Mooring Systems for Floating Offshore Wind: Integrity Management Concepts, Risks and Mitigation

World Forum Offshore Wind (WFO)

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Cover: Photo courtesy of BW Ideol and Centrale Nantes (V. Joncheray), *Floatgen demonstrator*

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Acknowledgments

WFO's 80+ members represent the entire offshore wind value chain including but not limited to utility companies, manufacturers, service firms, consultancies and other non-profit organizations.

This document is the result of one year's worth of monthly discussions between participating WFO members during meetings of WFO's Floating Offshore Wind Committee on the topic of 'Mooring Systems for Floating Offshore Wind'. WFO would like to thank everyone who has contributed their time and expertise during the discussions and additional analyses carried out for this study.

Disclaimer

The views in this report do not necessarily represent the views of all WFO members but are based on a synthesis of recorded insights undertaken by WFO and the WFO Moorings Subcommittee Chairman over the last year. The findings are also designed to serve as an initial account of the status, challenges and opportunities of floating offshore wind mooring systems and therefore should not be generalised and are subject to evolve along with the industry.

Foreword

One cannot diligently look at floating offshore wind without quickly drifting (no pun intended) into the meanders of mooring systems and solutions. Their impact on CAPEX and OPEX – without even tackling the environmental and recycling aspects – as well as the risks that need to be carefully mitigated to avoid jeopordizing the revenue source of floating wind (i.e. its dynamic electrical cable) are substantially more than anecdotal.

Pictures of capsized or drifting oil and gas structures still send shivers down the spines of many lenders and insurance experts and definitely justify that serial-installed floating wind assets (versus one-off oil & gas assets) deserve the most carefully engineered, sourced and installed solutions. Our Insurance Subcommittee's landmark initial white paper underlines the need for such a responsible approach.

Having said that, cost-competitiveness remains essential in our nascent industry's quest to match and even improve on the Levelised Cost of Energy (LCoE) of bottom-fixed wind by 2030 at the latest. Past and current efforts of our members need to be applauded but also require further support. Innovative materials and components as well as plug-and-play solutions reducing pre-lay and hook-up times will drive cost down. Building up a supply chain and creating local value as close as possible to each of our strategic markets while keeping a careful eye on mooring solutions' carbon footprint and their materials' recycling options will increasingly become key parameters in the purchasing decision process.

I thank our Subcommittee's Chair and active members for their work; I trust that their next white paper will bring even more relevant information to the market.

Floating wind is now, floating wind is big, floating wind is without a doubt going to be a key – if not the major – contributor to many countries' renewable energy targets.

Bruno G. GESCHIER
Chairman of WFO's Floating Offshore Wind Committee
Chief Sales & Marketing Officer of BW Ideol
Chairman of FOWT's Scientific and Technical Committee
Founding Chairman of WindEurope's Floating Offshore Wind Task Force (now Work Group)

Table of Contents

1 Introduction

The Moorings Subcommittee was founded as part of the Floating Offshore Wind Committee (FOWC) under the auspices of the World Forum Offshore Wind (WFO). Members whom attended the Moorings Subcommittee represent all sectors in the Floating Offshore Wind (FOW) industry, ranging from major international developers and contractors to research & development institutions, equipment manufacturers, engineering consultants, classification agencies and insurers.

Alongside the Moorings Subcommittee, two other subcommittees were founded: the Insurance Subcommittee and the Operation and Maintenance (O&M) Subcommittee. In addition to their individual achievements, both groups represent a great contribution to the work of the Moorings Subcommittee. The Insurance Subcommittee is focusing on developments with respect to insurance and project finance, whilst the O&M Subcommittee is analyzing different floating offshore wind maintenance and repair concepts. The three Subcommittees mutually foster the evolution of a "floating offshore wind dialogue" in that the outcomes of the discussions and the developments of the floating offshore wind know-how are shared across all groups. This work will shortly be bolstered by the newly formed Cables and Floating Substations Subcommittee which will further inform and guide the groups' activities.

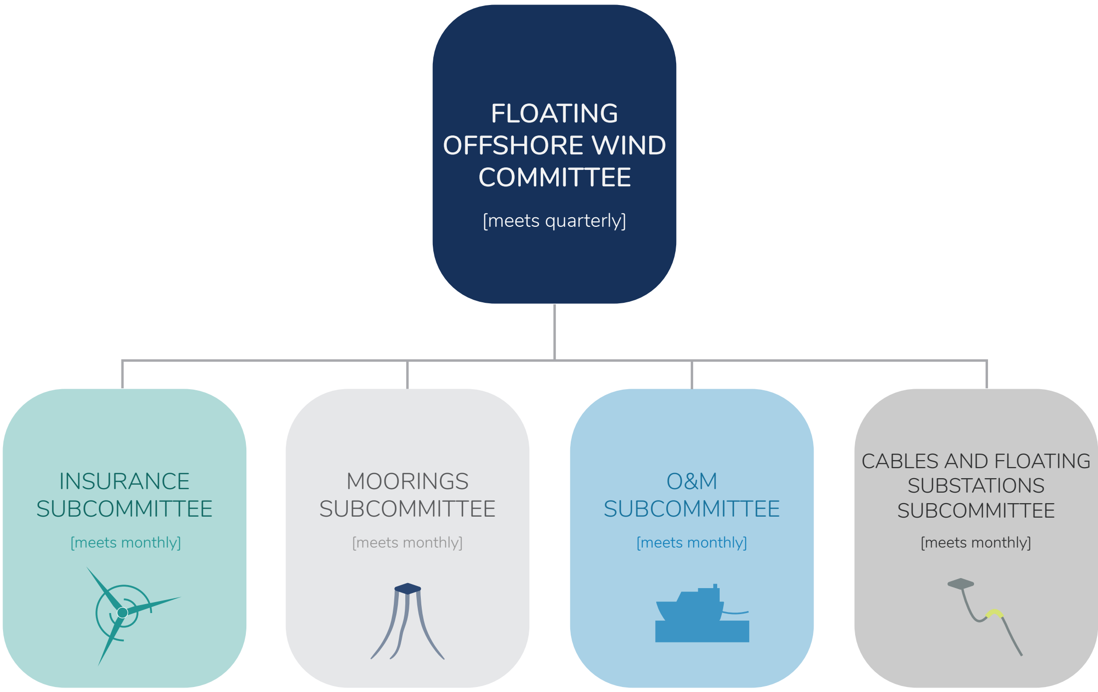


Figure 1. *WFO Floating Offshore Wind Committee Organizational Chart*

2 Mooring Systems for Floating Offshore Wind

The majority of global offshore wind resource lies in water depths exceeding 60 metres, which are not suited to conventional bottom-fixed turbines. Floating foundations are therefore necessary to maximise this potential. Whilst the floating offshore wind industry has been in development for more than a decade, there are limited small-scale/demonstrator projects in the water, representing around 126MW of total installed capacity to-date. However, current expectations are that up to 20.9GW of floating wind capacity will be installed by 2035[1] and 264GW by 2050[2]. This exponential growth, which requires rapid progression from pre-commerical to full-scale arrays, poses a significant challenge but is one that needs to be met if the industry is to deliver an energy transition that achieves global net zero ambitions.

2.1 Floating Foundations

Prevailing substructure design concepts, derived from offshore oil and gas experience, are illustrated below. Each has its own merits and challenges, but whilst spars account for the bulk of currently installed capacity, they are expected to be quickly surpassed by semi-submersibles based on projects presently in development -

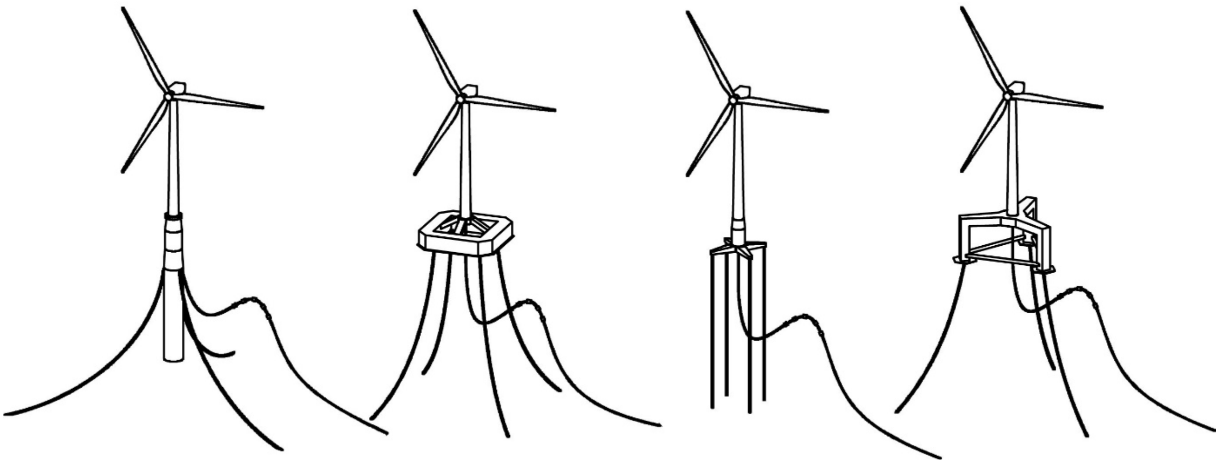


Figure 2. *Spar, Barge, TLP, Semi-Sub (from left to right)*[3]

Spar: The spar has a deep draft and is a ballast-stabilised structure. A well-established and simple technology that is inherently stable but has relatively large motions, its simple mooring system typically requires long, heavy mooring lines.

