in very deep waters, which are less applicable to most floating renewable energy installations.
- No existing cable standard gives detailed guidance on selection, design, and use of ancillary equipment such as bend stiffeners and buoyancy modules, especially for high voltage dynamic cables.

2 Fatigue is expected to be one of most the predominant failure modes for dynamic cables that the industry will have to address moving forward, primarily by ensuring adequate cable design.

- A combination of high tension and large curvature over many wave cycles is the primary cause for cable fatigue damage.
- Dynamic cable fatigue damage is in large part driven by curvature as the cable transitions from the water column into the I-tube. Due to the proximity with the sea surface and the floater, the cable will see the most hydrodynamic load applied to it and higher bending in this location. It is

[5] Using the failure rate data from Warnock et al. (2019) and additional sourced data regarding asset age and cable length.

also relatively close to the hang-off, where the weight-derived tension is the highest. However, all dynamic sections need to be carefully analysed as other locations can also be of concern.

- For the modelled cable design and environmental conditions, much greater fatigue damage was observed when the direction of environmental loads was closely aligned with the cable orientation. Based on these results, cable azimuth should be designed away from the prevalent wave directions.
- Greater cable diameter was found to induce higher hydrodynamic load ranges, and consequently higher stress ranges inside the cable, leading to reduced fatigue lifetime.
- Under the specific cable design and load conditions applied in the model, marine growth was found to increase fatigue life, primarily by decreasing curvature at the critical section where the cable exits the I-tube and bend stiffener.

3 **Comprehensive model inputs are required and should be validated for dynamic cable fatigue modelling to be accurate and applicable to real world scenarios.**

- Detailed site conditions, floater specific modelling (considering the floater's shape and weight distribution, its dynamic response to environmental loads), and mooring system specifications are essential in modelling and can help reduce failure risk.
- It is important to define an accurate and relevant cable segmentation, as well as to have consistent cable global parameters.
- Cable ancillaries (buoyancy modules, bending stiffeners, I-tube) must be modelled, including sensitivities regarding the containment between the dynamic cable and its ancillaries. Ancillary specifications should be provided by manufacturers as they become available.
- Consistent and related S-N curves and stress factor data must be provided and be consistent with the actual dynamic cable studied.
- Future studies would be advised to always run both with-current (and using the maximum floater offsets) and without-current cases to ensure all possible catenary shapes are captured, since it appears to have an effect. In addition, local analysis accounting for stick-slip behaviour in the cable is recommended.

4 **Dynamic cable accessories need to be appropriately designed and implemented to provide the necessary support to the full cable system and to prevent accessory related failures.**

- The dynamic cable system includes not only the cables themselves, but also a range of accessories and components used to connect, stabilise and protect the cables, as highlighted in Figure 15.
- Bend stiffeners were the accessories indicated as the most likely to impact the probability of the dynamic cable itself to fail in terms of how well it is designed, manufactured, or installed.
    - Dynamic bend stiffeners can be an excellent solution to cope with heavy axial loads and curvatures to avoid overbending and fatigue failure. However, these components are currently limited to a certain cable size.

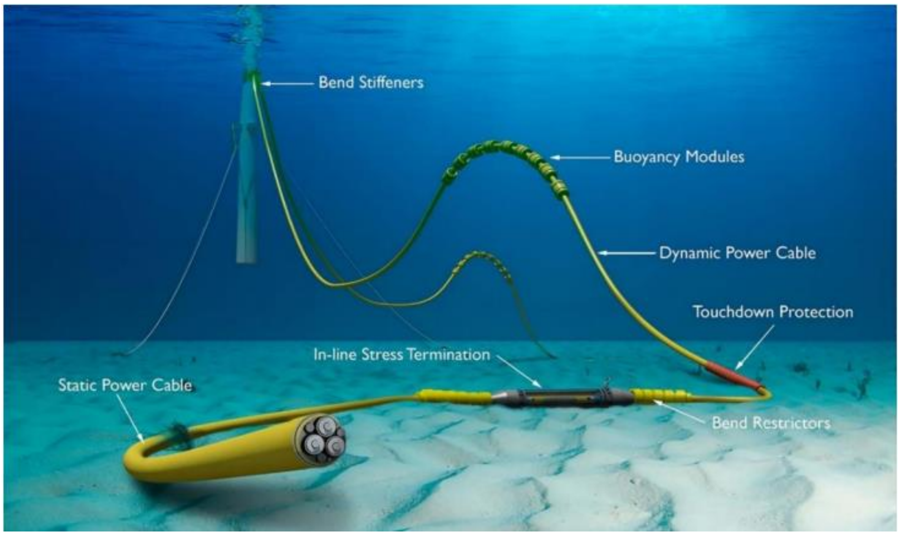

Figure 15. Primary components of dynamic subsea cable systems. (Joshua Bauer, NREL)

