FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

FAILURE IMPLICATIONS OF DIFFERENT MOORING SPREADS AND LINES

PUBLIC SUMMARY REPORT

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Author: S. Weller, T. Mackay, B. Yeats

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PREFACE – FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

The Offshore Renewable Energy Catapult (ORE) Catapult established the Floating Offshore Wind Centre of Excellence (FOW CoE) in 2019. The FOW CoE is a collaborative programme with industry, academic and stakeholder partners. The Vision of the FOW CoE is to establish an internationally recognised centre of excellence in floating offshore wind which will work towards reducing the Levelised Cost of Energy (LCOE) from floating wind to a commercially manageable rate, cut back development time for FOW farms and develop opportunities for the local supply chain, driving innovation in manufacturing, installation and Operations and Maintenance (O&M) methodologies in floating wind.

More details on the FOW CoE can be found on www.fowcoe.co.uk.

EXECUTIVE SUMMARY

In floating offshore wind (FOW) mooring systems a component or system failure may have a broad variety of consequences ranging from a relatively minor change in performance all the way up to complete loss of station keeping and damage to other units within the array. The loss of revenue, disruption and expense of recovery and repair would likely be harmful to the business and reputation of numerous stakeholders (developers, manufacturers, operators and end-users). The potential interaction between neighbouring platforms in a commercial FOW farm and other water users means that the risk of mooring failure and the implications of that must be assessed ultimately at a farm level, e.g., the requirements for platform separation in accidental limit states (ALS). There also exists the possibility that serviceability limit states (SLS) are exceeded that affect generation without gross mooring system failure.

The ***Risk and Failure Implications of Different Mooring Spreads and Number of Mooring Lines*** project investigated the implications of different mooring system topologies on the cost, risk and failure performance of FOW systems, where failure is defined initially as the loss of a single line in the mooring spread. Chain catenary, semi-taut and taut mooring systems were considered comprising 3, 6 and 9 mooring lines. The key implications of redundancy provision were explored via the identification of candidate designs (based on a commercial-scale turbine), followed by ALS simulations and lifecycle analysis.

ALS simulations confirmed the expected consequences of complete mooring component failure, including large platform horizontal excursions for the non-redundant mooring systems as well as two instances of cascade failure. Significant platform drift is likely to cause extensive inter-array cable (IAC) damage, incurring additional expense and turbine downtime. The lifecycle analysis reinforced this point, with offshore intervention costs dominating project costs for non-redundant systems, particularly for the more exposed site.

Overall, based on the assumptions used in this study the 2x3 line configuration appears to be an attractive compromise between redundancy provision and full-lifecycle levelised cost of energy (LCOE) across the three mooring system types considered. The study has highlighted that the lowest CAPEX solution is likely not the best for long-term farm LCOE as it may incur significant hidden costs which may accumulate during the lifetime of the project.

The study highlighted several potential levers to facilitate LCOE reduction in the context of FOW mooring systems:

1. **Provision of mooring line redundancy** – at the very least a degree of redundancy should be provided, particularly at vulnerable points of the IAC string.
2. **Increasing site accessibility** – if working significant wave height limits can be safely increased through remote operations or other technological advances, this would reduce lost generation (and revenue) due to downtime. Alternatively, sites could be targeted with good wind resource but more benign sea-state conditions.
3. **Reducing the number of failures** – by increasing the reliability of components, or reducing the number of components in the system, where appropriate.
4. **Streamlining of marine operations** – to reduce the time required on site and hence, vessel charter and fuel costs as well as turbine downtime.
5. **Reduction of mooring system CAPEX** – to reduce initial and replacement costs.

6. **Holistic consideration of mooring and cable consequences of failure** – simultaneous analysis of these subsystems from initial design optimisation through to lifecycle assessment in order to identify combined systems which are a starting point for detail designs and/or identifying design “sweet spots” and/or areas for further development.

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NOMENCLATURE

AHTS	Anchor Handling Tug Supply
ALS	Accidental Limit States
BoM	Bill of Materials
CAPEX	Capital Expenditure
CC	Consequence Class
CDF	Cumulative Distribution Function
CfD	Contracts for Difference
CLV	Cable Laying Vessel
CO_2	Carbon Dioxide
CoE	Centre of Excellence
CSA	Cross Sectional Area
DNV	Det Norske Veritas
ELC	Environmental Load Combination
FMEA	Failure Mode, Effects Analysis
FOW(T)	Floating Offshore Wind (Turbine)
HSE	Health and Safety Executive
IAC	Inter-Array Cable
IEA	International Energy Agency
JIP	Joint Industry Project
LCOE	Levelised Cost of Energy
LLR	Line Length Ratio
LRD	Load Reduction Device
MARIN	Maritime Research Institute Netherlands
MCNE	Monte Carlo Next Event
MIM	Mooring Integrity Management
MOO	Multi-Objective Optimisation
MRR&I	Moorings System Redundancy, Reliability and Integrity
MW	Megawatt
O&G	Oil & Gas
O&M	Operations & Maintenance
OFTO	Offshore Transmission Owner
OPEX	Operating Expenditure

ORE Catapult	Offshore Renewable Energy Catapult
OREDA	Offshore & Onshore Reliability Data
OTC	Offshore Technology Conference
PDF	Probability Distribution Function
PET	Polyester
QA	Quality Assurance
QCD	Quick Connect-Disconnect
RBI	Risk-Based Inspection
SLS	Serviceability Limit States
SPARTA	System Performance, Availability and Reliability Trend Analysis
TTF	Time To Failure
TTI-MR	TTI Marine Renewables (Ltd)
TQ	Technology Qualification
ULS	Ultimate Limit States
WD	Water Depth

TERMINOLOGY

Throughout this report various terms are used to describe a mooring system at varying levels of granularity or development. These are defined for clarity as:

- **Type**: Three spread mooring systems were agreed to be investigated in concord with ORE Catapult, broadly representing the main three types considered for FOW turbines;
    - Chain catenary;
    - Semi-taut (chain and polyester (PET) synthetic fibre rope) and;
    - Taut (PET rope only).
- **Configuration:** the mooring system configuration means to differentiate between the number of lines in the system i.e. 1x3, 2x3 and 3x3. For example, a 2x3 configuration has 6 lines in total consisting of 3 clusters of 2 lines per cluster. Since a **configuration** is a step more detailed than a type, a full description of a configuration also contains the description of the mooring system **type** and may also differentiate between different water depths;
- **Design:** the mooring system design means a specific and detailed make-up of a single mooring system that has passed all verification checks. This is the conclusion of the optimisation process and has sufficient detailed description of the mooring system to allow construction of the **Bill of Materials;**
- **Model:** the term model means any Orcaflex set-up that describes a specific mooring system design;
- **Bill of Materials (BoM):** simply the list of component parts that make up the mooring system design. For a full detailed design this would allow procurement of the system but at this stage allows high-level system costing and the input boundary conditions for consequence of failure analyses;
- **Redundancy**: Where redundant systems or redundancy is discussed herein the DNV-ST-0119 [1] definition is the governing definition. This states that redundancy is the:

  "…ability of a component or system to maintain or restore its function after a failure of a member of connection has occurred. Redundancy may be achieved for instance by strengthening or introducing alternative load paths. For example, if one mooring line in a mooring system is lost and the remaining part of the mooring system meets the ALS criterion, which is survival for at least a one-year load, then the initial undamaged mooring system is said to be redundant."

  In this work mooring system design compliance with this definition of redundancy is not assessed. The acceptability of any mooring system design in the failed case shall be dealt with explicitly with respect to achievement of technical function.
- **Tension / maximum tension:** where the term tension or maximum tension is used this explicitly means the actual tension recorded in the line during a simulation – the absolute value that could be reasonably assumed to occur in the real application. The term **characteristic tension** is explicitly used when the partial factored tension is discussed and the **characteristic tension** is computed as per DNV-ST-0119 [1], which in turn refers to DNV-OS-E301 Position Mooring [2] for the computation method.

Seasoned practitioners of reliability analysis use terms in a precise manner. For the hands-on engineer who infrequently participates in formal risk and reliability analysis certain terms are often used interchangeably, but precise terminology is important. The following definitions of key terms are used in this document and encouraged to be used precisely in the mooring industry:

- **Failure:** for the purposes of this work failure shall be taken to mean any loss of intended function. This may mean, for example, a small change in catenary stiffness due to loss of ballast weights. The mooring system retains tensile load path but it is not performing as originally designed (although the performance may still be acceptable).

- **Failure mode:** failure mode is taken to mean the **event** that causes the **failure** or the words that *describe* the failure such as “bearing seized”: it is descriptive and specific but does not attempt to identify the physical process that has led to the failure. In other words, it is the response to the question: “what could go wrong”? It may be useful to consider a failure mode as a combination of a noun (e.g., chain) and a verb (e.g., twists).

- **Failure mechanism:** the failure mechanism can be thought of as the **physical** (or chemical or otherwise) cause of the **failure mode.** This is where the list of common mechanisms comes in to play such as fretting, corrosion, yield, melting and so on. The noun-verb form of the **failure mode** can often be linked to the **failure mechanism** by inserting the words **due to** between the two e.g., chain breaks due to bending fatigue.

- Confusion regarding the interchangeability of terms can arise depending whether the failure occurs at the component or system level: what may be a failure mechanism at the system level may be a failure mode at the component level. Often a single failure mode may have numerous different mechanisms and it is offered that it is really the different mechanisms that are of primary concern at the mooring system level: there are only a few critical failure modes (e.g., line parts) but many different mechanisms (e.g., corrosion, fatigue, yield etc.).

Finally, the following terms are used in the lifecycle assessments carried out in this study:

- **Initial mooring system CAPEX:** The initial purchase price of the mooring system hardware.

- **Repair CAPEX:** The purchase price of hardware used to repair the mooring system (and export cable if relevant) following a failure event.

- **Repair OPEX:** The total operating cost associated with a failure event. This includes the repair CAPEX (see above), as well as vessel charter and fuel costs.

1 INTRODUCTION

1.1 PROJECT BACKGROUND

The global installed capacity of floating offshore wind (FOW) currently stands at 200MW with rapid growth predicted in the coming decades, e.g., 270GW by 2050 representing 15% of all offshore wind capacity [3]. In order for the LCOE of FOW systems to be acceptable, cost effective and fit-for-purpose mooring and anchoring designs are required which allow the capture of wind energy in a diverse range of water depths and environmental conditions. Currently, the LCOE for floating offshore wind is more than three times that of fixed offshore wind (which currently stands at ~63£/MWh). It is expected that the cost difference will fall to 30% by 2050 [4].

Considering the design requirements of commercial-scale FOW turbines (10MW+), synergies exist with the existing offshore sector and it is unsurprising that conventional mooring and anchoring systems, and respective components are being proposed in the first instance. A key current industry discussion is focused on the subject of inherent redundancy and safety factors adopted for FOW mooring systems. It is recognised that the risk profile for FOW systems is different from that of oil and gas (O&G) installations and that existing O&G design codes may be overly conservative but to draw strong conclusions on this requires a robust analysis of cost and risk.

