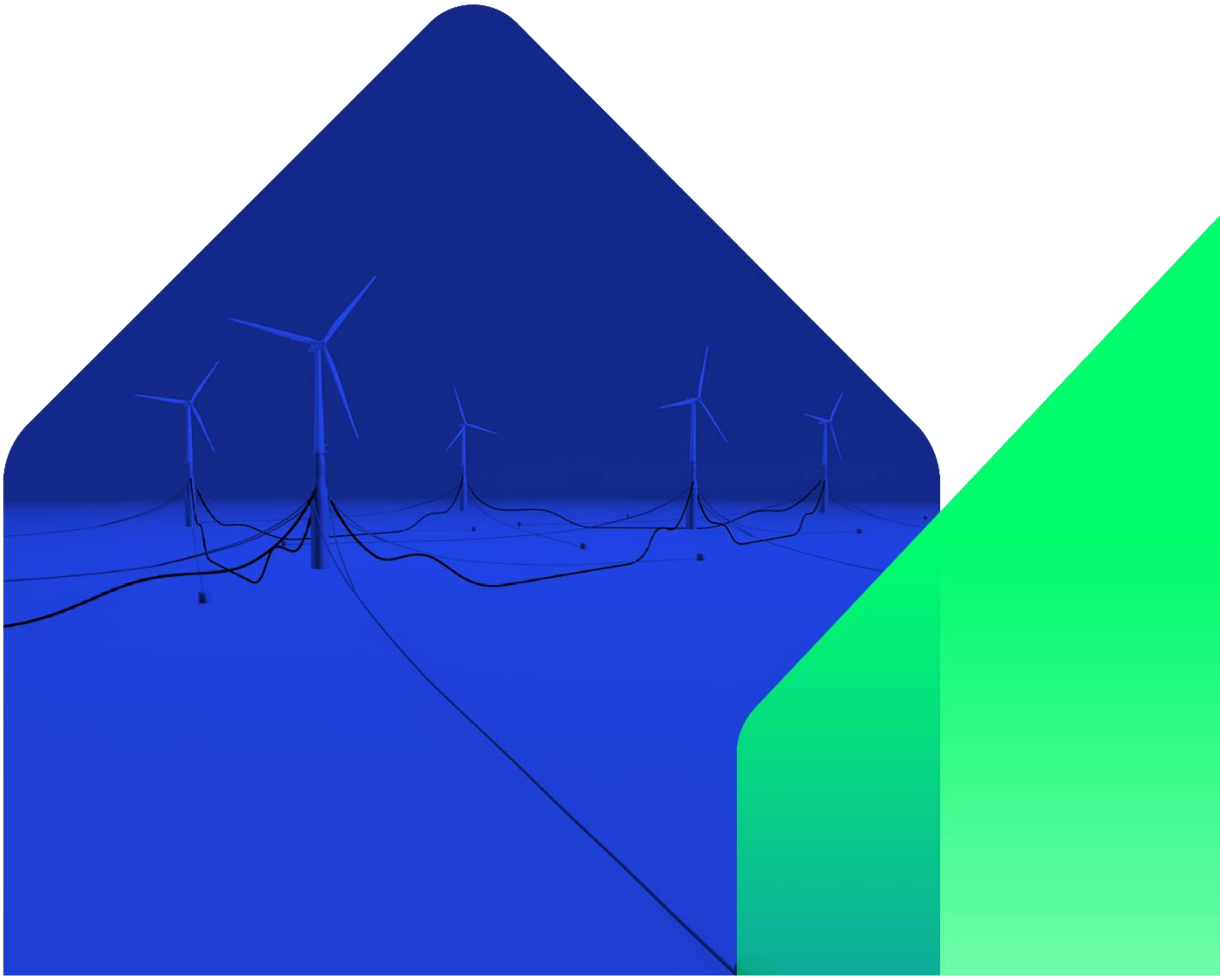
FLOATING WIND JOINT INDUSTRY PROGRAMME

Moorings system redundancy, reliability and integrity

December 2023



Contents

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Introduction

Mooring systems are a crucial component of a floating offshore wind 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 Joint Industry Programme (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:

- Investigate the likelihood and impact of mooring failure specific to floating offshore wind 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;
- Understand how the mooring system redundancy is affected by the integrated design of the mooring system, floating foundation, wind turbine generator (WTG) and control system;
- Understand and quantify potential failure rates, taking into consideration inspections during operation and their potential to address failure rates;
- 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;
- 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 study 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 floating offshore wind 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 usedthe regulsts 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 1: 15 MW reference substructure designs for the Floating Wind JIP. This project was based upon an updated version of the semi-submersible design.

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 floating offshore wind 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 2 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 beneign 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.