[1] BloombergNEF forecasts 5.3GW by 2030 and 20.9GW by 2035, Wind – 10 Predictions for 2022

[2] DNV, Energy Transition Outlook 2021

[3] Human exposure to motion during maintenance on floating offshore wind turbines, Scheu et al 2018, Ocean Engineering, Volume 165

Barge: Barges exhibit a square footprint and have the shallowest draft of all floating foundations. They are subject to high wave-induced motions but may incorporate a moonpool to supress this effect. Consequently, they require a more complex and robust mooring system.

Tension-Leg Platform (TLP): A tension-stabilised structure with relatively shallow draft, the TLP has a high degree of restraint and therefore experiences limited motions. It has a small footprint; however, significant vertical loads require mooring tendons to achieve high pretensions.

Semi-Submersible: The semi-sub is a relatively shallow draft, buoyancy-stabilised structure in which motions are limited by employing heave plates. It is a flexible foundation which can utilise a range of simple mooring systems but requires ballasting.

2.2 Station-Keeping

Mooring systems are critical to the station-keeping[4] of any permanent floating structure, and whilst the oil and gas sector has an extensive track record in this area, there is limited transferability when considering floating offshore wind. Wind farms of +1GW scale will comprise arrays well in excess of 50 floating turbines each having a minimum of three mooring lines, compared to deep water oil and gas terminals having single, very large structures employing multiple lines.

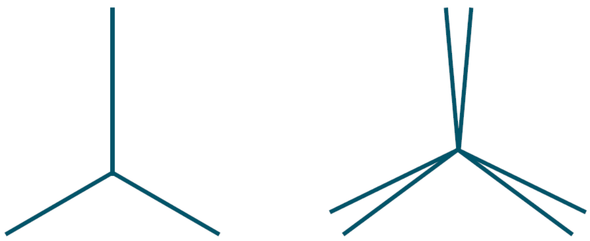


Figure 3. *Typical Semi-Sub 3x1-Line and 3x2-Line Mooring Spreads (from left to right)*

Operating conditions are also challenging. Shallow water[5] environments are non-linear, in which dynamic loads need to be considered, whereas the weight of equipment required for deep water[6] locations must be overcome. Mooring systems will need to be adapted to suit the substructure selected for each project, its overall design basis and individual site conditions. Furthermore, protection of dynamic power cables from damage by floater motions will be critical. Earthquake, tsunami, hurricane and typhoon risk will figure in certain geographies; therefore, a broad range of solutions are likely to be developed rather than one approach being favoured over another.

Floating foundations can be either 'compliant' or 'restrained' with respect to global motions, which are described as the 'six degrees of freedom' and detailed in Table 1: surge,

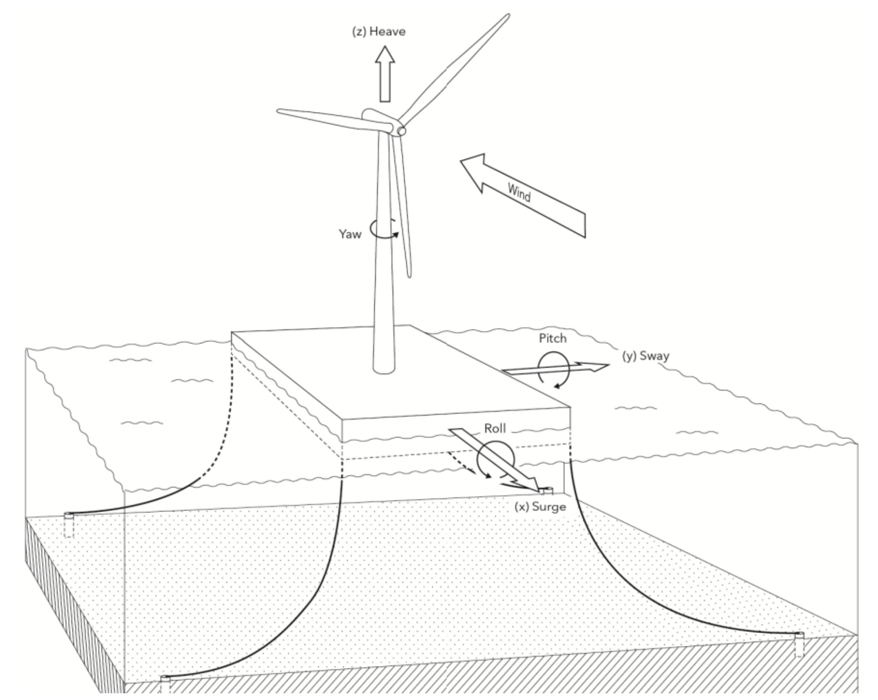
[4] To maintain a floating structure in a fixed position relative to a fixed point or within a defined sector relative to the fixed point. The station-keeping system includes the mooring lines or tendons, as applicable, as well as the anchor foundations that transfer forces from the system to the seabed.

[5] Typically 60 - 300m deep characterized by wavelengths greater than 10 times the water depth

[6] Usually +1,000m deep characterized by wavelengths shorter than about twice the water depth

sway, heave, roll, pitch and yaw. Spars, barges and semi-subs are compliant structures, whereas TLPs are constrained.

Table 1. *Source: Det Norske Veritas*[7]



Surge (x)	Displacement along longditudinal axis
Sway (y)	Displacement along lateral axis
Heave (z)	Displacement along vertical axis
Roll	Rotation about longditudinal axis
Pitch	Rotation about lateral axis
Yaw	Rotation about vertical axis

Typical station-keeping systems of compliant floaters are based on taut, semi-taut or catenary[8] mooring lines that transfer loads acting on the floater to anchors installed in the seabed. Anchoring solutions are decided on a case-by-case basis depending on the ground conditions at site and mooring system in use. The variety of mooring configurations are illustrated below (courtesy of First Marine Solutions, Morek Engineering and ORE Catapult's Floating Offshore Wind Centre of Excellence) and simply described as follows -

<u>Plain Catenary</u>: Comprising chain only between the anchor point and floater, the simple catenary mooring is commonly employed in conventional shallow water environments. Compliance is achieved by a restoring force characterised by the weight of chain employed, as opposed to its strength.

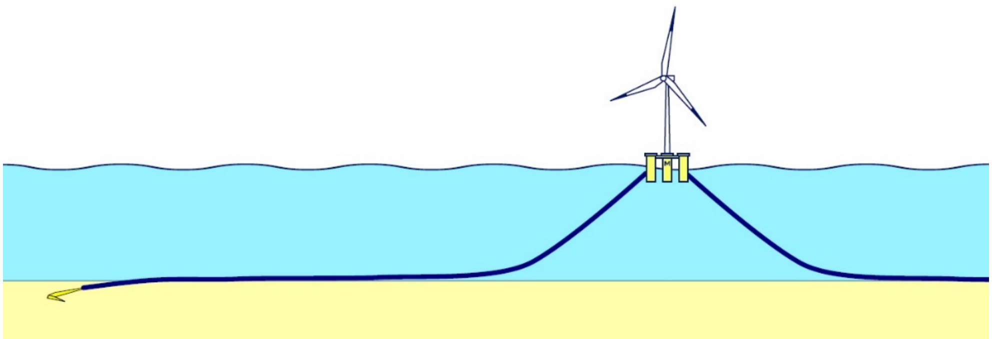


Figure 4. *Plain Catenary Mooring Spread*

[7] DNV-ST-0119 : Fig. 1-2

[8] Catenary simply describes the shape a free hanging chain forms and is similar to one side of a parabola

Multi-Catenary: An arrangement commonly utilising a synthetic rope/chain combination line. Initial compliance is achieved by the visco-elastic properties of a taut rope section and latterly by the weight of ground chain. Restoring force properties can be tuned by altering the arrangement of weighted and compliant sections, i.e. by the addition of clump weights, but a balance should be achieved between weight and stiffness to limit dynamic behaviour.

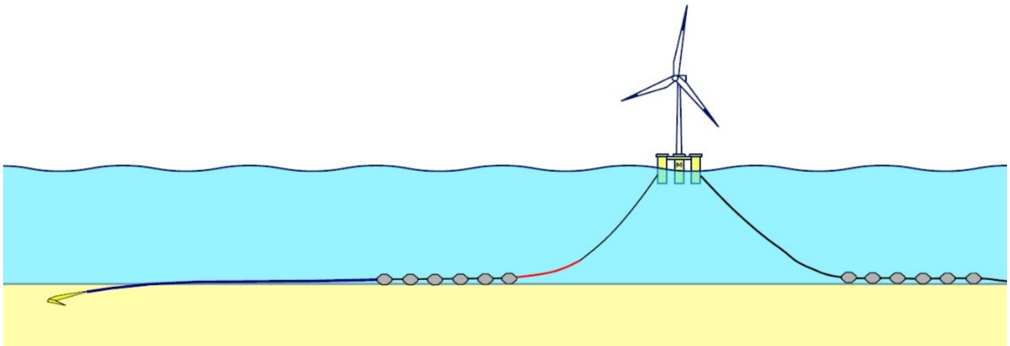


Figure 5. *Multi-Catenary Mooring Spread*

Buoyant Semi-Taut: Similary employing a synthetic rope/chain line, but with significantly reduced ground chain. Buoyancy modules are attached to the rope to prevent damage through contact with the seabed. Compliance is achieved predominantly by visco-elastic properties of the rope and the anchor points will experience significantly increased vertical uplift loads.