The specification of FOW mooring systems cannot be overly-conservative since this will increase the system capital expenditure (CAPEX). When combined with the need to reduce the number of offshore repair or replacement interventions these factors will have an impact on system LCOE. Consequently, it is likely that a specific platform type in a specific site and environment may not have a single optimum mooring system solution but instead there could exist a set of solutions which satisfy a broad range of often competing requirements. This in turn means that discovering and defining the optimum solution(s) is a complex task requiring refined system definition and analysis, which cannot be robustly achieved by approaching the design, optimisation and analysis too generically.

During 2023 TTI Marine Renewables (TTI-MR) Ltd was contracted by the Offshore Renewable Energy Catapult (ORE Catapult) to assess the consequence of mooring system failures in floating offshore wind turbine systems at a full lifecycle level. The *Risk and Failure Implications of Different Mooring Spreads and Number of Mooring Lines* project investigated the implications of different mooring system topologies on the cost, risk and failure performance of FOW systems. The project was conducted in three stages (Figure 1):

- The first stage of the project involved the identification of a set of tenable FOW mooring systems and their respective bills of materials (BoMs) for 18 combinations of mooring system type, configuration and water depth. An efficient approach to identify a large number of potential mooring systems (as a precursor to carrying out lifecycle reliability and cost assessments) is introduced in this report.
- Consequence of failure analysis was carried out in the second stage of the project.
- In the third stage of the project, lifecycle costs assessments were carried out on the mooring system designs identified in the first stage to consider the implications of mooring system design on FOW array LCOE over a 25-year period.

Figure 1: Workflow of the *Cost, Risk and Failure Implications of Different Mooring Spreads and Number of Mooring Lines* project.

2 REVIEW OF MOORING FAILURES

2.1 BACKGROUND

The immediate physical consequence of a complete mooring line failure (i.e., line parting and loss of tensile load path) is straightforward to compute in time domain analyses (see Section 4), or by simple logic in some cases. Conversely, understanding the sequence of events that led to any particular mooring system failure, and indeed predicting the cause of future failures, is fraught with uncertainty. It should also be recognised that a mooring line (component) failure may not result in a complete loss of function of that particular mooring line and the broader system in turn. Instead, it may be possible and likely that partial failures occur that denude function to some extent (a relevant example may be the loss of a number of chain ballast clumps changing the system stiffness but not losing the primary tensile load path). It may be difficult to detect the occurrence of such failures but if left unrectified they may leave the line and system vulnerable to more failures, either of the same or a different failure mode.

Typically, mooring system stakeholders (designers, buyers, installers and so on) rely heavily on the global oil and gas (O&G) sector track record in terms of understanding and appreciating failures. However, in the nascent FOW sector this must be treated cautiously and not taken as the whole story, for a number of reasons, which are introduced below.

The fact that unforeseen failures can still happen in this era of highly advanced engineering analysis built upon a vast accumulation of real-world experience is surprising to an extent, but analysis of failures occurring in the field usually finds unsurprising root causes. It is difficult to envisage what truly new or unique failure modes may occur and why they might occur now, in the floating wind sector. Instead, it is likely more beneficial to think about the fundamental differences in application between O&G and FOW sectors that may result in different failure modes or failure rates. In addition, it should go without saying that the FOW industry must not repeat the circumstances that led to the known failure cases in the O&G sector.

2.2 DIFFERENCES FROM THE O&G SECTOR

As mentioned, the O&G sector is the primary and only source of relevant failure rate information for the FOW mooring sector. However, this is limited in itself, for a variety of reasons, and it is important to recognise that prevailing failure rates in the O&G sector are likely not directly transferable to the FOW sector. The fundamental differences that will affect the propensity (or otherwise) for failures to occur in the FOW sector include:

- Firstly, the total number of FOW installations will greatly exceed the number of O&G floating installations currently deployed worldwide. Therefore, if a certain failure rate from O&G is directly transferred into FOW, the number of failures occurring shall increase due to the greater number of opportunities;

- Secondly, the mooring tension spectra shall be substantially different in the FOW sector. Fundamentally, the aerodynamic loading on O&G installations is passive and increases quadratically with wind speed. This means that for most of the life (lower average wind speeds) the drag force is minimised. Conversely, FOW systems are designed to actively attract load to maximise generation in lower wind speeds by varying the turbine blade pitch. This intrinsically means that the fundamental quadratic relationship between wind speed and aerodynamic load into the system is "broken" and the typical tension fatigue spectra often seen in the O&G sector no longer apply. The FOW application is much more demanding in fatigue and this risk is not to be underestimated;
- The risk profile for FOW systems is arguably lower than for manned O&G installations. This may be debatable on a commercial basis (where multiple assets may be affected by a single failure) but fundamentally humans are not based on board the FOW installation (c.f. hundreds of personnel on O&G platforms) and no hydrocarbons are involved. The corollary of this then is that the FOW industry may deliberately, or inadvertently, take more risks in design and installation. Arguably, if more risk is accepted it must be expected that more failures will occur than the established baseline. The counter-argument may be that FOW farm designers will be cognisant of the fact that design-level failures may permeate through an entire farm installation with immense ramifications and actually adopt a very conservative and risk-averse design approach;
- The fact that personnel are present on O&G installations means that the possibility exists for continuous monitoring, observation, inspection, adjustment, maintenance and repair (at least at the top-end). The much greater (single) asset value and topside space also means that hardware is installed for mooring line re-tensioning, if required. Monitoring solutions, on a FOW farm-scale, are to be developed and there may be advantages to be drawn from the multiple installations within a farm. These differences may change the likelihood of failures in the FOW sector compared to O&G;
- As the FOW sector expands it is likely that existing suppliers of mooring equipment may need to expand their production capacity (thus presumably installing more hardware and building new "lines") or new suppliers will enter the market. This brings with it the requirement for supplier qualification and product qualification for specific product lines and a lapse in this may increase quality risks.

There are no doubt innumerable other specific differences but the preceding five are viewed as being important top-level fundamental differences that affect the relevance of the O&G dataset and the intrinsic risk-profile of the FOW sector. This should be borne in mind when discussing absolute failure rate values from the O&G sector and may be used to assess the likelihood of new failure modes occurring or infrequent ones becoming more frequent.

2.3 SOURCES OF INFORMATION

It has been established that the FOW sector must rely on the O&G sector to provide our understanding of the mooring system failure baseline. In addition to recognising that the FOW sector has fundamental differences it must also be recognised that the O&G baseline is far from a complete and detailed account of all failures that have been experienced in the field. Typically, the industry reports only "significant" failure events that result in complete loss of mooring tension load path in one or more lines. Often in mooring systems with many lines (e.g., 8, 12, 16) even a one-line failure case is not deemed as truly significant: it is often viewed as a "component" failure as opposed to a mooring system failure. Consequently, it must be assumed that many minor failures, some of which could proceed to higher consequence failures without intervention, go unreported publicly. Correspondingly, it may also be possible to suffer minor failures that do not progress to more severe consequences and these may never be detected or reported.

Joint Industry Projects (JIPs) have often provided useful forums for the dissemination of mooring system integrity information and some of these include:

- Mooring integrity projects as part of DeepStar JIP: this JIP has a technical subcommittee on Floating Production Systems and MetOcean of which part covers mooring integrity;
- Mooring Integrity User Group as part of Floating Energy Research Forum: this User Group recently conducted a deep dive on the use and qualification of nylon fibre ropes for the FOW sector;
- DNV: DNV have recently launched a JIP on "optimising mooring and dynamic cable design requirements". Whilst focussing on design optimisation it may also consider failures;
- The Carbon Trust recently completed their Floating Wind JIP Moorings System Redundancy, Reliability and Integrity (MRR&I) but it is not known whether they have accessed any new data;
- Maritime Research Institute Netherlands (MARIN) is running various mooring system JIPs but these seem to focus more on condition monitoring and digital tools;
- OREDA (Offshore & Onshore Reliability Data) is a global project organisation of O&G majors that collects and shares reliability data. Mooring system reliability is unfortunately out of scope;
- The SPARTA (System Performance, Availability and Reliability Trend Analysis) project managed by ORE Catapult is a database for sharing offshore wind farm performance and maintenance data. This may be an ideal vector for the FOW industry to share mooring reliability data as the sector develops and information becomes available.

In addition to JIPs the UK Health and Safety Executive (HSE) issue "safety alerts" that tend to focus on the more significant failures experienced in the North Sea and other areas e.g., [5, 6]. To the best of our knowledge no one is collating the outputs from these discrete updates into a global repository of information. The last time a "fresh" global industry view was published was in 2013 and that was the seminal work of K-T. Ma et al (OTC 24025 A Historical Review on Integrity Issues of Permanent Mooring Systems) [7]. A further paper on a similar topic was presented at the Offshore Technology Conference (OTC) in 2014 summarising the results of an industry survey led by AMOG consulting as part of a DeepStar JIP project [8]. DNV authors also presented a state-of-the-art review of mooring integrity management at OTC in 2014 [9]. One of the authors of [9] (Martin Brown) was also author on an earlier work from the UK HSE: the Research Report RS444 on the subject of Floating Production System Mooring Integrity [10]. This was led by Noble Denton and was the output of a JIP. This document remains an excellent and relevant resource.

More recently the Moorings and Anchoring work packages led by the ORE Catapult Floating Offshore Wind Centre of Excellence (FOW CoE) has delivered useful outcomes. The PR28 project conducted a robust risk, reliability and failure mode assessment workshop. Thereafter the FOW CoE commissioned TTI-MR to deliver a Technology Qualification (TQ) Framework and TQ Tool. As part of the project a TQ case study report was delivered as well as a report summarising the overall Framework and website [11, 12]. The Framework report was accompanied with a TQ Register worksheet to aid the TQ planning process and the recording of evidence. In terms of failure modes/mechanisms this worksheet collated a fairly exhaustive list of potential causes, from various sources, for use in drop-down selection boxes in the Failure Modes and Effects Analysis (FMEA) worksheet.

In summary, the offshore O&G mooring industry has seen a focused and concerted collective effort on the subject of mooring integrity and failure reporting but this has tended to wax and wane in response to the incipient failure rates observed at any point in time, which is understandable. The beginnings of a shift towards interest in the FOW sector has been observed and the nascent FOW industry should strive to learn from previous mistakes and developments.

2.4 A NOTE ON THE APPLICABILITY AND STATISTICAL INTERPRETATION OF O&G FAILURE DATA

It is important to recognise that the failure rates often quoted in the O&G sector are based upon an incomplete suite of data. What’s more, the failure rates are (necessarily) presented as average values per line per annum. However, the average is not developed from a broad population of serially produced components or systems. Instead, it is the average of some discrete failures within a global distribution of broadly different installations, designs, generations and environments, where most systems do not suffer a failure. In other words, a continuous distribution within a population is not observed but instead discontinuous occurrences are observed and statistical descriptions fitted to them. This is almost the polar opposite of how failure statistics are developed in mass-produced systems whereby there is a massive empirical database of durability and reliability data and reliable statistical descriptions of them.