- Buoyancy modules also require further development in design, with emphasis on clamps used to secure the distributed buoyancy modules to the cable. Fewer, larger buoyancy modules can reduce the installation's time, costs, and HSE hazards, but considerations on the system's dynamic performance are necessary.

6.3. Industry needs and innovations

1 **Investment in cable testing facilities is needed to enable full scale, combined testing of dynamic cables. Investment in cable testing facilities is needed to enable full scale, combined testing of dynamic cables.**

- Current testing approaches that make use of S-N curves of material coupons are likely to lead to conservative estimates of the fatigue life of complete dynamic cables. Alternative methods should be investigated, such as full scale cable fatigue tests for representative cables, allowing to determine the fatigue life of the full assembly.
- Combined fatigue testing to concurrently assess dynamic cable performance under mechanical, electrical, and thermal stress would make testing more representative. Further development of non-destructive testing techniques to enable monitoring and assessment of fatigue failure during testing (rather than through dissection at the end) would improve failure detection and cable qualification.
- Testing for cable ancillaries should be more specified, including tests on their own (e.g., simulating extreme metocean conditions) as well as combined tests with the cable itself to get a more realistic assessment of failure modes and component capacities.

2 **The industry would greatly benefit from specific dynamic cable standards and load classes.**

- Increased effort is needed to develop bespoke standards for the offshore renewable energy industry and reduce reliance on oil and gas standards, where possible.

- The design and loading of dynamic cables are highly dependent on environmental conditions, installation method, cable configuration and floater type. As a result, current cable designs and test programs are project specific. However, large scale commercial installation will require a more standardised design and test program, including representative design load classes.

3 **Continued stakeholder cooperation and knowledge exchange will be crucial for further development of dynamic cable systems.**

- The development of new testing programmes and cable standards will require the collaboration of multiple stakeholders, including cable manufacturers, the ancillary supply chain, certification agencies, installation contractors, insurers, test facilities, researchers, and asset owners.
- An industry-wide platform for sharing the experience and knowledge between different segments of the industry could be very beneficial. A stronger interface between the suppliers and manufacturers of different components could facilitate the cable design process.
- The collection, classification and analysis of failure rate data is critical to determine and mitigate the highest risk failures. Higher data quality and more data availability will be instrumental for quantifying and reducing the risk of cable failure for floating wind installations.

References

Warnock, J., McMillan, D., Pilgrim, J. and Shenton, S., 2019. Failure rates of offshore wind transmission systems. *Energies*, *12*(14), p.2682.

7. Mooring system redundancy, reliability and integrity

7.1. Project overview

Mooring systems are a crucial component of a FOW asset. The assessment of reliability and failure for floating offshore wind turbine (FOWT) mooring systems has traditionally been drawn from sectors like Oil & Gas (O&G), where historical data indicates mooring failure rates are relatively high. In comparison to traditional floating marine assets, the FOWT mooring system will experience increased and varying loading due to the effect of the turbine. This, and the additional loads due to ever-increasing turbine sizes, are leading to high uncertainties surrounding project risk. To mitigate the risk of potential mooing line failures, higher levels of redundancy and/or conservatism may be incorporated in the mooring system design, resulting in increased capital expenditure (CAPEX) and operational expenditure (OPEX). This high level of conservatism will be difficult to introduce in commercial scale floating wind, as large numbers of mooring lines are required for multiple units, potentially making the mooring system commercially unviable.

This Moorings System Redundancy, Reliability & Integrity (MRR&I) project was delivered by a consortium led by AMOG, with sowento, Peak Wind and Offspring International, which provides both floating wind and O&G experience. The project, delivered through the Floating Wind JIP, investigated if high failure rates seen in other sectors should be applied to floating offshore wind. It sought to understand and identify how the industry can quantify potential floating wind-specific failures within project planning. This summary report outlines the project's key findings and highlights future requirements and needs for the industry.