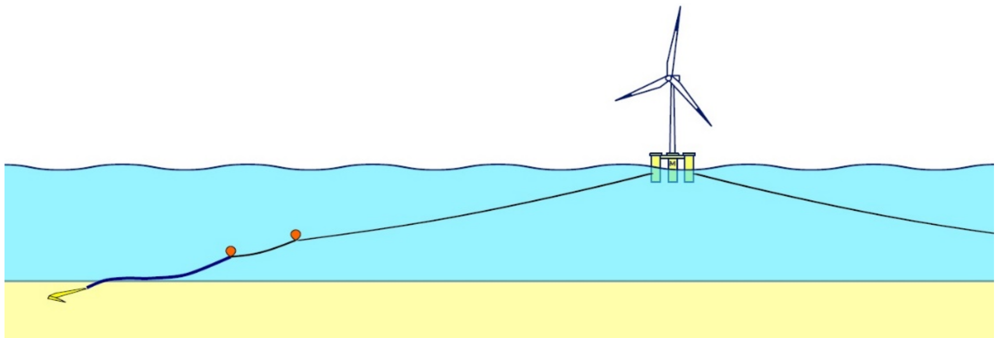


Figure 6. *Buoyant Semi-Taut Mooring Spread*

Taut: A system comprising rope tendons connected under tension to the anchor point. Lines experience high loads and the anchor must withstand vertical uplift. Short sections of chain and connectors may be employed at the termination points to allow the adjustment of length and overall tension.

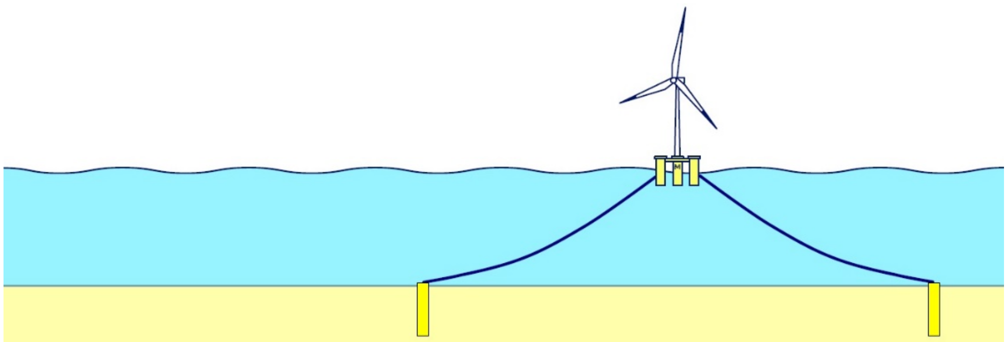


Figure 7. *Taut Mooring Spread*

Fundamentally, a mooring system should maintain the position and attitude of the floating structure and ensure the dynamic power cable remains within its design envelope. However, 'optimisation' of compliant mooring systems may result in non-redundant systems in which a mooring line failure may lead to loss of position, possible collision with adjacent structures and/or damage to power cables. Redundancy considerations are therefore an important part of mooring design and form part of the basis for selection of appropriate consequence class (which are outlined later).

Redundancy is a commonly used term but one which is often misunderstood. DNV, in its Standard for Floating Wind Turbine Structures (DNV-ST-0119), provides guidance that in some cases "… it is not so obvious if a station-keeping system is redundant or not. For example, failure of a slack mooring line in a 3x1-line system, causing a large drift-off, does not necessarily imply a system without redundancy." As outlined later, the n+1 concept is advocated as the preferred method of mitigating risk of single line failure, although redundancy can be achieve in a number of different ways.

2.3 Standards, Recommended Practice & Guidance

Regulatory frameworks differ from country to country and consequently there is no single global governing Standard with respect to the design, manufacture, assembly, installation, commissioning, operation, maintenance and decommissioning of Floating Offshore Wind Turbines (FOWT). However, a number of International Classification Societies have developed technical Standards which incorporate existing Rules, but these require development in response to innovation and growing operational experience. Furthermore, future harmonization is necessary to prevent ambiguity. Governing standards for each Classification Society are summarized below. Detailed individual frameworks can be found in the Appendix.

Table 2. *Source: ORE Catapult, Floating Offshore Wind Centre of Excellence*[9]

Class Society	Name	Title	Revision Date
International Electrotechnical Commission	IEC TS 61400-3-2	Wind energy generation systems - Part 3-2: Design requirements for floating offshore wind turbines	April 2019
American Bureau of Shipping	195	Guide for Building and Classing Floating Offshore Wind Turbines	July 2020
Bureau Veritas	NI 572 DT R02 E	Classification and Certification of Floating Offshore Wind Turbines	January 2019
Det Norske Veritas	DNV-ST-0119	Floating Wind Turbine Structures	June 2021
Lloyd's Register	LR GN2	Guidance Notes for Offshore Wind Farm Project Certification	July 2019

[9] Standards Mapping Report, Sept 2021 : Table 1-1

2.4 Levelised Cost of Energy

Compared to onshore and offshore bottom-fixed wind, the cost of electricity generated by floating wind turbines is relatively expensive. It is imperative to quickly bring down the Levelized Cost of Energy (LCoE) and many forecasts predict price parity will be achieved in the early 2030s. The ambition is to move quickly from initial demonstrator projects, bypassing pre-commercial limited scale developments, to full-scale +1GW arrays. This is clearly evidenced by bid results from Scotwind Leasing Round 1 where 10 of the 17 sites were awarded to floating wind technologies, representing 14.5GW of 25GW total offshore wind capacity.

It is anticipated that innovation and the adoption of new technologies will address the various challenges and help drive down cost, as will the industrialisation of production and deployment. The below forecast illustrates this trend with respect to various growth scenarios in the UK market, both with and without innovation. However, as we will come to see, a lack of experience/track record and its associated risks may preclude projects from securing adequate insurance cover. Furthermore, increased pressure to optimise mooring systems, the risk of serialisation of defects and lack of readiness in the supply chain/local content availability could exacerbate this issue.

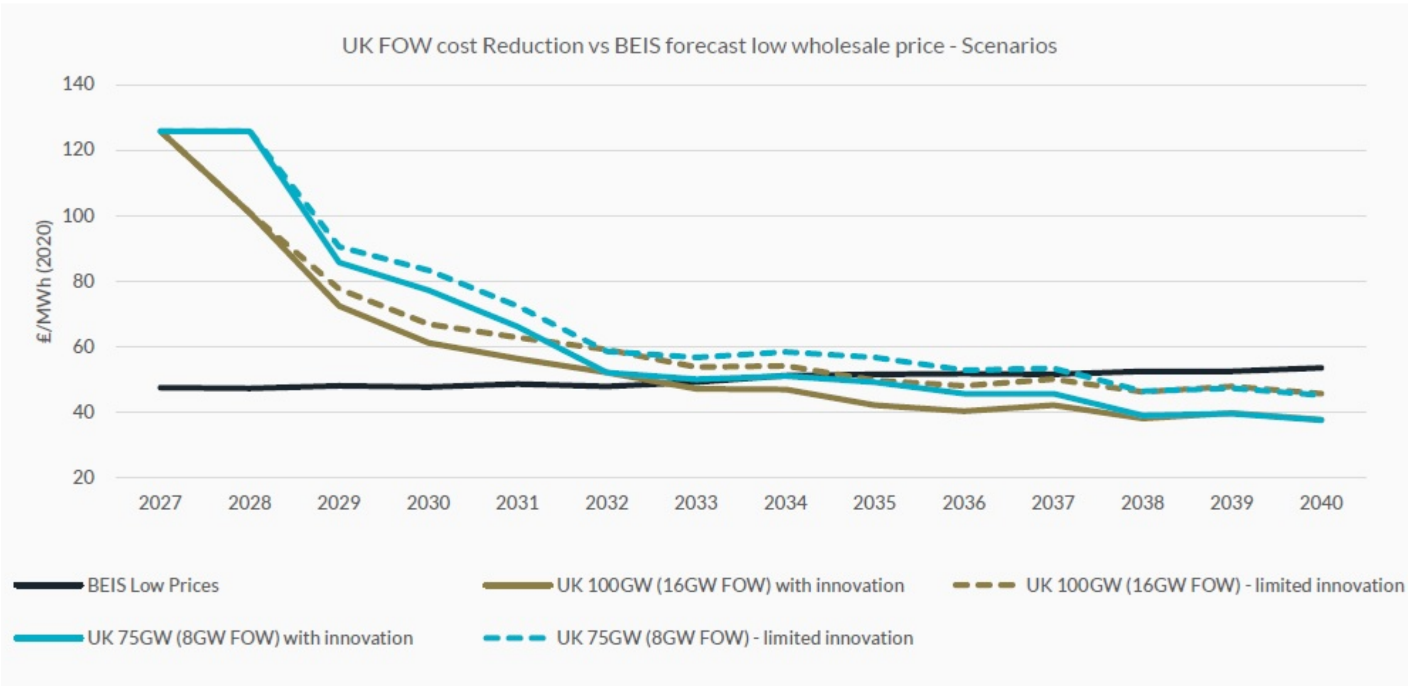


Figure 8. *UK Floating Offshore Wind Cost Reduction vs BEIS Forecast Wholesale Electricity Price. Source: ORE Catapult, Floating Offshore Wind Centre of Excellence*[10]

[10] Floating Offshore Wind: Cost Reduction Pathways to Subsidy Free, 2021

2.5 Insurability

The white paper published by WFO's Insurance Subcommittee concerning 'Insurability of Floating Offshore Wind' clearly lays out the basis for projects to demonstrate risk mitigation, especially with respect to cables and moorings.