Further, it is often assumed that mooring system failures are likely distributed through time on a classic bathtub-type curve (high early-life failure rate, low and near constant useful-life failure rate and increasing failure rate towards end of life). However, whenever absolute failure rates are presented or discussed they are usually always a single constant value that is taken to be representative of the through-life failure rate (some literature present failure frequency with respect to total installed time [8]).

In summary, the handling of field failure observations is fraught with statistical uncertainty, for a variety of reasons. The important upshot is for the mooring system designer to understand that the often-quoted failure rates are highly unlikely to be precise constant values nor broadly and generically applicable to all mooring system types and locations. The values quoted are a collation of the available data into a useable value but this value exists within a distribution (of unknown shape) and with a broad uncertainty band. Arguably, it is more important or helpful to understand the causes of failure. Finally, the sector must be thankful that the gamut of mooring integrity review work previously conducted imparts the realism that although systems are designed to achieve excellent reliability, failures still do continue to occur at rates higher than desired.

2.5 THE FAILURE MODES AND MECHANISMS

It has thus far been established that O&G mooring system failures occur. This has been the focus of work and the industry has attempted to develop failure rate values, but these are uncertain. The work has usefully highlighted the broad array of failure modes and mechanisms that have occurred and key trends therein. It has been observed that the highly-focussed work of certain JIPs has been in response to new failure modes appearing or becoming troublingly prevalent and these tend to become industry “hot topics”. Chain out-of-plane bending is a typical example of such a hot topic with some of the first known failures occurring in 2002 [13, 14]. Work was then undertaken to understand the failure mode and attempt to develop mitigations or controls. When the mitigations and controls are then applied in the industry the failure rate due to that mode reduces and the focus tends to wane on that mode and move onto, or wait, for the next hot topic to appear.

Axial compression fatigue of synthetic fibre ropes (specifically aramid fibre), is another classic example of the cycle of a previously unforeseen failure mode that surprised the industry, required highly detailed work to determine the root-cause, prior to controls being put in place and reducing the prevalent failure rate [15, 16]. By observation, one of the current hot topics is that of very high strength steel (e.g., R5/R6 chain) fracturing due to hydrogen embrittlement [17, 18]. An important learning from all of these hot topics is that despite the highly qualified and experienced global pool of mooring system practitioners the industry continues to experience failures that were previously unforeseen. The conclusion must be made that it is exceedingly difficult to foresee potential failure modes that have not been experienced previously, which is not unreasonable.

When reviewing the literature and other references it is clear that the temptation exists to generalise a range of potential failure modes or mechanisms into a single category or type or to group component (e.g., chain connector) failures into a type also. By way of example “installation” is often cited as a failure mode or mechanism. To be more precise, although a root-cause-analysis may conclude that a failure originated due to installation actions, the actual failure mechanism may cover a very wide range of deleterious actions (e.g., abrasion, cutting, over-tensioning, bending twisting and so on).

It is clear from the literature that installation-induced effects do account for a significant percentage of total system failures and a large portion of the early-life failures. The other early-life failures are typically attributed to material defects from the manufacturing process. Again, this can encompass a large range of actual failure mechanisms that depend on the components or system type and the materials used. To address the issue of installation-induced failures and material defects, improved quality assurance processes may be necessary in the FOW sector. This could involve implementing stricter quality control measures during the manufacturing process to minimise the occurrence of material defects. Additionally, enhanced quality assurance practices can help identify and address potential installation-induced failure mechanisms, such as providing comprehensive guidelines and training to ensure proper installation techniques are followed.

At the other end of the failure bathtub curve lie the end-of-life failures that are usually related to long-term damage accumulation mechanisms and are typically grouped into fatigue, wear and corrosion. These groups can be further granularized with numerous different types of corrosion, wear and fatigue. Failure modes related to long-term damage accumulation may be more preventable and less surprising with the use of appropriate inspection although this is not without its challenges (e.g. marine fouling, buried chain, size of critical defects).

When a typical mooring system is distilled to its essential parts it can be seen that there are relatively few component parts (Section 3 provides an overview of the systems developed in this project). This means that there are relatively few unique locations where failure may occur and a fairly focussed group of (known) failure mechanisms. For the most basic system descriptions it is not foreseen that the FOW sector should fundamentally affect the range of failure modes and mechanisms that are experienced in O&G (other than the differences in application, as discussed above). However, once ancillary components are added to a mooring system, such as mid-line buoyancy units or clump weights the potential for the occurrence of other failure modes increases. These items in particular were the focus of a deep-dive in the PR28 project. There are numerous specific mechanisms at play that mean these items may suffer a higher failure rate than the line primary tension components.

A similar argument appears when further complexities are added to the overall mooring system and These may include quick connect-disconnect (QCD) assemblies and load reduction devices (LRD). Both of these types of system are utilised in the primary mooring load path so the consequence of gross failure is significant. By definition these types of device are complex systems in their own right and therefore expose the overall mooring system to potentially many more failure mechanisms and opportunities. This is further compounded when considering the relative novelty of the devices, lack of field experience and minimal empirical evidence of their intrinsic failure rates. In addition to their intrinsic mechanical complexity, they also introduce complexity in function and therefore potential failure modes. At a mooring system level these devices must also be considered as a discontinuity that may lead to increased frequency of certain failure modes and mechanisms in the attached components as they may introduce new loadings into the system (e.g., chain twist). Therefore, the LRD or QCD itself may be reliable and durable but the failure rate of the attached line components may increase due to its presence (similarly, the failure rate may reduce if the LRD does offer fatigue benefits). This demonstrates the importance of robust Technology Qualification of novel components or systems and this TQ must assess the effects on the balance of the system due to interactions with the novel system.

In summary, it is deemed unlikely that the FOW sector shall introduce entirely novel failure mechanisms into the mooring system. The list of failure mechanisms relates to the governing physics and degradation mechanism of the materials utilised. However, the introduction of new component or system types or novel materials may introduce failure mechanisms that have previously not been observed in mooring systems. The OREC Mooring and Anchoring Technology Qualification Register provides a comprehensive list of potential failure mechanisms [11, 12].

2.6 SUMMARY

In summary, the FOW mooring sector shall learn from and build upon the O&G mooring sector. This provides our baseline understanding of mooring system failure modes, mechanisms and typical failure rates. It is reasonable to state that the prevalence of mooring system failures in the O&G sector is higher than intended. With the FOW sector tending more towards serial production it is likely that the same failure rates will become economically debilitating for the industry, so improvement is required. This is compounded with the potential for increased failure rates in systems and components due to the difference in operating duties expected for FOW systems. This is most likely manifest in fatigue damage accumulation and fatigue in general is particularly fraught with uncertainty.

The interaction of components that leads to failures should be of particular focus for the FOW mooring sector since there is a strong drive for innovative solutions and these tend towards more mechanically complex assemblies. Complexity drives the opportunity for experiencing a broader array of failure mechanisms and modes in turn. This general risk reinforces the importance of wholly robust Technology Qualification for novel components, assemblies and systems. If the industry builds upon the work done in O&G and proceeds in a risk-averse and robust systems engineering fashion surprises should be minimised and they should be dealt with properly when they occur.

3 MOORING SYSTEM DEFINITION

The first stage of the project involved the identification of a set of tenable FOW mooring systems and their respective bills of materials (BoMs) for 18 combinations of mooring system type (x3), configuration (x3) and water depth (x2). In the latter stages of the project the designs were subjected to mooring line failure consequence analysis (Section 4) and lifecycle cost assessments (Section 5).

3.1 METHODOLOGY

A multi-objective optimisation (MOO) design tool developed by TTI-MR was used in combination with dynamic solver Orcaflex [19] to rapidly identify a broad range of candidate mooring solutions for a given set of parameters, objectives, constraints and environmental load combinations (ELCs). It is important to note that the choice of anchor type was not addressed in this initial phase. The selection of appropriate anchor types is highly dependent on specific seabed conditions and could be addressed in subsequent detailed design stages.

The ULS analysis utilised the K03 15MW semi-sub FOW developed by Orcina based on the International Energy Agency (IEA) reference model [20]. The selection of this platform and turbine combination was based on nascent industry trends and the availability of verified reference models. A high-level overview of the process is provided herein and for more information the reader is directed to [21]. Although beyond the remit of the project, the design approach described herein could also be applied to front-end engineering design (FEED) and later design stages by optimising particular elements of a design as required.

Three mooring system types were considered to cover the range of material types that are being considered for FOW mooring systems: chain catenary (comprising Grade 5 chain), semi-taut (chain and polyester [PET] rope comprising parallel-laid sub-ropes) and taut (PET rope), see Figure 2 and Figure 3. Within the remit of this project additional components that provide buoyancy or additional weight were not included as they may be unnecessary and/or introduce additional failure modes and probabilities of failure occurrence. Furthermore their inclusion would have led to an unmanageable proliferation of designs. This meant that the rope length in semi-taut cases was limited to a maximum equal to the water depth. Three mooring line configurations were investigated using 1x3, 2x3 and 3x3 line clusters. The chain properties were based on the Sotra catalogue [22]. Most of the rope properties were supplied by Bridon Bekaert Ropes Group (BBRG). The response of synthetic ropes is dependent on the loading history [23], and as a result the modelled axial rope stiffness was derived from 100-year return period tension-tension tests carried out by TTI Testing Ltd.

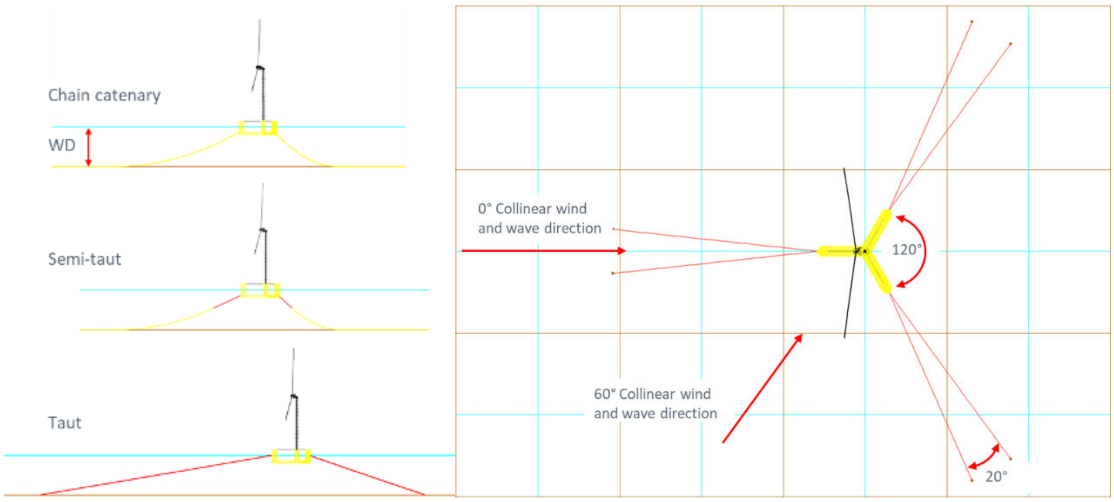

Figure 2: Three mooring system types and Orientation of the 2x3 mooring system to the environmental directions.