Project objectives

The project aim was to increase clarity around the definition of 'redundancy' in relation to a three-cluster mooring system – with either a single leg or two legs per cluster. The project objectives were to:

1. Investigate the likelihood and impact of mooring failure specific to FOW systems by undertaking analysis to understand the root cause of failures within O&G and how these could translate to failure rates in floating wind;
2. Understand how the mooring system redundancy is affected by the integrated design of the mooring system, floating foundation, WTG and control system;
3. Understand and quantify potential failure rates, taking into consideration inspections during operation and their potential to address failure rates;
4. Compare the through-life cost differences between redundant and non-redundant systems across a range of different mooring technologies, taking into consideration the relationship between initial CAPEX and ongoing OPEX of a project;
5. Undertake analysis of synthetic mooring line solutions in context to their potential to reduce failure rates and failure modes and quantify how they could benefit both CAPEX and OPEX.

Methodology

The project investigated mooring system risks and failure rates across the offshore wind industry for a 15 MW semi-submersible system. Both chain and semi-synthetic (polyester and chain) mooring systems were analysed and compared in 3x1 (one line per anchor) and 3x2 (two lines per anchor) mooring configurations.

The methodological approach was as follows:

- **Mooring Design Development:** Reviewed and iterated the previously development 15 MW Carbon Trust reference mooring designs for fatigue limit state (FLS) while maintaining ultimate limit state (ULS) compliance from global aero-hydro-servo-elastic simulations.
- **Failure Modes and Effects Analysis (FMEA):** Identification of degradation threats relevant to FOW moorings, through comparison with O&G and marine sectors.
- **Mooring Failure Rates:** Collation of mooring failure rates through assessment of historical failures in the O&G industry, adjustments for the FOWT sector and additional data from the literature.
- **CAPEX Assessment:** Development of a CAPEX basis for each mooring configuration developed.
- **Reliability, Availability and Maintainability (RAM) Analysis**: Simulation with RAM models to determine mooring system availability and OPEX through-life; inclusive of inspection, sparing and remediation event modelling. These simulations used the results from the global response modelling to accurately capture floating wind specific degradation mechanisms.
- **Gap Analysis and Industry Requirements Review:** Identification of needs for the industry on a lifecycle basis along with areas for future research; including standardisation pathways and qualification plans for synthetics.

The following key assumptions were made for simulation studies:

- The redundant mooring system must maintain cable connection after the loss of a mooring leg. The 3x1 mooring designs were considered non-redundant, as after the loss of a line the WTG was unable to maintain station, exceeding the dynamic cable watch circle, resulting in a loss of connection.
- The mooring systems were designed to be compliant with industry standards for ultimate limit state (ULS), fatigue limit state (FLS) and accidental limit state (ALS).
- Moderate environmental conditions were used, with a modelled water depth of 150 m.

Figure 16: 15 MW reference substructure designs for the Floating Wind JIP. This project was based upon an updated version of the semi-submersible design.

7.2. Key findings

1 **Many of the mooring degradation threats present in the O&G industry are also applicable to floating offshore wind, however, this may change as the industry develops and new technologies emerge.**

- Threats, such as manufacturing defects and installation damage, are independent of the loading experienced by the mooring system. While well understood from the traditional energy sector, learnings such as increased installation knowledge/experience following initial large scale commercial array installations and specific FOWT fabrication processes may reduce these.
- FOWTs are subject to relative motions and forces on the system, which was shown to exacerbate some existing threats such as fatigue and wear, when compared to existing O&G installations.
- Innovation would be required in mooring designs for FOW to reduce costs. New technologies such as Nylon ropes and Load Reduction Devices may feature in future mooring systems. These technologies require extensive qualification and certification for full scale and long term floating wind applications.
- New technology may introduce further degradation threats that are not present in current mooring systems. The threats introduced which are relevant to FOW may produce a divergence of design and failure modes away from the current O&G and maritime sectors, currently used as the basis for floating wind.
- Activities that foster collaboration and knowledge sharing will assist in understanding and mitigating these. Examples include the development of an industry-wide failure/threat database and joint studies that aim to increase the theoretical understanding of degradation threats.