Whilst there is long-term experience in bottom-fixed offshore wind, availability of cover for the nascent floating offshore wind sector is limited. There are few insurers willing to underwrite this risk and the market has restricted capacity due to: the proliferation of floater concepts, a wide variety of available mooring and anchoring systems, innovation/new technologies being considered, and a lack of operational track record. Since 2020, international insurers have started to respond to negative financial results by -

1. Reducing the coverage of insurance wordings
2. Increasing deductibles
3. Increasing premiums

Significant claims in the bottom-fixed offshore wind sector have recently compounded the above reaction with both deductibles and premium levels for floating offshore wind projects being many times higher than for bottom-fixed. Furthermore, the application of London Engineering Group[11] (LEG) clauses may be limited to LEG 1 and LEG 2 until suitable experience is established. Consequently, insurer(s) shall not be liable for -

LEG 1/96 - Loss or damage due to defects of material workmanship design plan or specification, i.e. completely excludes the loss or damage and the loss of revenue

LEG 2/96 - All costs rendered necessary by defects of material workmanship design plan specification and should damage occur to any portion of the Insured Property containing any of the said defects the cost of replacement or rectification which is hereby excluded is that cost which would have been incurred if replacement or rectification of the Insured Property had been put in hand immediately prior to the said damage, i.e. excludes the costs which would have been incurred immediately before the loss or damage occurred, but not loss or revenue

It may be some time before coverage will extend to the higher LEG 3 wording, i.e. only excluding the costs for improvements and betterments (not loss, damage or loss of revenue).

LEG 3/06 - All costs rendered necessary by defects of material workmanship design plan or specification and should damage (which for the purposes of this exclusion shall include any patent detrimental change in the physical condition of the Insured Property) occur to any portion of the Insured Property containing any of the said defects the cost of replacement or rectification which is hereby

[11] London Engineering Group is a consultative body for insurers of engineering class. The group produces coverage clauses which vary in their exclusions with respect to engineering risks

excluded is that cost incurred to improve the original material workmanship design plan or specification.

At this stage, there is no clear relationship between classification and LEG-insurability, which means projects using new technologies with limited track records should consider quantifying the additional risk between LEG 1 and LEG 2 at a very early stage and establish risk mitigation measures. Projects planning to use new technologies which offer promising cost-saving perspectives might be willing and able to take the additional risk between LEG 2 and LEG 1 and to mitigate it technically. Such an early-stage risk analysis and mitigation methodology will have an important impact on the availability of Project Finance.

2.6 Design Basis

The purpose of any mooring system is to maintain station and control floater 'global motions' as described in Section 2.2. Systems will vary according to prevailing environmental conditions, water depth, ground conditions, floater type, mooring arrangement and power cable dynamic configuration selected. The applicable 'Standards, Recommended Practices and Guidance' are identified in Section 2.3, and each design should comply with prescribed 'limit states' defined therein -

1. **Ultimate Limit State (ULS) -** maximum structural stiffness or load-carrying capacity of the intact system beyond which the probability of failure is unacceptable
2. **Fatigue Limit State (FLS) -** maximum stress concentration or damage accumulation, resulting in structural failure due to cyclic loading below the ULS
3. **Accidental Limit State (ALS) -** the minimum survival condition required to maintain structural integrity in a damaged condition (transient and stationary), or in presence of abnormal environmental conditions. The return period for which defines the number of years between events characterized by a similar magnitude, e.g. a 50-year wave height, has a 2% probability of being exceeded in any one year

Target safety levels, which vary from country to country, are defined and each design is attributed a class according to the consequences of a structural failure -

1. **Consequence Class 1 (CC1) -** where failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent structure, and environmental impacts
2. **Consequence Class 2 (CC2) -** where failure may well lead to unacceptable consequences of these types

Target safety levels for mooring systems relate to an annual probability of failure of 1 x 10^{-4} for CC1 or 1 x 10^{-5} for CC2.

Typically, mooring systems are designed to achieve CC1 unless they are non-redundant, in which case CC2 applies. DNV-ST-0119 defines redundancy as the "…ability of a component or system to maintain or restore its function after a failure of a member or connection has occurred." For example, if one mooring line is lost, the remaining part of the mooring system must meet the ALS criterion for at least a one-year[12] load for post-damage cases, provided that the damage is controlled within a reasonably short timeframe, as well as a robustness check for the intact system in 500-year return period conditions. Consequently, redundancy can be achieved in different ways and its practical application is the balance between ULS and ALS –

1. **Alternative Load Paths -** The n+1[13] concept is advocated as the preferred method of mitigating risk of single line failure, i.e. having 3x2-line as opposed to 3x1-line mooring spreads, where the remaining lines maintain station-keeping closer to the floater's original position
2. **Strengthening -** Improving the structural integrity of remaining mooring lines to accommodate the ALS load case when the turbine may be considerably offset from its regular operating position, i.e. increasing the size of equipment employed

In addition to this, each design should consider 'robustness' against possible systematic errors. For instance, the less mature a technology, the higher the need for robustness. Whilst it is expected that innovation and the adoption of new technologies will overcome various challenges and drive down LCoE, the limited availability of project finance/insurance cover as well as the potential for serialisation of defects may warrant a conservative approach at first.

DNV-RP-E308 suggests "…mooring design starts with a whole-system quantitative risk assessment. The risk analysis should study different line failure scenarios and consider the potential drift-off consequences. Understanding the risk profile and the risk reduction required to bring scenarios and consequences to an acceptable level provides a way to compare strategies to achieve commensurate expenditure on the mooring system."

DNV-RP-0286 recommends "…global analysis of floating offshore wind turbines, including substructures, and of separate components, i.e. wind turbine, floater and station-keeping systems." This so-called 'Coupled Analysis' makes sure the real-time interactions between these elements are taken into account synchronously during the design stage. The coupled analysis should be performed in time domain with aero-hydro-servo-elastic simulation codes in order to capture the typically non-linear system behaviour of mooring systems of FOWTs.

2.7 Mooring Integrity Management

A seminal study[14] into mooring failures in oil and gas floating production systems between 1997 and 2013 reported single line failure rates of 2.5 x 10^{-3} per line per year and multiple line failure rates ≈3.5 x 10^{-3} per unit per year, i.e. much higher than prescribed in the relevant

[12] The load resulting from extreme environmental conditions expected to occur within a year

[13] The n-1 notation was previously referenced in the Insurance Subcommittee White Paper, but both are valid. For instance, in Germany, "n-1 Sicherheit" means in the event of a failure, the mooring system maintains FOWT position and energy production

[14] OTC-25273-MS: Industry Survey of Past Failures, Pre-emptive Replacements and Reported Degradations for Mooring Systems of Floating Production Units, Fontaine et al 2014

design codes. The resulting improvements in understanding and managing failure modes/degradation mechanisms has no doubt reduced these rates. However, direct translation of these results to develop corresponding failure rates for FOWT moorings is problematic at present, despite many of the underlying degradation threats across the life cycle of an oil and gas floating production mooring system being applicable. A recent assessment by DNV estimated mooring system failure rates for floating wind of between 0.1% - 2%[15], leading them to express an opinion that developers should "…plan for failure." Therefore, mooring integrity issues need to be given much greater consideration during the design phase and applied throughout the mooring life cycle.

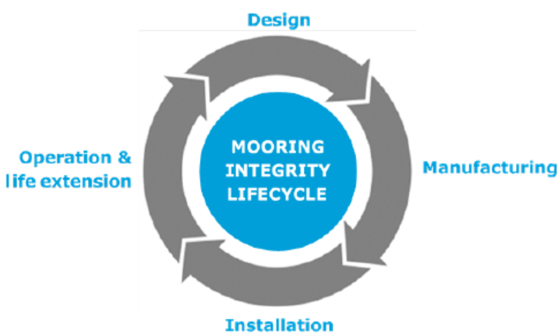


Figure 9. *Mooring System Life Cycle*[16]

Figure 10. *Integrity Management Process*[16]

Mooring Integrity Management (MIM) is a process for ensuring a mooring's fitness-for-service over its entire life cycle (see Fig. 9 and 10), managing the effects of damage, deterioration, changes in loading and accidental overload. MIM programmes should detect abnormal conditions or factors outwith the original design envelope through regular inspection and monitoring. The process is iterative, providing data that may be used to undertake remedial action, protect against accidents or loss, estimate remaining service life and support life extension requests. By monitoring the response of various aspects of the system, changes can be identified and rectification actioned.

The integrity management (IM) process provides an opportunity to adopt risk-based principles that consider the likelihood of damage and its potential consequences in order to develop a risk matrix (see Fig. 11). Mitigation should be put in place to reduce or remove identified risks and/or consequence of failure, and a list of initiation triggers should be developed to determine if parameters have changed. Typical examples include changes in platform offset, differences in magnitude or frequency responses from load monitoring. Immediate and short-term incident response planning should also be evaluated along with the availability and condition of any spares or emergency repair equipment. Note, however, the risk profile of a mooring may change over time.