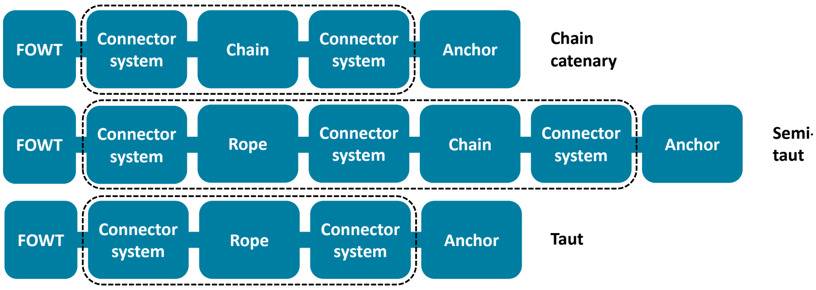

Figure 3: Mooring line system schematics. Components considered as part of the CAPEX calculation are enclosed in dashed boxes. Note: the 'Connector system' is a generic terms for simple joining components such as shackles and H-links. It does not cover more complex components, such as QCD systems.

Two water depths (WDs), 100m and 500m, were considered in the project (Table 1); for concision only the 100m results are presented in this section. The former depth was defined as a typical UK site although it is known that some ScotWind candidate locations are shallower. The 500m water depth site was selected to allow consideration of potential deeper sites (e.g., a site located far-west of Shetland), since this may fundamentally affect the lifecycle cost and consequence analyses. A set of wind, wave and current environmental conditions were defined which are representative of a typical highly energetic UK/ScotWind type site with significant wave heights up to 13m.

Table 1: Site locations and water depths.

Water depth [m]	Description	Latitude	Longitude
100	ScotWind NE8	58.25	-1.25
500	West of Shetland	60.75	-2.75

Mooring system CAPEX was calculated using cost factors based on publicly available data, as well as TTI-MR and ORE Catapult internal cost databases, some of which are linked to real-world purchases of similar or identical hardware. Note: the overall CAPEX does not include the purchase cost of anchors, or the cost of initial system installation.

Referring to Figure 4 the analysis was carried out in three stages in order to efficiently identify a set of tenable mooring systems for the 18 combinations of mooring system type, configuration and water depth.

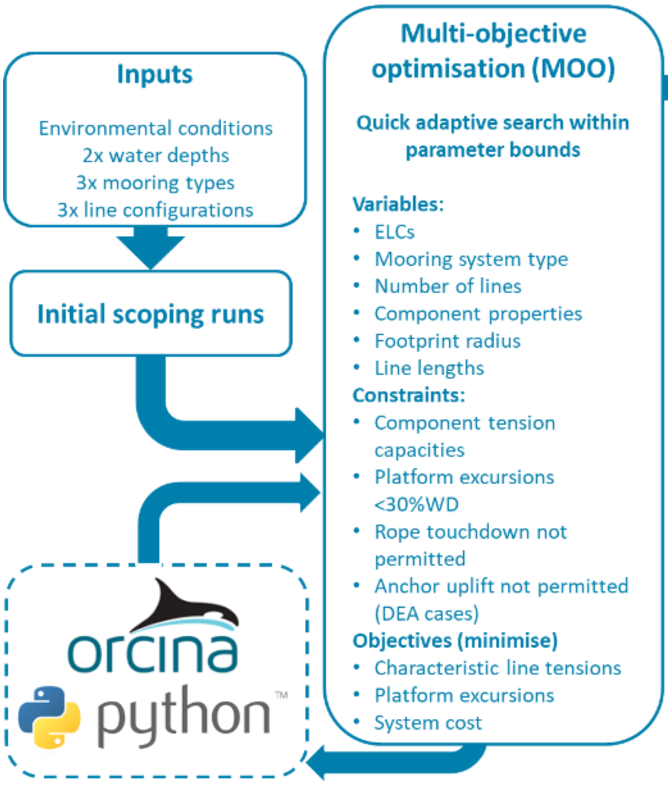

Figure 4: Overview of the design identification process.

Stage 1: Initial simulations

Initial 3-hour simulations were carried out on representative mooring systems to identify the ELCs which resulted in extreme tension and/or platform excursions. Three sets of wind and wave seeds (and time origins) were applied to 15 wind, wave and current combinations resulting in 45 sea-states, which were then used as a basis to identify optimal mooring systems. This process was repeated for each mooring system type (x3) and water depth (x2).

Stage 2: Optimisation simulations

The MOO design tool was run for 10 generations to produce a set of solutions, which were a compromise of the specified objective functions. Each candidate solution in a population of 100 was subject to a subset of the 5 worst-case ELCs trialled in Stage 1. Any candidates which violated the imposed constraints (e.g., partial safety factors to Consequence Class 1 [CC1] [1]) were rejected.

Stage 3: Verification simulations

The optimisation stage yielded a large number of potential solutions and hence Pareto fronts between the specified objective functions were utilised to select optimal candidate designs for verification. The identified candidates were subjected to multiple realisations of 3-hour storm sea-states. BoMs, using the taxonomy shown in Figure 3 were generated for all systems which passed the specified constraints.

3.2 RESULTS

The analysis resulted in a total of 217 verified designs across all mooring system types, configurations and water depths, with 9 to 15 individual designs per configuration and water depth couple. A large set of solutions were selected in order to enable robust conclusions to be made in the later project stages based on notably different designs. The selection included candidates which had the lowest maximum mooring tensions, platform excursions and system CAPEX. Results for the 100m WD site are summarised in Table 2.

Table 2: Parameter ranges of the verified candidate solutions for the 100m water depth site. Configurations are denoted as C = chain catenary, ST = semi-taut and T = taut with the total number of lines indicated for each case.

	Line length ratio (LLR[1]) [-]		**Mooring footprint radius [m]**		**Mooring component capacity [kN]**		**Rope length [m]**	
	Min	Max	Min	Max	Min	Max	Min	Max
C1x3	1.00	1.01	667	2500	13847	28371	N/A	
C2x3	1.01	1.01	707	1805	7877	30173		
C3x3	1.00	1.01	629	2221	7877	29400		
ST1x3	1.00	1.01	830	2333	16769	30173	61	92
ST2x3	1.00	1.02	624	2052	7877	30173	57	94
ST3x3	1.01	1.01	774	1717	7877	30173	54	100
T1x3	0.97	0.98	580	1378	22821	29444	518	1288
T2x3	0.97	0.98	604	1087	10584	24805	541	1016
T3x3	0.97	0.99	516	1279	6615	20285	459	1195

Figure 5 and Figure 6 provide a summary of the most pertinent results for the 100m WD site, encompassing all the simulated environmental conditions. The plotted quantities have been normalised by the results associated with the lowest calculated CAPEX solution, which has the following parameters:

- Type: Taut PET
- Number of lines: 6 (2x3)
- Rope MBL: 11025kN
- LLR: 0.98
- Mooring footprint radius: 604m

Comparing the range of solutions yielded and the results presented in Figure 5 and Figure 6, the following conclusions can be drawn.

- Taut system pretensions tend to be higher than semi-taut and chain catenary systems, but this is largely because rope contact with the seabed was not permitted in the analyses (Figure 5). The pretension results highlighted the importance of considering the installation and maintenance practicalities of a mooring system (in particular vessel capabilities and through-life requirements) early in the pre-FEED process to filter out untenable designs and/or highlight challenges. As

[1] Line length ratio (LLR) is the ratio between the total mooring line length and the hypotenuse of a triangle whose sides are the horizontal and vertical distances between the fairlead and anchor points in still water. Hence a LLR > 1 is used for lines featuring a catenary shape and LLR < 1 for pretensioned taut systems. This is reported for information.

expected for all systems, pretensions and maximum line tensions decrease with increased load sharing, and this is particularly apparent when comparing the 1x3 to 2x3 systems.

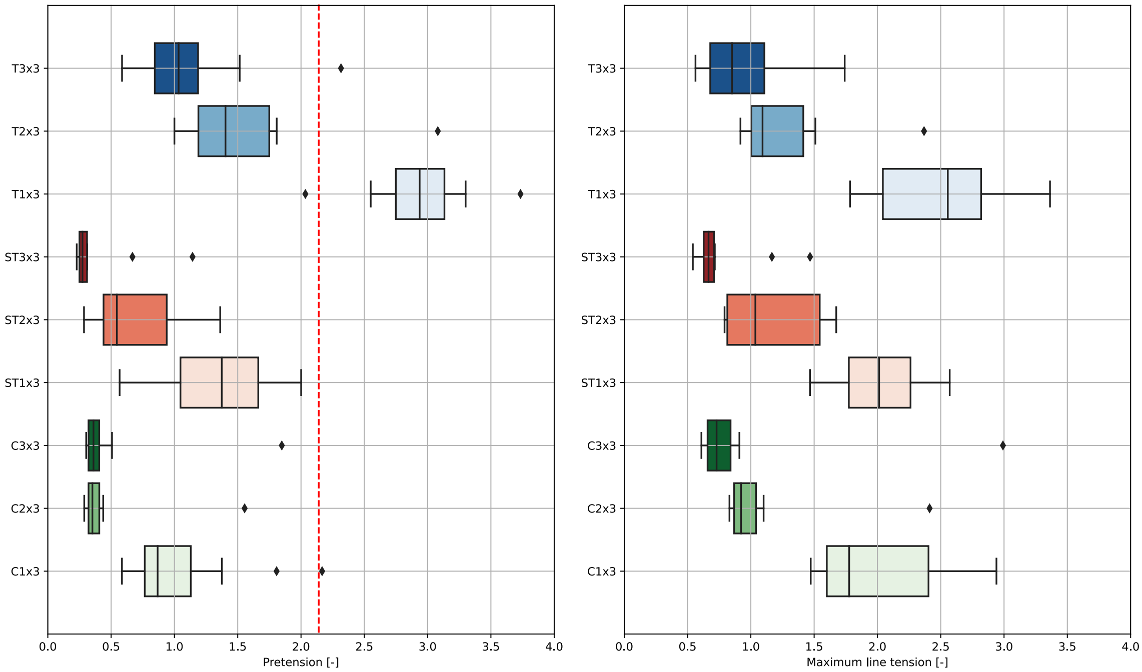

Figure 5: Mooring line pretension and maximum tension boxplots for each mooring configuration (left and right respectively). Results are normalised by the lowest CAPEX configuration (taut 2x3 system). Configurations are denoted as C = chain catenary, ST = semi-taut and T = taut with the total number of lines indicated for each case. For reference the maximum current installation vessel bollard pull of 477 Tonnes (MPV Island Victory, [24]) is included as a dashed red line, although it should be noted that pretensions below this limit do not imply an ability to carry out pretensioning. The boxes indicate the result quartiles, whilst outliers within and beyond of the 1.5 interquartile range are shown as whiskers and markers respectively.