2 **Significant risks were found to arise from common mode failure threats, such as poor design affecting the whole array, as well as start of life threats.**

- Common mode failures, such as poor design or manufacturing defects, are highlighted as a significant risk to the economic viability of a wind farm. Multiple FOWT units may be affected by the same degradation threat. Figure 17 shows the cost and occurrence of degradation threats for a 50-unit wind farm, and spotlights manufacturing defects as one of the highest costs across the wind farm lifetime. Of note is the low occurrence of fatigue-related failures, resulting from the mooring system designs being compliant with Fatigue Limit State code requirements in an assumed benign corrosion environment.
- Start of life threats that have a high likelihood of occurrence, such as manufacturing defects and installation damage, were found to be significant due to the high potential remediation cost and its effect on the viability case of a FOWT farm. Minimising the likelihood of failures and system downtime early in the farm's lifetime will be a key consideration given the impact of availability on the wind farm's rate of return.
- Risks arising from through-life threats, such as corrosion and wear processes, could be reduced through the development of suitable approaches to the provision of functional spares, and the use of risk-based inspection methodologies (RBI).
- If there is accelerated development of commercial scale wind farms, there is an increased probability that a variety of failure issues may arise. It is important to manage these risks through

a robust and rigorous design process and the application of a well understood Mooring Integrity Management strategy.

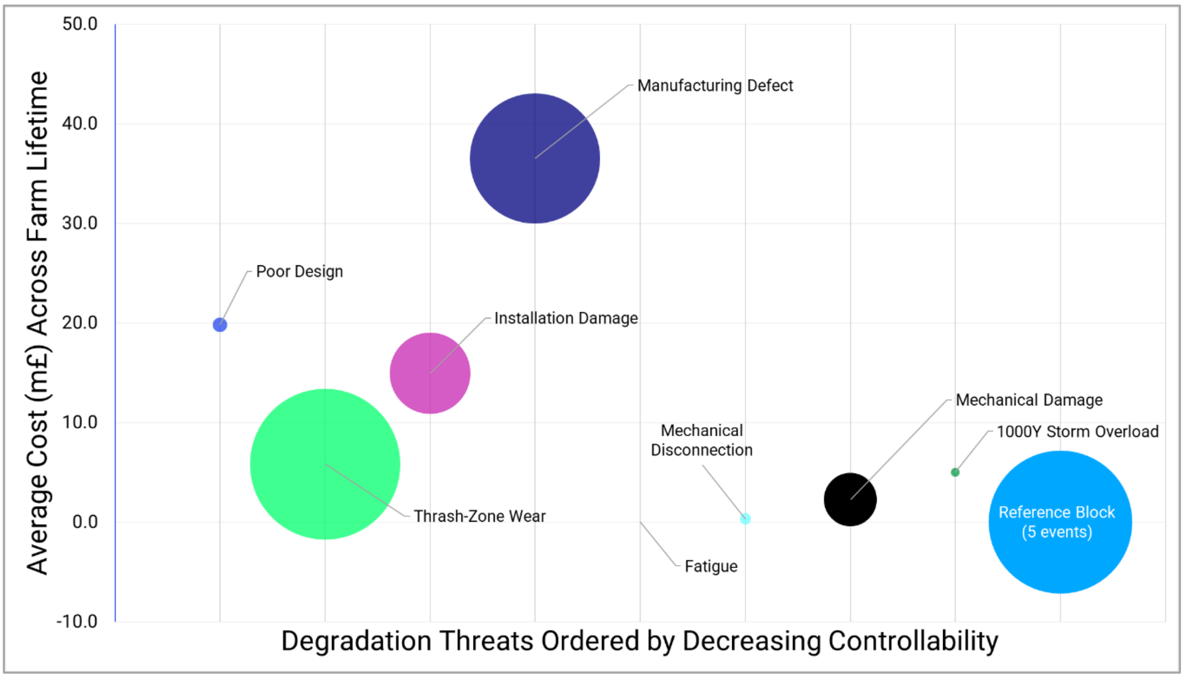

Figure 17: Cost and occurrence of degradation threats across a 50-unit farm.