A fitness-for-service assessment should be performed if an initiation trigger was identified in the evaluation of IM data. Likewise, a recent failure in a similar mooring system, research

[15] DNV Presentation: Moorings Subcommittee #2, K. Argyriadis and A. Argyros 2021

[16] DNV-RP-E308 - Mooring Integrity Management

that invalidates original design assumptions, changes in environmental or operating conditions should also prompt a review. Therefore, the IM process should be defined as early as possible in the design phase and an inspection plan drawn-up identifying the frequency and scope of inspections, methods and equipment to be used.

Consequence of Failure				
	High	Risk Level 2	Risk Level 1	Risk Level 1
	Medium	Risk Level 3	Risk Level 2	Risk Level 1
	Low	Risk Level 3	Risk Level 3	Risk Level 2
		Low	Medium	High
		Likelihood of Failure		

(1) **Risk Level 1** - RED - major focus of resources, increased inspection frequency/intensity and/or more detailed engineering

(2) **Risk Level 2** - YELLOW -moderate focus of resources

(3) **Risk Level 3** - GREEN - less focus of resources, reduced inspection frequency and/or scope

Figure 11. *Risk Categorisation Matrix*[17]

Integrity management data falls into two broad categories -

1. **Characteristic Data -** the baseline data that represents the mooring at installation and includes the as-designed condition, as-built condition, and as-installed condition
2. **Condition Data -** represents the changes to characteristic data that have occurred during the life of the mooring and include data from in-service inspections, damage evaluation, corrosion protection; strengthening, modification or repair data; condition monitoring data and operational incident data

Inspection and monitoring are therefore key elements of any IM programme and a Risk Based Inspection (RBI) approach is usually adopted. Direct measurement through continual monitoring, periodic measurement or visual inspections are preferred; however, inferences from indirect measurements, i.e. platform motions and 'Digital Twins', may be used. A risk assessment should then be employed to rank the criticality of certain mooring components within the matrix, but other factors such as interfaces between equipment, location within the line, fatigue, corrosion and other degradation mechanisms should be considered. Of course, the condition of monitoring systems themselves should not be overlooked by any IM strategy.

[17] API RP 2MIM – Mooring Integrity Management

3 Risks & Mitigation

There are no reported failures in FOWT mooring lines to-date, but this is perhaps due to there being few small-scale/demonstrator projects in the water for a limited time. Furthermore, these are not located in the harshest operating environments and likely employ cautiously over-engineered mooring systems (as is common for emerging technologies). However, if as detailed in Section 2.7 that annual single line failure rates are estimated in the region 0.1% - 2%, an understanding of the main threats and associated mitigations is critical. Whilst innovation and new technologies are expected to overcome many challenges, risk will be higher in the short-term due to limited track record and experience, which may be compounded by rapid progression to full scale +1GW arrays utilising a serialised approach. Therefore, the consequence of early failures may be a lack of insurance cover or project finance that might curtail the industry's growth. An early conservative approach is therefore warranted.

Importantly, we also need to understand what constitutes a 'failure', which does not necessarily imply a catastrophic event where damage causes the loss of one or more lines. For example, it may be a reduction of tension in which floater excursion falls outside the design envelope, risking damage to power cables; or indeed the pre-emptive replacement of equipment identified by an integrity management programme as being damaged or degraded beyond design expectations. In each case, energy production may be interrupted, causing loss of revenue if not a total loss of the floater.

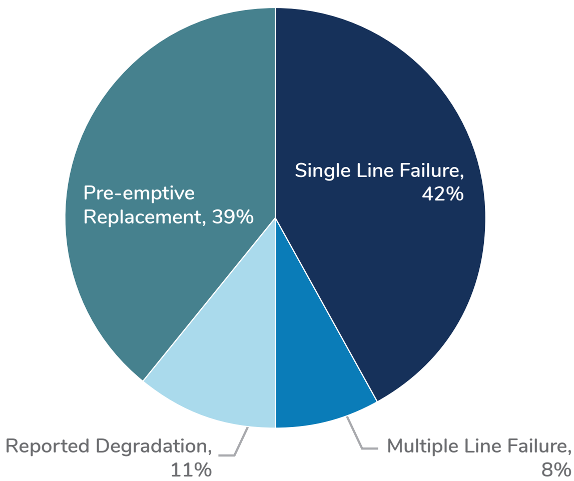


Figure 12. *Failure Event Type*
Source: OTC-25273-MS

3.1 Failure Modes and Degradation Mechanisms

Common failure modes and degradation mechanisms are well understood as evidenced by findings from the aforementioned OTC-25273-MS study into mooring failures in oil and gas floating production systems (refer Fig. 13 to Fig. 16 below). The most prevalent causes of single line failures were fatigue[18] and corrosion[19], with 49% of damage sustained during operation, 19% of failures due to design issues and 6% attributed to manufacturing (construction).

Design issues will vary with floater type/mooring system selected and be affected by type/configuration of equipment within the mooring line. However, issues may be addressed by ensuring sufficient and accurate site data is available, that adequate strength/fatigue analysis has been performed, likely failure modes are assessed and coupled analysis conducted. Furthermore, the design should set out a clear integrity management strategy/philosophy and provide for easy change-out/replacement of equipment where necessary.

Manufacturing issues should be controlled through careful selection of approved suppliers with proven experience and equipment/technology track-record. A robust 'Quality Assurance/Quality Control' system that fully documents the results of tests in accordance with class rules and highlights non-conformances/remedial actions taken is essential to establishing the 'as-built' condition necessary for distinguishing between manufacturing defects and infant mortality due to random or unknown failure mechanisms. Results should be independently verified and enhanced testing regimes considered, including Non-Destructive Examination (NDE), e.g. radiographic, ultrasonic, magnetic particle inspection.

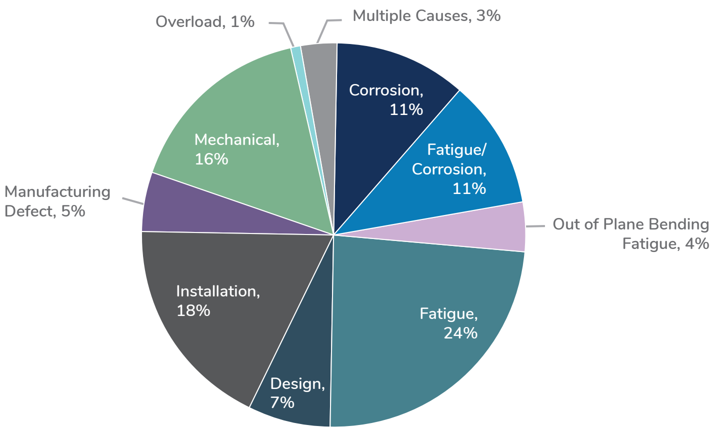


Figure 13. *Prevalent Failure Modes*

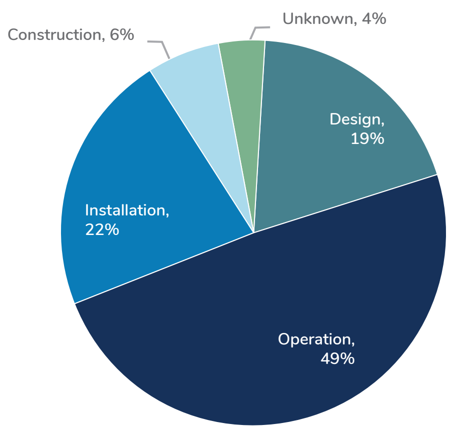


Figure 14. *Phase of Failure Event*

Source: OTC-25273-MS

The most commonly failed component is chain representing 46% of all events, of which almost half occurred in the upper sections, particularly at the stopper/fairlead. Behaviour of chain links in this section should therefore be carefully evaluated during the design phase to minimize the risk of failure, and particular attention should be paid to corrosion in the splash zone. However, chain is the most represented component, being present in 76% of surveyed systems and subject to the highest pre-emptive replacement.

[18] Initiation and propagation of cracks due to cyclic loading

[19] The deterioration of a material through chemical reaction. Typically chemical or electrochemical whereby metal degrades through oxidisation, but may also be induced by microbiological activity

Failures associated with steel wire rope account for 31% of all events, which is unsurprising as it is more easily damaged during installation but was also widely represented in 47% of systems. However, multiple line failure events are dominated by wire at 60% compared to 13% for chain, suggesting chain degradation can be adequately controlled through an appropriate IM programme. It is also worth noting that reported failures in polyester ropes, which represent only 3% of the total survey, were all caused by mechanical damage. However, these statistics may be somewhat distorted as the use of polyester for permanent moorings was in its infancy at the time of the survey with only 9% of facilities using or having used it. Consequently, prevalent failure modes may have not yet emerged.