- Adding a relatively short length of synthetic fibre rope to a chain catenary system (i.e., semi-taut) makes minimal difference to the performance of the system from a functional perspective. This is because the maximum length of rope used in the analyses was limited to the water depth to avoid rope touchdown and hence it is a relatively short length with limited inherent compliance (compared to the compliance of the catenary geometry). Clearly, the selection and use of mooring ropes (and other components) must be considered holistically in terms of long-term durability, cost, potential failure modes etc.
- The taut systems typically demonstrated lower horizontal platform excursions than the semi-taut and chain catenary systems. There is no clear trend of motion ranges with the number of mooring lines in each system. Whilst a large number of configurations passed the excursion limit of 30% of water depth (30%WD), it should be noted that this threshold is an assumed value, reflecting preliminary safety and operational considerations rather than a derived criterion from detailed site-specific analysis. As a result, the number of feasible solutions is likely to reduce if more stringent design requirements associated with the export cable or otherwise were to be imposed.
- The inclusion of additional lines into any system does not necessarily increase system CAPEX since line MBL and other parameters can be optimised. Furthermore, there may be benefits in terms of platform motions and line tensions. In fact, the results show that an increased number of lines can actually result in a lower CAPEX mooring system. Furthermore, there may also be benefits to adding extra lines (i.e., the level of redundancy in the system and how this affects Class rules, ease of installation, cost of anchors etc.)

- Excluding anchoring solutions and the cost of installation, taut mooring systems offer the lowest system CAPEX by a significant margin (Figure 6) and small mooring footprint radii are achievable (Table 2**Error! Reference source not found.**). This finding is clearly dependent on the relative cost f actors used, which, for most mooring component materials, are highly variable.

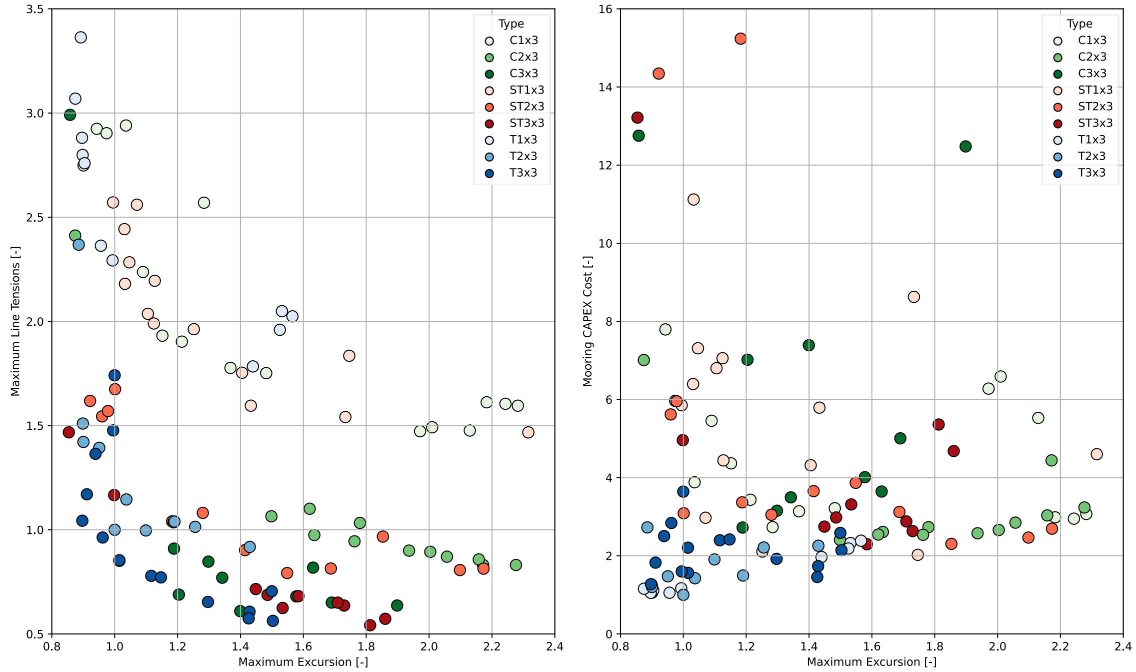

Figure 6: Maximum platform excursions versus maximum line tensions and maximum platform excursions versus CAPEX for all mooring configurations (left and right respectively).

Although a 1x3 mooring system may intuitively appear non-redundant, [1] states that if the system retains ALS survivability in a 1-year return period storm, then it can be considered redundant. However, this might not be acceptable to IACs or neighbouring assets, and hence it was decided to assess the 1x3 chain catenary designs in terms of CC2. A manual check of the existing designs found that 60% and 100% of the 100m and 500m designs respectively would pass the CC2 criteria. Those which did not pass were associated with the lowest CAPEX designs and tended to have higher line tension utilisation (i.e., were closer to the partial factor limit). The designs which passed were more of a compromise between the objectives (CAPEX, line tensions and platform excursions) and inherently had more of a margin in terms of utilisation. A separate set of mooring systems was also designed specifically to pass CC2 using the MOO design tool. These designs featured slightly larger chain sizes (and hence increased CAPEX) and had somewhat higher line tensions, but it does not appear to be significantly more challenging to design for CC2 partial factors.

It is acknowledged that if the basis and/or assumptions of the study were to be modified, then the outcomes may differ from those presented in this section. For example, consideration of anchors was beyond the scope of this study.

4 CONSEQUENCES OF FAILURE

In order to assess the impact of mooring line failures on line tensions, platform motions and nacelle accelerations, ALS simulations were carried out on the mooring system designs introduced in Section 3 to cover the eighteen combinations of mooring type, configuration and water depth.

4.1 METHODOLOGY

To simulate the ALS scenarios, the most heavily loaded mooring line noted during the ULS dynamic simulations was removed from each mooring system design. In all 1x3 configurations, the seaward mooring line was removed, while in all 2x3 and 3x3 configurations one of the seaward lines was removed (Figure 7 showed the removed line in blue).

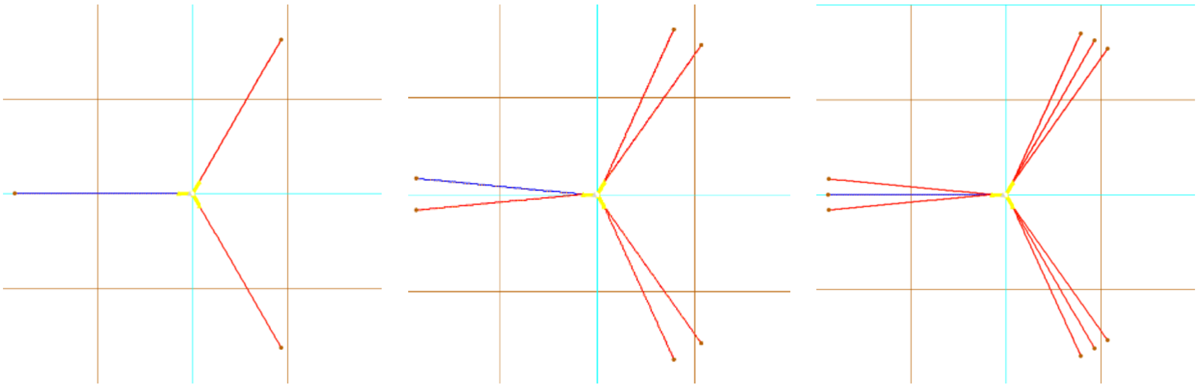

Figure 7: Plan view of the 1x3, 2x3 and 3x3 systems, with lines removed for the ALS simulations indicated in blue. The 0° environmental heading runs from left to right in these images.

In order to represent severe storm scenarios in which mooring line failure (due to highly energetic line tensions) could occur, the designs were subjected to the same 50-year return period environmental conditions used in the ULS analysis ELCs (Section 3). Failure could of course occur in milder conditions due to other mechanisms e.g., fatigue and the analyses of these was beyond the scope of this study. 1-year return period conditions were also utilised to determine if the remaining mooring system demonstrated redundancy, in the context of DNV-ST-0119 ALS safety factors [1].

The ALS simulation results were assessed using the same design criteria as for the intact mooring system simulations, albeit ALS partial safety factors were used (mean load factor: 1.0, dynamic load factor: 1.1), based on [1] for CC1.

4.2 RESULTS

The ALS simulations yielded the following conclusions:

- For both water depths, maximum line tensions increase (ALS/ULS > 1) for the 2x3 and 3x3 configurations across all mooring types (Figure 8). Notably, most of the 1x3 configurations showed decreases in max line tensions due to significant drifting of the platform and consequent redistribution of loads between the remaining leeward lines.
- None of the 1x3 configurations met the ALS criteria for either the 1- or 50-year return period conditions. Approximately 41% of the 2x3 configurations and 59% of the 3x3 configurations successfully met the ALS criteria when subjected to 50-year return period conditions, demonstrating that the provision of redundant lines is essential in case line failure occurs. For this return period three of the 1x3 designs failed the specified ALS characteristic tension criteria due to the redistribution of loads. Eight designs experienced anchor uplift and several incurred rope touchdown, the latter was attributed to the reduction in system pretension that would occur following line failure.
- Only one design, (a taut 500m 2x3 configuration), experienced a cascade failure, wherein a remaining seaward line experienced maximum line tensions of up to 102% MBL. To determine the

impact of the cascade failure, the design was reanalysed using the 50-year ELCs with the highest loaded mooring line removed. As expected, the platform drifted off-station in a similar manner to the 1x3 configurations and subsequently a further cascade failure would have occurred due to line tensions exceeding the MBL of the remaining four lines. Crucially this illustrates that adopting a 2x3 configuration does not inherently provide redundancy and that limit state analysis is required in order to ensure that a design is suitable for the expected environmental conditions.