3 **Fatigue loading was identified as the governing design parameter critical for FOW design.**

- For moderate sea states, low-frequency platform motion dominates fatigue loads, due to excitation by second-order slow-drift forces and wind turbulence. First order wave forcing might have an influence for conditions or sites with severe to harsh wave conditions.
- The magnitude of second-order slow-drift loads is determined not only by the significant wave height but also by the dominant wave periods, which can result in counter intuitive large load responses at lower sea-states. The effect of mean tensions in the calculation of fatigue should be included, as neglecting mean tensions will be considered non-conservative.
- Increased wind turbulence, potentially due to full or partial wake situations, throughout the turbine's lifetime is a sensitive parameter on the mooring fatigue loading.
- The wind turbine generator torque and blade pitch controller has a large effect on low frequency platform motion and therefore mooring fatigue. The biggest controller impact for FOWTs is seen at operating points slightly above rated wind speeds, with an active blade pitch controller. However, controllers can be tuned at these operating points for reduced low-frequency motion without significant additional actuator wear, which is promising for an increased lifetime or lighter mooring designs.
- Creep of synthetic ropes should be considered in the design and maintenance plan. The permanent extension, resulting from a severe loading event, can result in the platform no longer maintaining its station limits/exceeding the design watch circle. Therefore, re-tensioning of the mooring lines may have to be considered throughout the system's lifetime.

4 **Mooring configurations that have redundancy may provide a lower risk solution when compared to non-redundant systems.**

- Redundant systems were found to experience a reduced number of higher consequence failure events, which would impact the dynamic infield cables and could foreseeably impact surrounding infrastructure in the case of a system losing its station keeping ability.
- Redundant systems saw improved start-of-life availability during the early years of operation when compared to non-redundant systems. The selection of a redundant design over a non-redundant design is nuanced as factors such as capital costs, installation scheduling and installation risk, may alter a project's overall risk tolerance. It also assumes a redundant system continues to operate in the event of a one line failure event.
- Additional factors need to be considered during the design phase, such as emergency response and incident planning, and the ability to effect repairs in situ, which may be of particular importance for non-redundant system configurations.

5 **The cost or availability benefit of different mooring system configurations is highly dependent on specific design factors.**

- Factors such as varying water depth, controller design, and the overall development's insurance and contractual strategies would all impact the mooring system configuration and hence the overall economic viability.
- The availability of the specific project hybrid system examined was found to be lower than the all-chain system due to the additional failure mechanisms introduced into the system from the synthetic components and their associated hardware. This is a finding attributable to the specific system design basis.
- In addition to the higher rates of failure, the consequences of failure were also more severe, as synthetic components on non-failed mooring lines were found to contact the seabed, which with current guidance would likely trigger replacement.
- As with redundancy, project developers should consider the specifics of their development and system design, along with the whole-of-project implications when selecting the mooring system materials for their specific development.

6 **Operational optimisations such as implementing a risk-based inspection (RBI) regime and carrying sufficient spares were found to provide significant benefits.**

- Implementing a combined risk based inspection and monitoring regime along with sufficient sparing in early life were two measures found to provide significant economic benefits for the wind farms modelled.
- Despite the best endeavours employed through the design, manufacturing, and installation phases, there remains the possibility of the emergence of unanticipated threats in the operating phase. This is particularly prominent during the early years of an asset's lifetime, as shown in Figure 18 below, as understanding and experience are being acquired.

- Inspection, monitoring, and sparing practices will therefore need to account for such unanticipated threats to allow for efficient remediation of issues, should they arise. As demonstrated in Figure 18, this coincides with the infant mortality (beginning) and wear-out (end of life) stages of the mooring system.