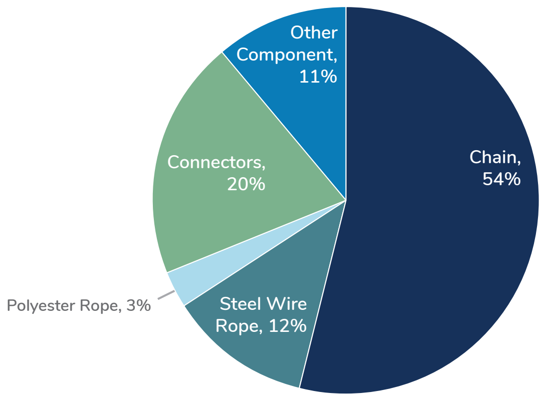


Figure 15. *Single Line Failure by Component*

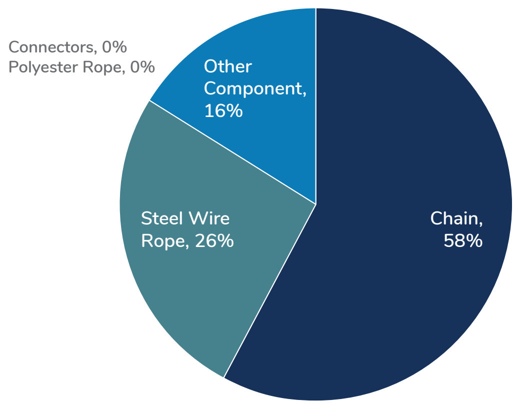


Figure 16. *Pre-emptive Replacement by Component*

Source: OTC-25273-MS

A small number of 'Out-of Plane Bending' (OPB) failures were reported, but these are becoming increasingly relevant. OPB is a somewhat new phenomenon identified in 2002 following the failure, at the fairlead, of 3 mooring lines on TotalFinaElf's offloading buoy at the Girassol deep water field, offhsore Angola. Loss of inter-link articulation under load causes one link to behave like a beam whilst the adjacent link is subject to rotational displacement from first order floater motions. This induces cyclic bending stresses which accumulate to cause crack initiation and rapid popagation to fatigue failure. The below images (courtesy of AMOG) highlight bending stresses associated with tension-tension in-plane and out-of-plane bending. DNV[20] noted that a better understanding of OPB, especially in systems with high pretensions, can help remove unnecessary conservatism associated with costly and heavy multi-level articulated chain stoppers. Dedicated OPB testing of chain samples at the 1:1 project scale is necessary to enable design optimisation.

[20] dnv.com Laboratories and Test Facilities Article: Cross-learning between oil and gas and floating offshore wind: Optimizing mooring design to cut cost and weight, Pedro Barros 2021

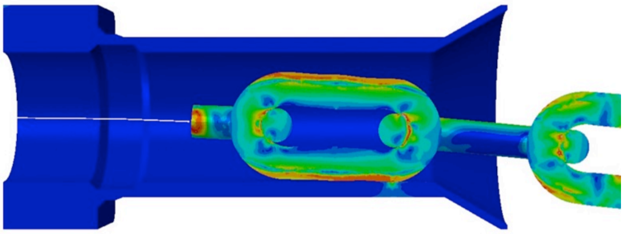


Figure 17. *In-Plane Bending*

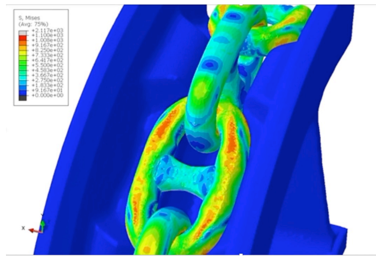


Figure 18. *Out-of-Plane Bending*

Source: AMOG Consulting[21]

One less well understood but important factor is 'installation' which represents 18% of failures, with 22% of damage caused during the installation phase. Risks may vary according to design choices made, e.g. anchor type, line configuration, upper connection mechanism and tensioning system. The type and critically the size of equipment will also have a bearing on the installation campaign, vessel selection and ultimately cost. To mitigate these threats, a detailed risk assessment should be undertaken during the design stage which takes account of onshore mobilisation activities and possible seabed congestion, including potential damage to power cables during pre-lay, wet-storage and hook-up activities. The main concerns are damage caused during handling which may result from twisting, side-loading/overloading, misassembled items or poorly designed connections and unauthorized repairs (e.g. welding). Poor anchor installation/positioning and incorrect or inconsistent line pretensions may also result in failure.

The white paper published by WFO's O&M Subcommittee regarding 'Challenges and Opportunities of Major Maintenance for Floating Offshore Wind' clearly identified the need to de-risk operations by designing specific procedures. Therefore, detailed installation plans and handling procedures should be developed that consider necessary tooling, crew training and monitoring processes. Integrity management activities should not be neglected at this stage with the verified 'as-installed' condition also being critical to distinguishing between installation damage, manufacturing defects and infant mortality due to random or unknown failure mechanisms.

Many of the underlying degradation threats of oil and gas floating production systems outlined above will be applicable to FOWT moorings, and the criticality of certain locations within the mooring line will remain important, e.g. top chains, connectors and interfaces between equipment. However, floating wind turbines present a very different mooring challenge compared to oil and gas. The design basis and line configuration may differ dramatically, not least in non-linear shallow water environments where dynamic loads need to be considered. In addition, the thrust force from the turbine is large and inceases quadratically with the wind speed up to the rated wind speed[22]. For higher wind speeds above rated, the mean thrust decreases again through the controller, which protects the turbine from overloading (see Fig. 19). As a consequence, FOWT mooring lines are likely to run at

[21] OMAE2020-18609: Investigations Into Fatigue of OPB Loaded Offshore Mooring Chains, Farrow et al 2020

[22] Rated wind speed is the wind speed up to which the wind turbine extracts the maximum possible power from the wind. At higher wind speeds, a non-zero blade pitch angle leads to a constant mean power equal to the rated power of the turbine, through suboptimal operation and therefore reduced loads. The rated wind speed is for most turbines around 30% above common mean wind speeds.

higher mean loads for the life of the field as large forces appear for a significant percentage of the turbine's lifetime.

Regarding fluctuating thrust loads, another important aspect is the "negative damping" induced by the blade pitch controller, the controller active above rated wind speeds. The negative damping means that the FOWT damping, especially in the platform pitch degree of freedom, becomes very small or even negative. There are various controller design methodologies to avoid this negative damping phenomenon. Still, a risk remains for the controller to not behave as expected, i.e. following a change in system parameters away from the design condition. Such a change could therefore lead to increased fatigue loads on different components and should be taken into account in the risk assessment.

Subsequently, a number of failure modes and degradation mechanisms will not yet be understood. Furthermore, it is anticipated that the use of chain and wire will be significantly reduced in favour of synthetic rope and new technologies employed. Novel failure mechanisms will be particularly challenging because, by nature, they are unforeseen and cannot be easily prevented by existing integrity practices.

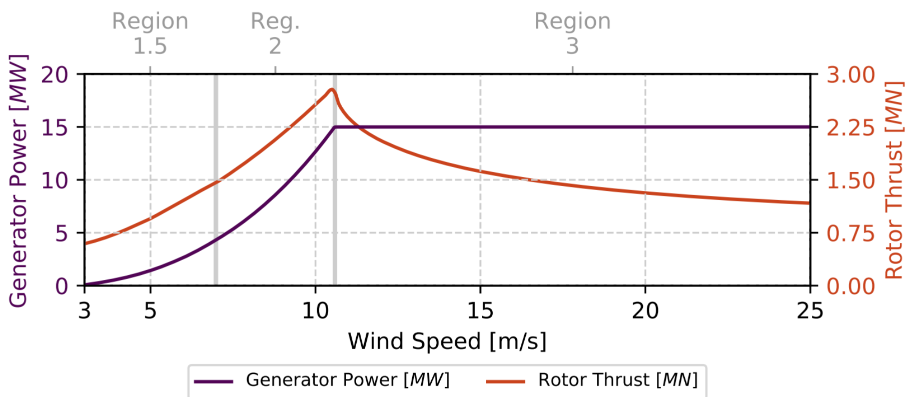


Figure 19. *Generator Power and Rotor Thrust Curves as a Function of Wind Speed Source: IEA Wind TCP Task 37*[23]

3.2 Failure Distribution

The bathtub curve, so-called because of its shape, is widely used to describe the reliability of a product and/or pattern of failure generally observed. It is illustrated in Fig. 20 by the blue line. The vertical axis represents the failure rate and horizontal axis time. The resultant curve is achieved by mapping three distinct functions -

1. A decreasing failure rate characterized by early failures, illustrated by the red line
2. A constant and random failure rate, shown by the green line
3. An increasing failure rate characterized by late failures, exhibited as a yellow line

[23] Definition of the IEA Wind 15-Megawatt offshore reference wind turbine, Gaertner et al 2020

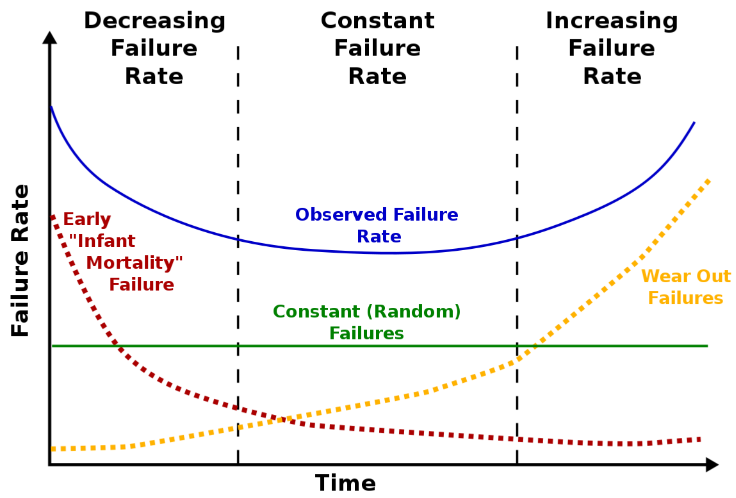


Figure 20. *The 'Bathtub Curve'*
Source: U.S. Army document, retrieved from Wikipedia

'Infant Mortality' is an issue originally highlighted by a study into high failure rates of permanent mooring systems in the offshore oil and gas industry during the period 2001-2011[24]. The study observed that "More than half of [failure] incidents happened during the first 5 years of their design lives" with more occurring within "…the very first year than any other year." These early failures are associated with design faults, manufacturing defects and installation damage, often becoming evident during the first significant loading event (e.g. storms). Integrity management is crucial at this stage: an enhanced inspection regime is recommended during the first 3 to 5 years of operation, which will help identify novel failure mechanisms. Most importantly, the characteristic 'as-designed', 'as-built' and 'as-installed' condition records are critical to establishing baseline data for on-going structural health monitoring.