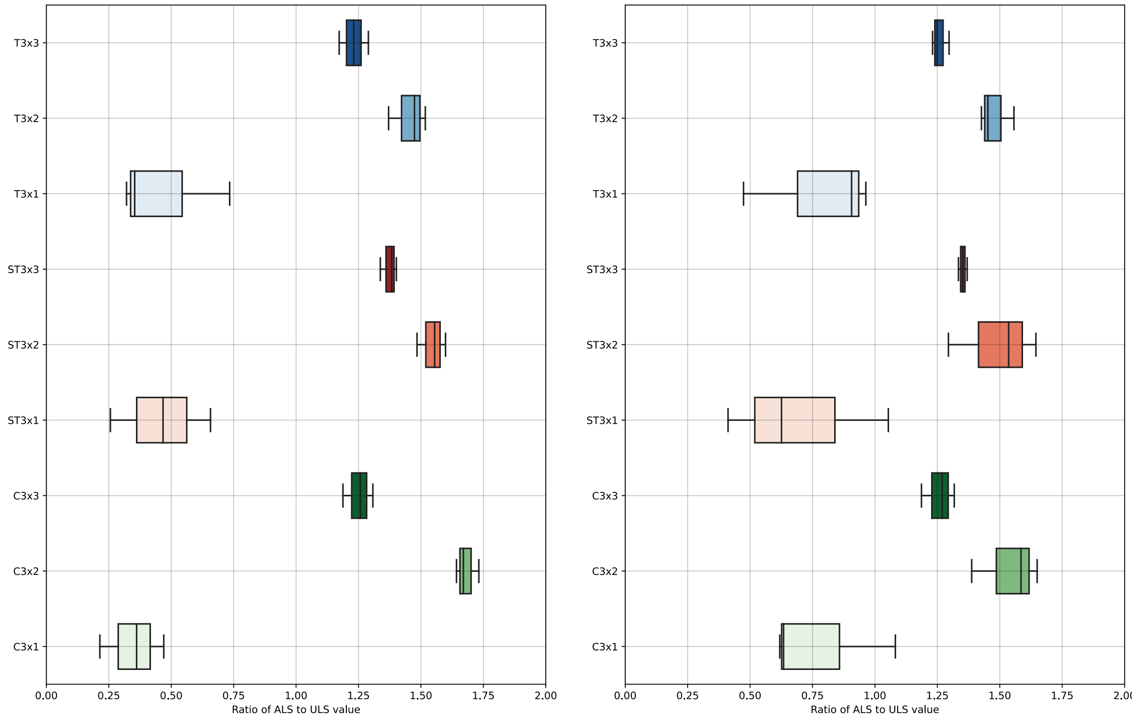

Figure 8: Ratio of ALS to ULS mooring line maximum tension boxplots for each mooring configuration at the (left) 100m and (right) 500m sites subjected to 50-year return period conditions. In the proceeding plots, the different configurations are denoted as C = chain catenary, ST = semi-taut and T = taut with the total number of lines indicated for each case. The boxes indicate the result quartiles, whilst outliers within and beyond of the 1.5 interquartile range are shown as whiskers and markers respectively.

- Notable increases of maximum horizontal platform excursions (calculated from the vector sum of the platform surge and sway time-series) were simulated with one line removed (Figure 9). The 1x3 configurations experienced significant excursions well beyond the defined excursion limit due to the loss of the seaward line. While both 2x3 and 3x3 configurations also saw substantial increases in platform excursions, the majority remained within the platform excursion limit. Assuming similar turbine separation distances to the Hywind Scotland and Kincardine Offshore Wind Farm arrays (between six to nine rotor diameters) would, for the 15MW turbine used in this study equate to a separation distance of between 1440m and 2160m. Notably in the simulated ALS scenarios, apart from the cascade failure case mentioned above, all of the 2x3 and 3x3 configurations easily avoid turbine-to-turbine clashing, due to excess excursions (assuming that the anchors do not fail). Understandably, the significantly greater excursion of the 1x3 configurations means that a failed turbine clashing into a neighbouring asset is a very likely outcome.

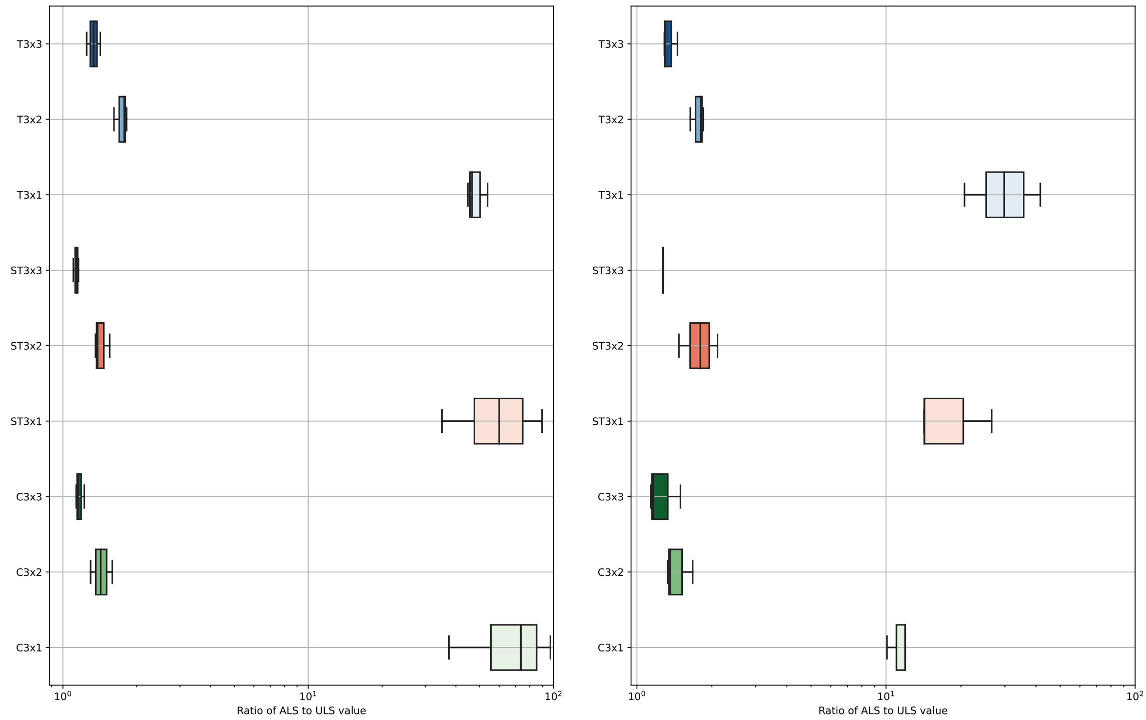

Figure 9: Ratio of ALS to ULS maximum horizontal platform excursion boxplots for each mooring configuration at the (left) 100m and (right) 500m sites subjected to 50-year return period conditions. Note: Log scale on the x-axis.

- The loss of mooring system stiffness following line failure is also likely to influence platform rotations and accelerations of the nacelle. The simulation cases demonstrated notable increases in platform yaw, particularly after removal of the seaward line of the 1x3 configurations. Moreover, many of the non-redundant mooring systems demonstrated increases in platform roll and pitch motions as well as nacelle accelerations, particularly for the 1x3 configurations. Whilst platform and nacelle responses were not the primary focus of this study, the simulation results could help to inform turbine generation strategies; i.e., is it necessary to shut-down the turbine if system responses remain within acceptable bounds in the event of a mooring line failure?

5 LIFECYCLE ASSESSMENT

5.1 METHODOLOGY

The principal Classification Societies have different CC definitions as well as risk tolerances for different mooring configurations, and even component types (e.g., ClassNK compared to DNV codes [1, 25]). In the absence of operational experience and data in the FOW sector, it is necessary to carry out broad-ranging analyses comprising multiple linked factors which are often reliant on imprecise input information on parameters or assumptions. Therefore a probabilistic approach is required to understand uncertainties and confidence as a forerunner to obtaining evidence via field experience and TQ programmes [11].

Lifecycle analysis was carried out on the mooring system designs identified in Section 3 to determine the impact of mooring system type, configuration and site location on lifecycle costs. The assessment was carried out using a Monte-Carlo Next Event (MCNE)-based approach developed by TTI-MR, within which random events (i.e., component failures) were generated that trigger repair actions in order to simulate scenarios which are as close as possible to reality. As with all Monte Carlo-based approaches, any variability of the input parameter(s) means that there will be a set of probability distributions which characterise the spread of potential results. Initial convergence runs indicated that 750 simulations were sufficient to characterise the revenue lost distribution for each of the analysed scenarios. For brevity all of the input parameters used are not included in this report and instead are summarised in Table 3.

Table 3: Baseline input parameters.

Inputs	
Weather windows	Durations, waiting times, sea-states
Vessel parameters	Cost, fuel burn, operating sea-state, transit speed, CO_2
Component reliabilities	Failure rates and distributions
Repair durations	Storyboarded operations
Mooring system design details	BoMs (inc. CAPEX) and replacement component CAPEX
Site	Distance to port, environment, water depth
IAC string	Layout, power export redundancy
Turbine parameters	Capacity factor, Contracts for Difference (CfD), turbine rating
Project design life	25 years

The main stages of the analysis were as follows:

1. The start point of the analysis assumed that the mooring systems were installed in summer. The analysis was run for the design life of the project (25 years) for a notional 900 MW array comprising sixty 15MW turbines).
2. For each mooring system design, relevant component types were identified in the Bill of Materials (BoM; Figure 3). Failure times were randomly assigned from exponential distributions (Figure 10) based on the mean failure rate for each component (taken from the TTI database and published data). After the simulated component replacement occurred, a new failure rate was assigned. Furthermore, line failure positions and IAC intervention types were randomly assigned to reflect either direct (i.e., when a failure occurs) or in-direct (seasonal vessel charter costs and turbine capacity factor) variability.

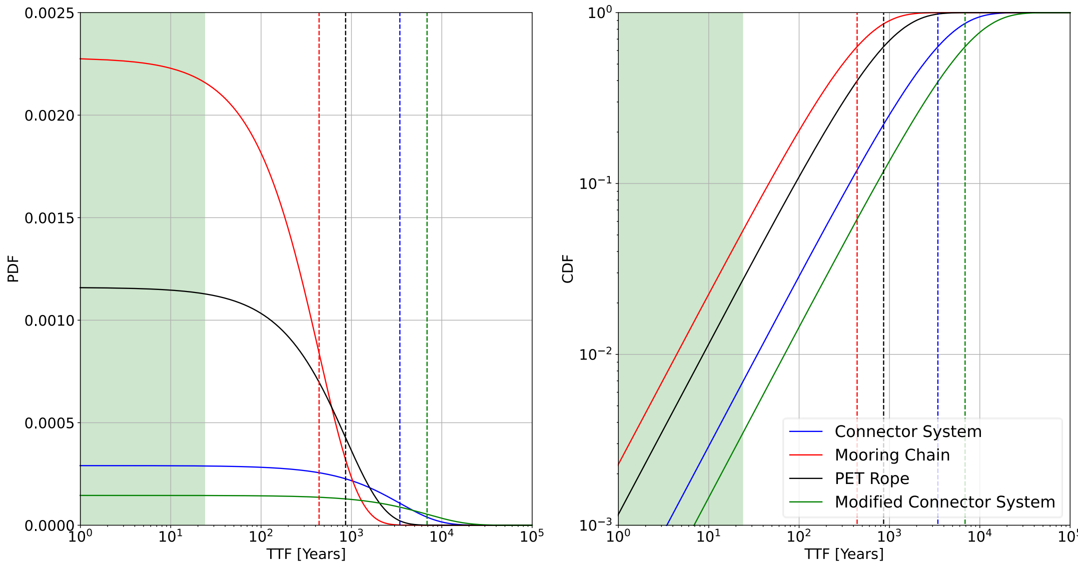

Figure 10: Probability distribution functions and cumulative distribution functions with the time to failure (TTF; log scale) of the mooring components used in the study, including connector systems (blue lines), PET ropes (black lines) and mooring chains (red lines). Mean failure rates are shown for each component as dashed lines and the design life is shown as a light green region.