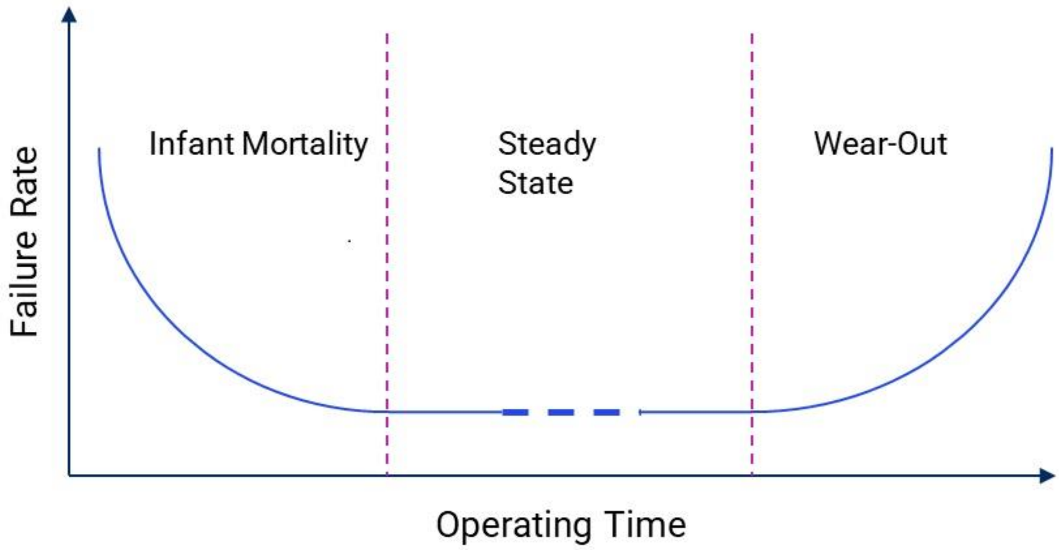

Figure 18. Typical bathtub shaped failure curve throughout the lifetime of the mooring system.

7.3. Industry needs and innovations

1 **Opportunities exist for further development of standards and guidance for managing mooring components throughout the lifetime of the floating offshore wind farm.**

There are a number of key areas for standards & practices development including:

- Improved guidance and best practice for the transport, load-out and installation of mooring hardware will minimise instances of damage during installation and therefore reduce potential shutdown instances arising from early life failure.
- During operation, clear guidelines for the re-use of mooring components that may have been placed in adverse operational conditions as a result of a mooring failure (such as touch down) will be vital for the expedient reinstatement of a system.
- Improved guidance during the design phase, particularly in the areas of:
    - Design responses post failure.
    - Application of synthetic rope model design processes, accounting for pre-stretching of synthetic ropes.
    - Clustering/bracketing of the design basis for groups of turbines across large wind farms, to assess emerging risks.

2 **Employing a comprehensive mooring integrity management strategy (MIM) from the design phase onwards will be crucial in minimising failure threats through-life.**

- Wind farm design will play a significant role in mitigating common mode failure threats, which pose a significant challenge to the commercial viability of an array. Overload is one example, where unlike O&G sector, multiple units will be exposed to the same severe storm.
- It is essential to understand the robustness and resilience to which specific mooring systems are designed, and it is crucial to align them with the risk tolerance while considering the potential outcomes of events like severe storms. An exhaustive design process and a comprehensive mooring integrity management strategy (MIM) with spare parts strategies, will be necessary. This can be achieved by applying appropriate controls, set in place across design, manufacturing, and installation phases.
- The industry should emphasize design quality assurance given the severity of common mode design flaws. Design flaw failures can be reduced through:
    - Proper characterisation of the environment and design basis.
    - Utilisation of industry best practices, along with ensuring materials selected are used within an envelope to which they're qualified.

3 **Emerging mooring technologies should be qualified against functional requirements, and only used in applications for which they are properly qualified.**

- New technologies (such as nylon lines or load reduction devices) will be developed to improve the viability of floating wind farms. An assessment of functional requirements for these new materials and components will be required to ensure functionality at full scale.
- Without rigorous qualification plans, components and materials may operate outside of their verified performance windows. This increases the risk of common cause failures across multiple units, which consequently impacts the viability, bankability and insurability of large scale floating wind developments.

4 **Mooring system design needs to be considered as part of a holistic wind farm design process.**

- Whilst the focus of this project was on the mooring system specifically, there are clear interdependencies between turbine, controller, hull, cable, and mooring design. Mooring design cannot occur separately from the design process of these other systems.
- The implications for the dynamic cable system, and the possible interactions between other units and infrastructure in the event of a mooring failure, emphasise the significance of considering whole-of-farm consequences and therefore redundant mooring configurations.
- There is a significant opportunity for mooring cost optimisation if the wind turbine controller and associated systems can be tuned to reduce the fatigue loading on the moorings. Ultimate loads in a one-line-failed situation can drive a redundant system design. These transient loads depend on the safety system, which might or might not shut down the turbine after detecting a mooring failure.
- Experience from other sectors shows cost optimisations in one phase of the project may result in significant expenditure in another phase, and only by considering the full system and lifecycle can the most cost effective solution be developed.

8. Floating Wind JIP Stage 3

8.1. Stage 3 programme objectives

Stage 3 of the Floating Wind JIP commenced in 2022 and projects are expected to run until early 2027. With several commercial scale floating offshore wind farm projects in design phase and having the ambition to be commissioned by 2030, the industry needs to address several challenges. The 17 Floating Wind JIP partners agreed on the following Stage 3 ambitions for each focus area. Stage 3 projects will be targeted to address these ambitions.