The central section of the curve, or 'Useful Life', is the most stable with lowest combined failure rate. Infant mortality threats have subsided and common failure modes/degradation mechanisms are not yet prevalent. Failures are likely to be random and typically associated with accidental overload, incidents and stochastic events, e.g. damage to synthetic rope caused by over-trawling. Integrity management, however, remains important for condition monitoring and fitness-for-service assessment.

The latter part of the curve, or 'Wear Out' period, corresponds with accelerated degradation, e.g. fatigue, corrosion and wear. Consequently the failure rate increases and threats become a focus of concern. Integrity management is key in developing intervention strategies/emergency responses to improve availability.

The impact of Regulatory 'Shut-In'[25] criteria in failed line conditions should also be understood. Allowable operating states and acceptable insurance risks should be identified

[24] OTC 24025: A Historical Review on Integrity Issues of Permanent Mooring Systems, Ma et al 2013

[25] Term used in the oil and gas industry to describe the authority of a Regulator, i.e. Health & Safety Executive's Energy Division in UK, to shut down production of an asset in the event of a safety issue

and mitigations considered. In relation to sparing strategies, Ma et al[20] observed the "…availability of spare[s]… during installation allows for relatively easy replacement of components that get damaged, as there are many instances of damaged components being installed and 'accepted' as no spares were available. The spare components also provide the ability to replace a damaged or failed leg more rapidly, as manufacturing a replacement can take 6 to 12 months. Designing the original mooring system for ease of installation and replacement can indirectly lead to better mooring integrity and should be included in the original mooring system specification." Similarly, the earlier referenced O&M white paper identified the need for innovations in mooring connectors that allow for quick connection-disconnection and a spare parts strategy to reduce downtime and loss of revenue. This is particularly relevant to common, serialised mooring designs that may improve overall availability.

3.3 Innovations

Innovations essential to the commercialization of floating offshore wind need to achieve sufficient Technology Readiness Levels (TRL) to secure project financing and insurance coverage. The American Petroleum Institute's (API) 17N TRL methodology was initially drafted in 2009 for the qualification of subsea equipment. The table has since been "written into major petroleum companies' procedures as a tool to assess the level of progress of subsea design, fabrication and components' qualification"[26] and should therefore be considered suitable floating offshore wind applications.

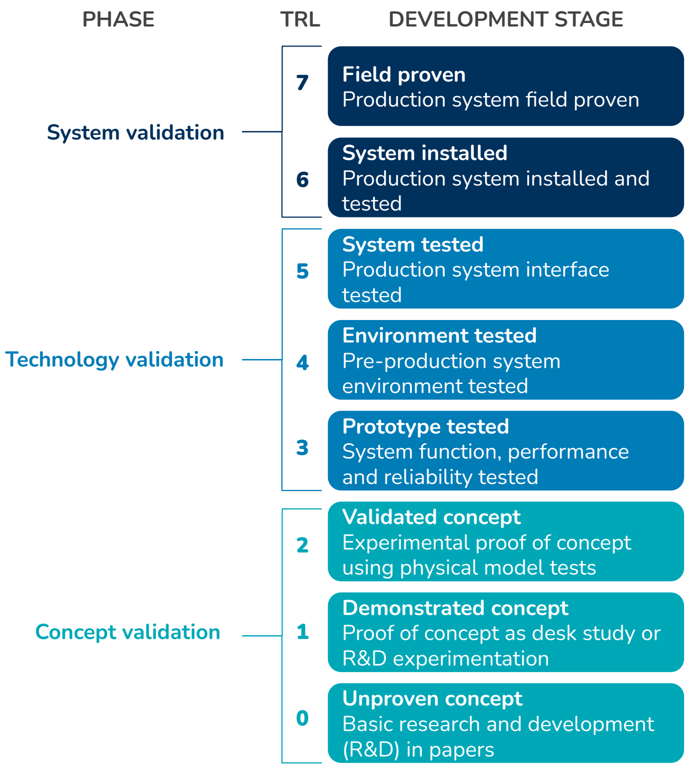


Figure 21. *TRL for Subsea Technology Readiness Level Assessment*
Source: API 2009

[26] Subsea system readiness level assessment, Yasseri 2013, Underwater Technology, Volume 31, Number 2

Recent Insurance Subcommittee meetings highlighted the challenge for new products to achieve a minimum TRL 6 (i.e. successfully perform in a demonstrator project), and particularly their transition to TRL 7 (i.e. successfully perform in a commercial-scale project). Further discussions identified the following critical questions -

1. Given very limited opportunities for integration within demonstrator projects, how can products quickly qualify the highest TRLs at commercial scale to meet rapid LCoE reduction objectives?
2. It was considered that progress through TRLs 1-5 is relatively straightforward. However, who will be responsibile for TRL assessment and accreditation, especially at TRLs 6-7 and particularly when products perform as part of a system?
3. What is the threshold at which insurers are comfortable underwriting new technologies or, as detailed in Section 2.5, must projects initially adopt the risk between LEG 1 and LEG 2? Furthermore, to attain higher coverage, will insurers mandate independent evaluation schemes, i.e. type approval and classification, that assess readiness and consider manufacturing elements?

The transition from TRL 6 to 7 will require wider participation. Suppliers should be ready to drive progress and provide transparency to their clients, i.e. project developers; industry collaboration will be key to overcoming intellectual property issues and restrictive contractual clauses to allow an innovation's use across multiple projects; and a standardized approach, at the commercial level, should be developed for the floating wind industry. In the meantime, technical risk assessment and mitigation strategies as part of an overall mooring integrity management programme will enable projects to properly handle the adoption of new technologies. Dialogue with insurers and financers, and perhaps dedicated government support in the form of technology development grants or adopting a position as insurer of last resort, may help shape a common understanding of such technical risk mitigation programmes and ultimately increase comfort levels.

3.3.1 Synthetic Rope

It is expected that the use of wire rope and chain will be reduced in favour of synthetic rope; however, their deployment in offshore mooring systems is by no means new. In 1995, Petrobras' FPSO[27] P13 was the first permanently moored platform to use synthetic rope, which paved the way for development of polyester mooring systems that now have a well-proven track record with more than 1,000 kilometres installed globally.

Synthetic ropes have no corrosion issues, superior fatigue performance and lower observed failure rates. They are cost-effective, suitable for mass production and have good handleability/transportability. A range of yarns are available, each displaying different compliance characteristics, and their selection is based on a variety of factors to suit the mooring design, e.g. construction, visco-elastic behaviour, creep, UV resistance and cost. They have been adopted successfully by several FOWT developers in a number of demonstrator projects and are undergoing further qualification for shallow water environments.

[27] Offshore oil and gas Floating Production Storage and Offloading unit

Typically, fibre ropes have been deployed in deep water environments where weight is critical and stiffness important to minimizing offset. However, an emerging trend is towards mooring systems with greater compliance which allows for shorter lines and lower breaking loads. Designers are therefore exploring the elasticity of nylon ropes. Whilst nylon has been used extensively in the oil and gas industry for temporary mooring applications, these ropes have not been validated for use in long-term mooring applications in the same way as polyester and HMPE as the material is unlikely to achieve a high fatigue life without the use of special lubricants.