3. A repair storyboard dictionary based on a review of past FOW and O&G marine operations, was accessed to determine the required procedure(s), i.e., the number of vessels required, duration(s) for repair and vessel fuel consumptions. Depending on the mooring system type/configuration (and location of the fault along the line) this may have included anchor resetting, replacement of the electric cables etc. If cable damage occurred (for non-redundant systems) it was randomly assigned either a 'repair' or 'replace' intervention requirement. It was assumed damage would be limited to two IACs per failure and hence the platform-cable interface would be either undamaged or built for quick connection-disconnection. Three different vessel types were used for the mooring repair operations, anchor handling tug supply (AHTS) vessels, large offshore tugs and (when cable damage was sustained), cable lay vessels (CLVs).

4. The (30-year hindcast) weather-window time-series for the site was queried in order to determine the next available weather window based on the time required to charter the vessels, transit to the O&M port, mobilise, transit to/from the site, carry out the repairs and demobilise the vessels. Repairs are carried out as soon as is feasible and those which could not completed within one weather window necessitated vessels to be stationed either on site or in port until the next window became available.

5. For the identified time interval vessel costs (including chartering and fuel) were calculated based on the type of vessel, the period of time that the vessel is required and the type of activity being undertaken. CO_2 emissions were also calculated as well as the replacement component CAPEX (sourced from the BoM).

6. The above steps were then repeated for the remaining turbines in each string, accounting for the consequences of mooring line failure on neighbouring turbines. For example, loss of a mooring line in a non-redundant system could result in damage to the export cable which (if located at a critical part of the string) would make the adjacent turbine unavailable. Referring to Figure 11 each string has a by-pass capacity of up to 150MW. For non-redundant mooring systems the position of the turbine in the IAC string can also influence total string (and

therefore array) downtime. Therefore, it is possible a mooring failure event causes shutdown of two turbines and hence double the downtime.

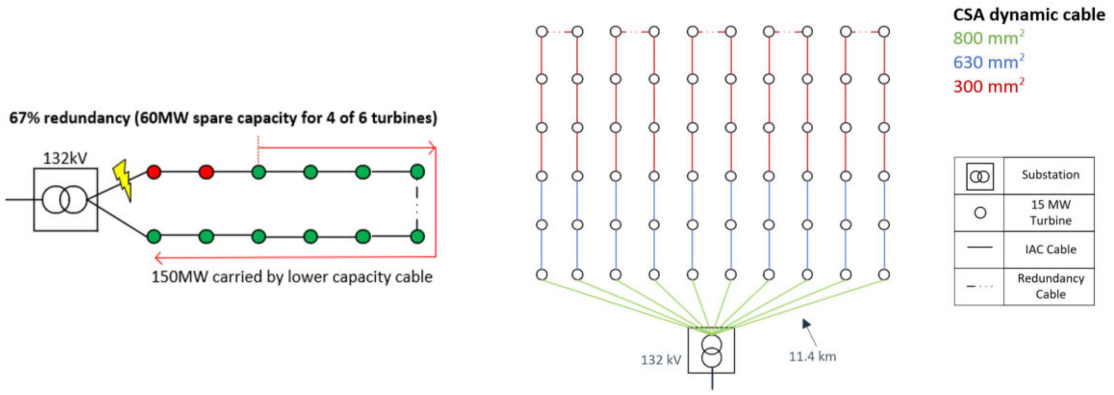

Figure 11: String and array layouts (supplied by ORE Catapult). The cross-sectional area (CSA) of the different cables is shown in the right-hand figure.

7. The total incurred downtime and revenue lost due to mooring system failures were calculated for the complete array, over the duration of the array design life, to allow comparisons to be made between the different mooring system types, configurations and sites. These calculations involved typical capacity factor monthly trends and an assumed contract for difference (CfD) electricity selling price. Vessel charter costs and turbine capacity factors were assumed to vary throughout the year (Figure 12). Sensitivity analysis runs were also carried out to determine the impact of varying key parameters on project LCOE, including altering the site safe working limit (in terms of significant wave height), component failure rates, the "home" location of the O&M vessels and also the turbine generation strategy following mooring component failure.

It is acknowledged that the analysis approach utilised assumptions and simplifications which had an impact on the simulation results. The perceived limitations of the adopted analysis method are listed in Table 4.

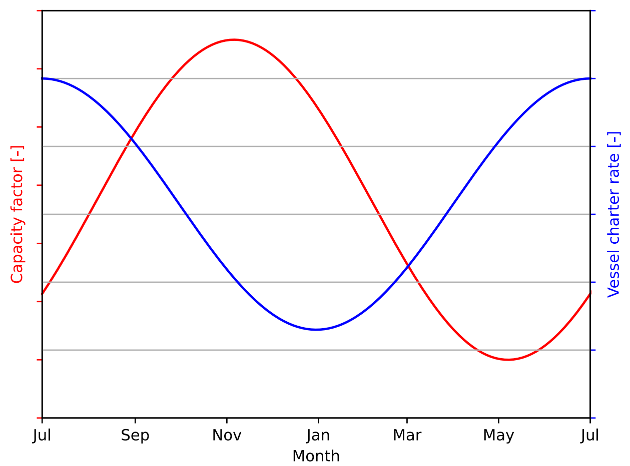

Figure 12: Synthetic AHTS vessel charter rate and wind turbine capacity factor time-series.

Table 4: Perceived limitations of the analysis method.

Limitation	Implication(s)	Mitigation
A large number of simulations is required to obtain result ranges and/or distributions.	A complex model would require a large amount of time to carry out sufficiently robust analysis.	The modelling approach has been designed to be a balance between model complexity, the availability (and fidelity) of input parameters and required project outputs.
It may be difficult to determine trends at higher system levels (i.e., string and array).	If uncertainty ranges are applied to many input parameters, then differences between the mooring system types and configurations may become "blurred".	The model is designed to allow insight into output parameters at all system levels with a limited number of input parameter variability. The alternative (to a Monte Carlo-type approach) could be highly specific analysis from which it would be difficult to generate broad conclusions for the sector.
Mean failure rates from the O&G sector were used.	These may not be relevant for FOW mooring systems and hence lead to misleading conclusions.	The failure rates used are a comprehensive dataset based on over 3 decades of reported O&G incidents. In the future these could be substituted for FOW data when it becomes available. Sensitivity analyses may be performed on failure rate input parameters.
Initial installation operation and anchor costs were beyond the scope of the study.	A full picture of project costs is not provided by the analysis.	Qualitative commentary is provided on how these aspects may influence lifecycle costs. Recommendations are provided for future work.

5.2 RESULTS

For the scenarios studied the following conclusions are drawn:

Total project costs for non-redundant systems were up to 7.4x higher than for redundant systems. For the non-redundant systems the high project costs were associated with repair and/or replacement of the IACs, both in terms of CAPEX and OPEX. Non-redundant mooring system failures required a significant amount of time to be spent on site and hence large amounts of fuel burnt, charter cost and downtime. As a consequence **vessel chartering was the dominant cost centre, on average representing up to 65% and 81% of total project costs for redundant and non-redundant systems respectively (Figure 14).** Figure 13 shows the legend for the Figure 14 charts. The highest total repair CAPEX (semi-taut 1x3 system, 100m water depth) incurred a total of 37 failures over one simulation (recalling that a simulation is a 900 MW FOW farm over a 25 year design life). For the same system type the minimum repair CAPEX associated with 3 failures over one simulation (500m water depth). This illustrates the range of potential outcomes associated with probabilistic methods when there are uncertainties associated with component performance.

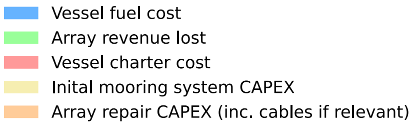

Figure 13: Pie chart legend.

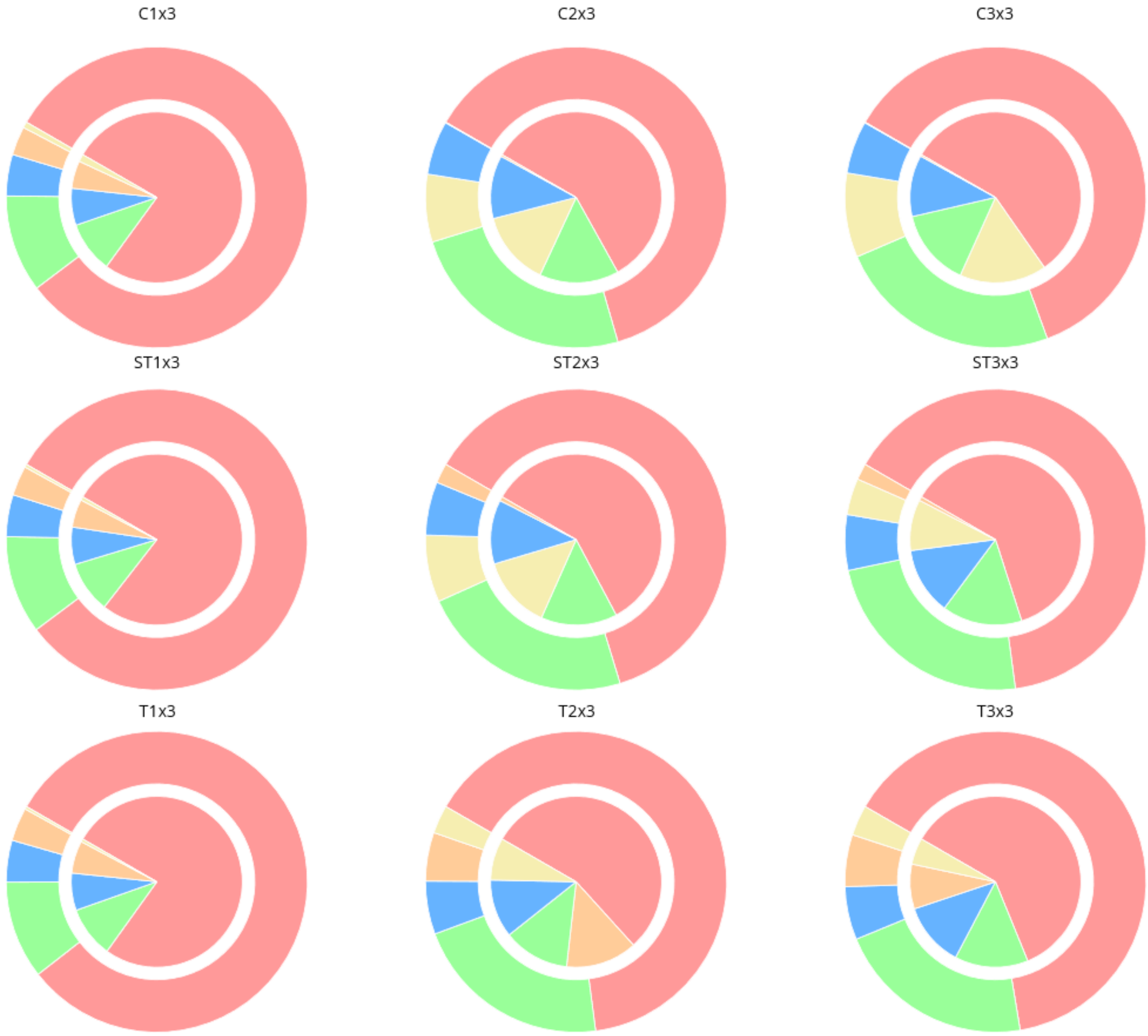

Figure 14: Cost pie charts for the (inner circle) 100m and (outer ring) 500m water depth scenarios. See Figure 13 for the pie chart legend.