Mooring systems

1	Define optimal mooring layout and anchoring for different challenging environments and model subsea interactions.
2	Better understand the integrity of mooring lines through improved monitoring techniques.
3	Understand how geographical and material selection affect the availability and manufacturing capabilities of different mooring and anchoring solutions.

Asset integrity

1	Scale up technologies such as ROVs and wider autonomous systems to improve monitoring and inspection operations.
2	Improve modelling systems such as the development digital twin and AI solutions to understand lifecycle integrity at component, floater and windfarm level.

Electrical systems

1	Understand full electrical system design for commercial scale floating wind farms.
2	Define dynamic array and export cable architecture for commercial scale floating wind.
3	Advance understanding of dynamic cable failures to accelerate towards more reliable and insurable systems.

Logistics

1	Understand the required port developments for commercial scale floating wind farms assembly in key markets.
2	Understand how water depth and environment affects the entire installation process.
3	Remove barriers to allow for commercial scale major component exchange offshore.
4	Understand how wet storage will be managed/addressed by the port and the wider industry.
5	Understand how the increase in ports bearing capacity requirements will be addressed by the industry.

Windfarm optimisation

1	Assess technology developments such as ballast, sizing and cost to support with both floater and tower developments.
2	Understand floating specific windfarm layout and turbine specific developments to maximise yield.
3	Define floating specific controllers and modifications required in context to floating specific turbines.

Foundations

1	Understand how different materials and manufacturing processes affect the commercialisation of different floater designs.
2	Improve the modelling and design process for integrated floater designs.
3	Improve the understanding of foundation design and performance.

8.2. Stage 3 programme activity

The Floating Wind JIP is running eight projects through Stage 3 Phase I, which kicked off in 2023; overviews of the eight S3P1 projects can be found below. Stage 3 Phase II projects are currently undergoing tendering and seven projects are expected to be run through this phase. For further information on Phase II projects, please visit the Carbon Trust tender website.

Maximum operating sea-state evaluation

Contractor: AMOG (lead), sowento & London Marine Consultants

The use of maximum operating sea-states (MOSS) is defined in IEC 61400-3-2 and has the potential to reduce loading levels across the system by limiting wind turbine generator (WTG) operational windows. While implementation in the standard is defined, suitable practical implementations for this type of system are not yet widely understood within the floating wind industry. This project will understand how maximum operating sea-states can be optimised for commercial scale floating offshore wind.

The objectives of this project are to:

- Understand the potential cost saving for unit design by using maximum operating sea-states.
- Define and outline a process by which MOSS can be optimised for project implementation.
- Evaluate the potential implementations of MOSS within the floating wind unit control architecture.
- Identify solutions that require limited modifications to the overall system (both hardware and software).

Power curve validation for floating turbines

Contractor: Technical University of Denmark (DTU)

Although turbine power curves are a key driver for assessing the value of an offshore wind project there is at present no industry accepted approach of power curve validation once the construction of a floating wind project is complete. Best practices are currently based on the fixed bottom turbine approach, and floating specific aspects are currently not considered in standards. Having a specific power curve validation process for floating wind turbines would reduce yield uncertainties, improve the bankability of floating wind projects, and reduce the levelised cost of energy.

The objectives of the project are to:

- Determine the key parameters which need to be considered for floating wind specific power curve validation.
- Determine the uncertainty relating to each 'bin' of the power curve when using different methods of wind resource assessment.

Wet storage and quick connecting of dynamic cables

Contractor: 2HOffshore

There is a growing need for technologies to improve installation and operation and maintenance (O&M) procedures and quick connector technologies could significantly reduce the installation duration. As such understanding the technology options available to enable quick (dis)connection and wet storage for tow-to-port (TTP) operations, along with their risks and limiting factors will be key.

The objectives of this project are to:

- Understand and evaluate different connection technologies for the dynamic cable focusing on the connection procedure, speed of connection, and duration of connection operations of different technologies compared to traditional methods.
- Understand different wet storage options when disconnecting the dynamic cable to enable TTP operations.
- Ultimately, compare relevant connection technologies to determine the most feasible and safe options for connection and disconnection of dynamic cables in a commercial floating offshore wind farm configuration.