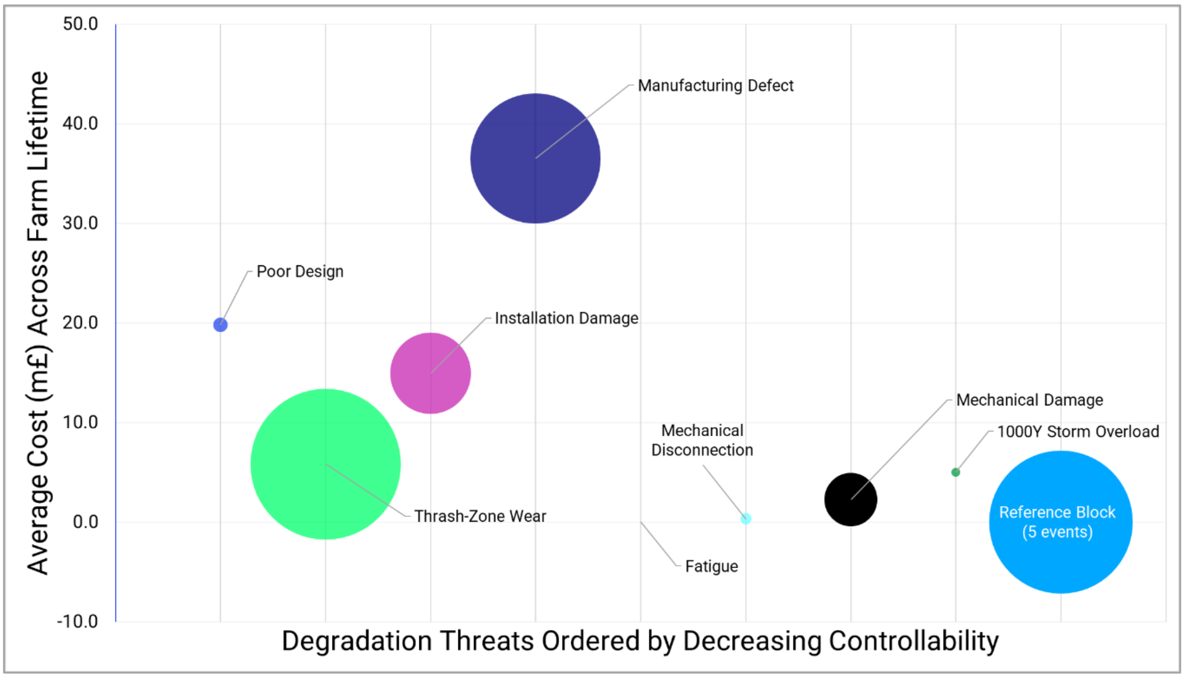

Figure 2: Cost and occurrence of degradation threats across a 50-unit farm.

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 3 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 3, this coincides with the infant mortality (beginning) and wear-out (end of life) stages of the mooring system.

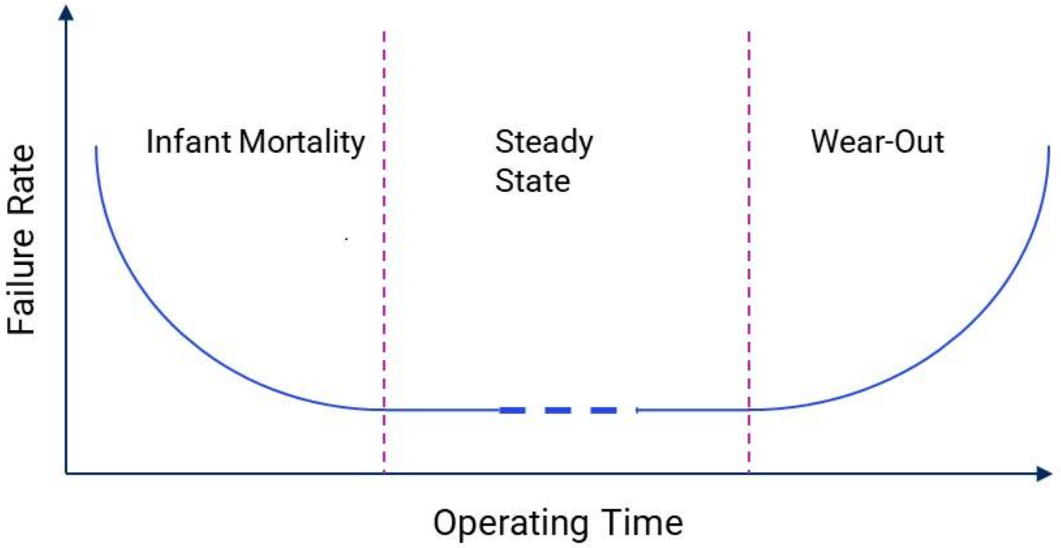

Figure 3: Typical Bathtub shaped failure curve throughout the lifetime of the mooring system

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.

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.

The primary objective of the Floating Wind JIP is to overcome technical challenges and advance opportunities for commercial scale floating wind. Since its formation in 2016, the programme scope has evolved from feasibility studies to specific challenges focusing on:

- Large scale deployment
- Industrialisation
- De-risking technology challenges
- Identifying innovative solutions
- Cost reduction

This Moorings System Redundancy, Reliability and Integrity (MRR&I) study was delivered under Stage 2 Phase V of the floating wind JIP. Contrasting to previous phases, the Floating Wind JIP partners decided to publish individual project reports for Phase V due to an increased number of projects with different durations. The summary reports for previous Stage 2 phases can be found here: Phase I, Phase II, Phase III and Phase IV.

Stage 1 (2016-17)
Feasibility of floating offshore wind

3 projects
5 project partners

Stage 2 (2017-22)
Technical challenges of floating offshore wind

35 projects
2 technology competitions
17 project partners

Stage 3 (2022-26)
Technology development for large-scale offshore wind

8 projects in Phase 1
More opportunities to come

Electrical systems	Mooring systems	Logistics
Windfarm optimisation	Foundations	Asset Integrity and monitoring

Research areas

The Floating Wind JIP selected six research areas where further understanding and advancement is required to reach full commercialisation of floating offshore wind projects.

These research areas are explored through different Carbon Trust research mechanisms such as common R&D projects, discretionary projects and industry competition

ABOUT THE CARBON TRUST

Who we are

Our mission is to accelerate the move to a decarbonised future. We are your expert guide to turn your climate ambition into impact.

We have been climate pioneers for more than 20 years, partnering with leading businesses, governments and financial institutions to drive positive climate action. To date, our 400 experts globally have helped set 200+ science-based targets and guided 3,000+ organisations and cities across five continents on their route to Net Zero.

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