The baseline simulations yielded array ay1vailabilities between 97.9% - 100.0% over the project lifetime which is the same order of magnitude as the average offshore transmission owner (OFTO) availability for fixed offshore wind (98.9% for 2021/2022; [26]**).** A maximum simulated unavailability of 2.1% may not seem to be significant, but it should be remembered that any downtime due to mooring system failures would be additional to maintenance activities for other FOW subsystems. Subsea cables, for example, are associated with the majority of offshore wind insurance claims [27]. **For most system types the second largest cost centre was the revenue lost across the array due to downtime.** Total turbine downtime is dependent on the number of mooring system failures as well as the duration of marine operations and the availability of suitable weather windows. Downtimes could be reduced if the mooring system has sufficient redundancy to allow turbine generation to occur whilst the mooring system is awaiting repair. Further compounding the costs incurred was the availability of suitable weather windows, particularly at the (more exposed) 500m site. If a failure occurred over the winter months access to the site was severely restricted, and even when a suitable weather window became available, it might not have been sufficiently long to complete the marine operation, leading to vessels placed on standby at the site or in port. Basing the vessels in the nearest O&M port can reduce overall chartering times, but could incur additional expense to keep the vessels and crew on standby. This was less of an issue for systems which required just mooring system repair (the maximum of which was assumed to take 3.7 days on site). **The availability of appropriate weather windows is directly related to the level of environmental exposure of the site and hence project OPEX.** The availability of weather windows (for safe working) was based upon a single proxy; significant wave height. **Sensitivity analysis of weather window limits demonstrated that if marine operations can be carried out in a broader range of conditions, increased site availability allows repairs to be carried out more easily, reducing operational costs and system downtime.** It is acknowledged that marine operations can be constrained by other factors (e.g., peak wave period, wind and current loading as well as restrictions on available daylight).

The number (and type) of components in a particular mooring design influences the number of failures experienced over a project and hence the number of required marine operations and total repair costs. This would suggest that it is beneficial to simplify (i.e., minimise the number of components) the design of the mooring system. However, the results also demonstrate that a degree of mooring system redundancy is critical to avoiding (expensive) cable damage and subsequent prolonged turbine downtime. **Sensitivity analysis demonstrated that opting for higher reliability versions of components is likely to result in lower probabilities of failure, and hence less costly offshore interventions over the design lifetime.** Therefore, even if the components themselves have a higher initial CAPEX, the increased reliability will benefit the overall LCOE of the project.

The initial mooring system CAPEX[2] of the taut systems is significantly lower than the semi-taut and chain catenary systems. Whilst the PET rope cost (per unit mass) is higher than the unit cost of chain used in this study, PET fibres typically have a strength-to-weight ratio which is approximately 2.5x higher than steel [28] and therefore can provide comparable loading capacities at a reduced mass. If tenable anchoring solutions exist for the site in question, taut systems typically have a smaller mooring footprint radii than catenary or semi-taut systems and hence line lengths are shorter to the benefit of overall system CAPEX. There is considerable overlap between the CAPEX of the semi-taut and chain catenary systems. In some cases the increased compliance of the semi-taut system actually required larger chain sizes to constrain platform excursion (which was often the limiting case). In these cases using larger chain sizes therefore negated any cost savings from introducing a length of synthetic fibre rope into the system. Compared to the other cost centres, the site water depth has a relatively small impact on the initial CAPEX (and repair CAPEX) of the mooring system due to the quantity of materials required.

Overall project costs are highly dependent on site availability and mooring system redundancy provision. Mooring system failures at the ends of the electrical string were simulated, which led to two adjacent turbines being out of action until the failed mooring system (and cables) were reinstated. This leads to the conclusion that it may be beneficial to overall array performance and LCOE to consider different mooring system designs at different IAC locations, i.e., increasing the redundancy at critical point(s) along the IAC string. Non-redundant mooring systems incurred high downtime durations (a combined total of over 31.3 years for the 500m water depth site, equivalent to an array availability of

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[2] Defined as the off-the-shelf price of the components, not including the cost of anchors or installation operations.

97.9% over the project lifetime). Comparatively, all of the redundant system array downtimes totalled less than 2.2 years and 9.4 years for the 100m and 500m water depths respectively.

6 CONCLUSIONS

This summary report has outlined FOW mooring system identification and consequence of failure analyses carried out during the *Risk and Failure Implications of Different Mooring Spreads and Number of Mooring Lines* project (MA02). In order to carry out this investigation multi-objective optimisation and lifecycle cost analysis tools developed by TTI-MR have been used in conjunction with Orcaflex and a set of input parameters which are broadly relevant to the current status of the sector. This study has demonstrated that a detailed project lifecycle computation requires many inputs and assumptions, all of which have intrinsic uncertainty. The scenarios studied herein have demonstrated that decisions made at the design stage can minimise overall lifecycle cost when the consequence(s) of failure(s) are considered. Furthermore, in order to draw conclusions which are broadly applicable to the FOW sector lifecycle assessments need to be carried out on multiple designs.

Perhaps the most pertinent overall conclusion from the mooring identification work is that, the design of these mooring systems is a compromise and it must be thought of as such. When considering multiple objectives it is unlikely that one “best” solution exists. Indeed, there is considerable overlap the results for the different mooring system types. For example, in order to minimise platform excursions, higher characteristic tensions may need to be tolerated which could, for some designs, incur high CAPEX. If applied to a farm of FOWs, this approach can be used to determine the impact of mooring system design on the LCOE of the array. This work has demonstrated that multi-objective optimisation enables the identification of many different solutions to tackle the design challenge, all of which offer somewhat different benefits compared to each other. The final selected design for an individual FOW and design(s) for a FOW farm may depend on numerous other factors such as geotechnics, supply chain, Classification Society rules, in-house philosophy and so on.

The ALS simulations highlighted the potential consequences of a commercial-scale turbine sustaining the complete failure of a mooring component. The subsequent loss of station keeping ability resulted in large platform horizontal excursions for the non-redundant mooring systems as well as two instances of cascade failure. It is likely that significant platform drift will cause extensive IAC damage (unless quick-release systems are included), necessitating lengthy and expensive marine operations to be carried out. The simulated platform rotations and nacelle accelerations could be used to inform turbine shutdown strategies in the event of mooring line failure, i.e., assessing whether mooring line failure be tolerated and hence turbine production can continue. Furthermore, there may be opportunities to optimise mooring system designs to allow nacelle motions to be acceptable / beneficial for power generation.

The implications of redundancy provision were reinforced in the lifecycle analyses, with the costs incurred to carry out offshore interventions dominating project costs for non-redundant systems, particularly for the more exposed site. The results suggest that mooring systems located at critical points on the export cable string for current capacity may require or benefit from higher levels of redundancy or measures to reduce the likelihood of failure. Sensitivity runs were carried out to determine the impact of altering the critical input parameters on lifecycle costs. Of these hypothetical scenarios, the highest impacts were yielded from increasing the weather window significant wave height limit and increasing the reliability of components. The baseline predicted farm availability was computed to be around 98% due to mooring system failures alone. Arguably this is too great an unavailability for mooring systems alone and in turn it can be concluded that better reliability than the established baseline in the O&G industry is required. It is not foreseen that the FOW sector should experience novel failure mechanisms compared to the O&G baseline but the potential for the introduction of increased complexity, the move towards a more high-volume manufacturing and greater number of installations and changes in the application loading spectra all mean that there is tangible risk that the O&G baseline failure rate may increase in the early days of FOW array roll-out.

Improving reliability and weather window operability are pertinent topics which should be explored in more detail by the industry. This study has utilised several decades of hindcast data to investigate weather window probabilities and simulate repair operations. In reality, reactive operations planning would be reliant on the combination of hindcast probabilities and short-term weather forecasts with associated uncertainties. The results also bring into question the long-term economic efficiency of locating FOW arrays in extremely exposed sites where site accessibility is governed by the prevailing environmental conditions and the fatigue spectra imparted to the mooring system may be more severe.

Although the initial installation and anchor costs were not included in the analyses, the relative share of the array revenue lost and vessel fuel costs CAPEX segments were small compared to the vessel charter costs. It is impossible to predict fleet availability or vessel capabilities over the next 25 years. However, if working significant wave height limits can be safely increased, this will open up more weather windows and reduce waiting times, charter costs, fuel consumption (and subsequent vessel emissions) and revenue lost due to turbine downtime. OPEX savings may also be possible as installation and repair procedures become streamlined (i.e., the concept of learning rates), perhaps facilitated through standardisation of components, as well as efficient spares strategies etc.

Overall, based on the assumptions and scenarios used in this study the 2x3 line configuration appears to be an attractive compromise between redundancy provision and project LCOE and this trend appears to be valid for the chain catenary, semi-taut and taut mooring systems considered in this study. More broadly, this study has highlighted that the cheapest CAPEX solution is likely not the best for long-term farm LCOE and the key design decisions should be assessed in a similar fashion to that presented herein. To simply accept the lowest CAPEX solution is to potentially accept significant hidden costs which may accumulate during the lifetime of the project.

7 RECOMMENDATIONS

With the aforementioned conclusions in mind, the following focus areas can be ranked (in order of most to least impactful in terms of LCOE reduction). It should be noted that this list has been based on the outcomes of the study presented in this report and adopts a “prevention is better than cure” philosophy. Some of these focus areas potentially conflict and ultimately, the prioritisation of focus areas will be made on a risk-return trade-off (or similar) basis.

1. **Provision of mooring line redundancy –** at the very least a degree of redundancy should be provided, particularly at vulnerable points of the IAC string.
2. **Increasing site accessibility** – if working significant wave height limits can be safely increased through remote operations or other technological advances, this would reduce lost generation (and revenue) due to downtime. Alternatively, sites could be targeted with good wind resource but more benign sea-state conditions.
3. **Reducing the number of failures** – by increasing the reliability of components, or reducing the number of components in the system where appropriate.
4. **Streamlining of marine operations** – to reduce the time required on site and hence, vessel charter and fuel costs as well as turbine downtime.
5. **Reduction of mooring system CAPEX** – to reduce initial and replacement costs.
6. **Holistic consideration of mooring and cable consequences of failure** – at an early design stage, by carrying out simultaneous analysis of these subsystems from initial design optimisation through to lifecycle assessment. Instead of considering these systems in isolation, this will allow combined mooring-cable systems to be identified as a starting point for detail designs and/or identifying design “sweet spots” and/or areas for further development.

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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

ORE Catapult
Inovo
121 George Street
Glasgow, G1 1RD

+44 (0)333 004 1400