Larger static pitch angles

Contractor: Frazer-Nash Consultancy

In relation to the early concept level design stage of a floating system the floater pitch angle can have a significant impact on the floater design process. As such it is important to understand how larger static pitch angles (LSPA) effect power production and floating platform design.

The objectives of the project are to:

- Understand the effects of static pitch angles and determine the conditions under which a trade-off between power generation and floater mass may justify greater static pitch angles.
- Evaluate the different test case scenarios and floater technologies to determine how flexible static pitch (loads on the RNA, power generation loss) can be and how this would affect the floating substructure design (mass, dimension, etc.) as well as the levelised cost of energy (LCOE).
- Assess the potential trade-off between power production and floating platform designs (mass, dimensions, technology) when allowing higher static floater tilt as well as investigating the impact of deflection upon wake effects upon the wider LCOE system.

Commercial scale mooring integrity management

Contractor: AMOG (lead), SOFEC, ABS and Skowronnek & Bechnak

Mooring technology has been applied successfully in offshore applications such as floating production, storage and offloading units (FPSOs) in the oil and gas industry and in terms of O&M requirements some parallels and learnings can be drawn from these applications. This project aims to investigate what an integrity management strategy should look like for commercial scale floating offshore wind specifically.

The objectives of the project are to:

- Develop a floating wind scale mooring integrity management (MIM) plan based on risk control, inspection sampling and risk based inspection (RBI) requirements dependent on redundancy and robustness considerations.
- Investigate digital twins, physical inspections and remote monitoring.
- Produce documentation to support MIM standardisation to different players, including classification societies, insurance companies and suppliers.
- Identify how the industry could work together to use data from floating wind farms in the same sea to help inform integrity management of floating wind farms in the wider context.

Guidance for dynamic cables

Contractor: 2HOffshore

There are currently limited design guidelines for dynamic cables that will be used for commercial scale floating offshore wind. This limited detail and the need for greater understanding will be key to the development of commercial scale floating wind. This project will develop independent fatigue guidelines for the electrical endurance of dynamic cables (both export and inter array) by considering prediction methodologies and collating input from analogous industries as well as previous relevant work completed by the Floating Wind JIP.

The objectives of the project are to:

- Undertake a review of the existing guidelines within the offshore wind and analogous industries in context to dynamic cables.
- Engage with the relevant stakeholders across offshore wind and analogous industries to better understand the requirements.
- Develop an industry guideline document which can be used by suppliers, developers and operators in context to dynamic cable fatigue assessment and lifetime prediction to support warranty and insurability.

Dynamic cable condition monitoring

Contractor: Arup

Predicting premature failures in dynamic cables is critical to ensuring continuity of power production from floating wind and for achieving initial project insurability. It is currently not known what the most reliable and cost effective monitoring techniques or technologies are for mitigation of risks around dynamic cables. Specifically, these risks include ensuring electrical and mechanical limitations are not exceeded, identifying the required O&M strategies, and what understanding what criteria is required to enable confidence in their insurability.

The objectives of the project are to:

- Undertake a comparison of dynamic cable condition monitoring solutions that can provide reliable data, regardless of the current technology readiness level (TRL), risks or safety concerns.
- Undertake a gap analysis to identify opportunities for improving the studied technology solutions.
- Provide an O&M strategy for dynamic cable condition monitoring systems in floating offshore wind.

Prevention of marine growth

Contractor: Endures(lead), Kent

Marine growth on foundations, cables, and mooring lines increases the loads and corrosivity which can impact the stability and durability of both structures and individual components. The aim of the project is to understand the effect of marine growth over the lifetime of a commercial asset including how marine growth differs across geographics regions and how this growth can be predicted.

The objectives of the project are to:

- Map typical marine growth on various types of materials and surfaces and identify variation dependent on geographical locations.
- Understand whether approaches and standards in other marine sectors (e.g., oil and gas) are applicable to floating wind.
- Review current standards and where applicable propose new guidelines for the design of floating wind assets with respect to loads and other factors caused by marine growth.
- Provide a realistic assessment of the minimum intervention requirements for marine growth over the full lifetime of floating foundations.
- Identify technological solutions that could reduce marine growth over the lifetime of an asset (focusing on passive measures, such as coatings), as well as technologies for the inspection and removal of marine growth from subsea structures, including CAPEX and OPEX estimates for the proposed solutions.

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Published in the UK: 2024