The use of synthetic rope will enable costs savings, not only from reduced mooring footprints but also relative material cost and operational reliability. Still, achieving high line pretensions may be challenging and there are specific design issues which need to be addressed -

1. **Marine fouling**, a highly localised issue in which the growth of marine organisms within the top 30m of water can result in rope penetration/damage, increased drag and added weight to the mooring line, affecting its overall response. In most cases these threats can be mitigated by the addition of protective filters/jackets and a comprehensive ROV cleaning regime
2. **Seabed contact** resulting in materials ingress, accelerated wear and/or abrasion. This threat may also be mitigated by the used of filters/custom designed jackets and the use of buoyant ropes/buoyancy units to keep ropes from seabed contact. However, potential damage at the connection point with buoyancy units should not be discounted
3. **Mechanical damage**, mentioned in Section 3.1 as being responsible for 100% of failures observed in polyester ropes, may also be protected against by cut-resitant jackets. However, threats from impact events such as over-trawling might be mitigated through the deployment of marine traffic monitoring, advanced warning systems and ongoing dialogue with fisheries and port authorities
4. Some fibre ropes rely upon seawater as a **cooling medium**, so in these instances the anchor points for fibre mooring lines should remain below sea level

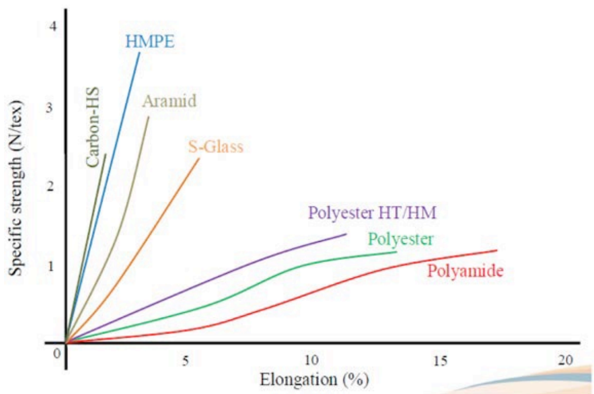


Figure 22. *Fibre Rope Stress/Strain Behaviour Comparison*[28] ***Figure 23.*** *Marine Fouling*[29]

[28] OTC-30830-MS: Evaluating Offshore Rope Fibres: Impact on Mooring Systems Integrity and Performance, Bastos et al 2020

[29] Bridon-Bekaert Ropes Group Presentation: Moorings Subcommittee Meeting #8, C. Dewijngaert 2021

The rapid scale-up of rope manufacturing is not expected to be a problem; however, conventional rope terminations requiring splicing does present a major bottleneck with very few skilled exponents globally. Therefore, new termination methodologies will need to be developed to speed up delivery. Decommissioning of mooring lines comprising high volumes of synthetic rope should be considered as the material is not currently recyclable.

3.3.2 Load Reduction Devices

Load Reduction Devices (LRDs) are a new concept of which there are a variety of designs at differing stages of qualification. LRDs address the issue of high wind thrust loads and dynamic wave action by providing compliance in a passive, non-linear fashion and can be incorporated anywhere in the mooring line (but usually in the upper sections). The effect is a more than 50% reduction in peak loading and 30% reduction in fatigue cycle amplitude, resulting in an estimated 5-8% saving in CAPEX assuming an equivalent reduction in equipment size and therefore installation costs. An associated reduction in OPEX is also possible through reduced damage and increased platform/turbine uptime, which coupled with potential life extension results in reduced LCoE.

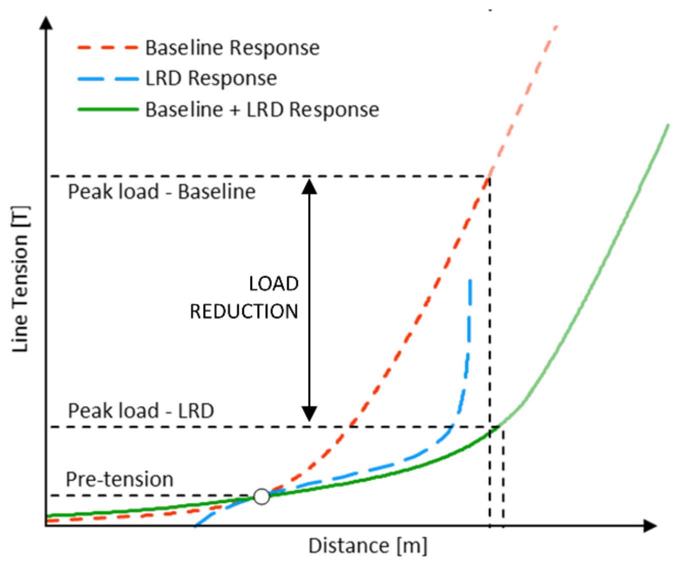


Figure 24. *Force vs. Extension Response Curve (courtesy of Dublin Offshore)*

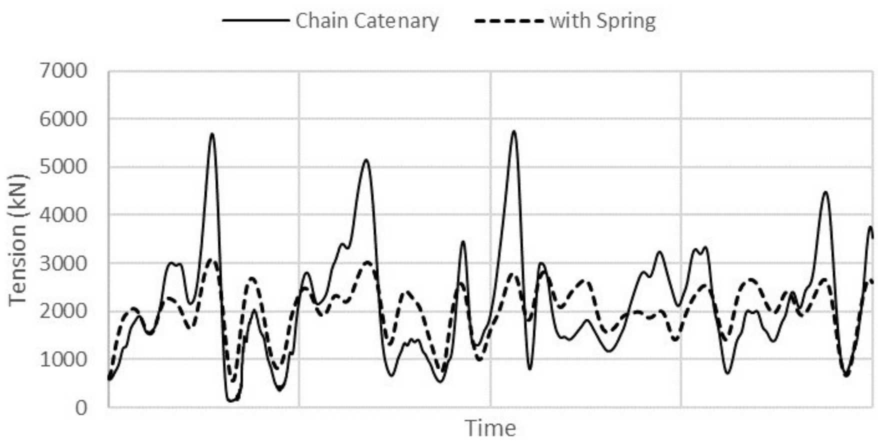


Figure 25. *Peak Load Comparison (courtesy of Tfi Marine)*

Importantly, seabed impact can be lessened through reduced mooring footprints; LRDs may help alleviate supply chain pressures by reducing demand for equipment; increased storm protection may allow exploitation of more aggressive sites; and units may provide real-time data used for operations, identifying extreme events, evaluating fatigue and supporting digital twins.

3.3.3 Digital Twins

As set-out in Section 2.7, IM programmes usually adopt a risk-based approach, i.e. direct measurement through continual monitoring, periodic measurement or visual inspections. However, there are certain limitations, e.g. lack of accessibility due to equipment location, marine growth and poor data/reliability (especially from subsea load cells). Therefore, inferences regards global motions made from indirect measurements might also be used. These so-called 'digital twins' typically utilise 'motion and position' data from DGPS[30] and infer 'mooring line tensions' from triaxial Accelerometers & Gyroscopes to model and determine fatigue damage.

The ultimate aim is to limit the use of subsea inspections, reduce operating costs, provide continuous anomaly detection and remote warning systems that trigger incident/emergency response, inform risk-based inspections and enhance sparing strategies. The technology is relatively inexpensive and limited data transfer is required; however, developers should take care to specify the most reliable and robust instrumentation available. Furthermore, whilst artificial intelligence, neural networks and machine learning are being used more widely, the algorithms need training to detect abnormal conditions and should be refined over time to reduce the number of identified anomalies. The process should be iterative with models continually adjusted to integrate baseline characteristic data, cumulative damage, unexpected events and on-going condition data. Solving issues on data sharing and ownership between multiple stakeholders will also be critical for developing fully-integrated digital twins that support integrity management programmes, optimise mooring designs and individual component improvements. This challenge was reflected in comments during the Moorings Subcommittee discussions: "Trying to make interconnections between instruments and hardware is very difficult. We have the data technology and analysis models but tying them all together is the issue."

3.4 Product Extensions

3.4.1 Shared Anchors

There are a variety of options with respect to anchors, e.g. drag embedment, vertically loaded (VLA), pile (suction, diven, torpedo, micro, helical), suction embedment plate (SEPLA), whose selection will be influenced by local soil conditions and have a bearing on mooring system type/arrangement. Shared anchor systems, where multiple floater lines are connected to one anchor, are currently being developed. For example, Equinor's Hywind Tampen project

[30] Differential GPS provides improved accuracy from 15m nominal GPS accuracy down to 1-3cm at best, and ideally will provide horizontal position and altitude

will use 19 anchors for 11 turbines, which is dramatically less than the earlier Hywind Scotland project that used 15 anchors on 5 turbines. The benefits are an associated reduction in equipment cost by a factor of up to 6 for certain geometries, fewer expensive geotechnical site investigations and reduction in peak demand by up to 30%. However, anchors will need to resist multiple-directional loading and the impact on soil capacity. Furthermore, these arrangements may be more suited to deep water environments and the consequence of cascade effects resulting from single/multiple line failures will need to be addressed. Lastly, standardisation and advanced modelling need to be considered. The Moorings Subcommittee reflected that shared anchors are "…technically possible, but added components, multiple failure modes, n+1 configuraitons and complex installation may offset any saving in mooring line cost." Shared moorings are also being considered (refer Fig. 27) but are further away from being well understood, let alone deployed.

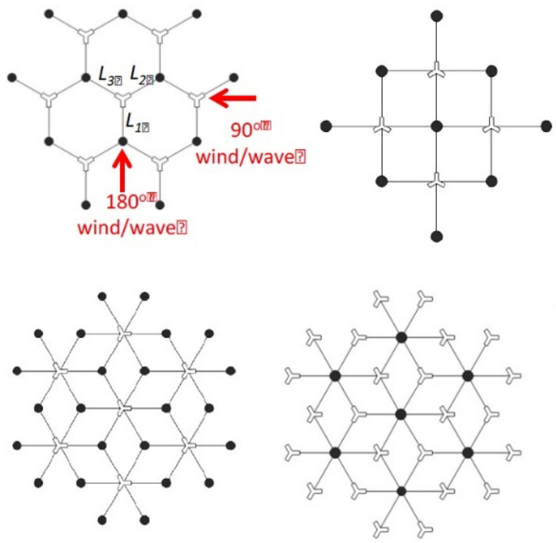


Figure 26. *Shared Anchor Geometries*[31]

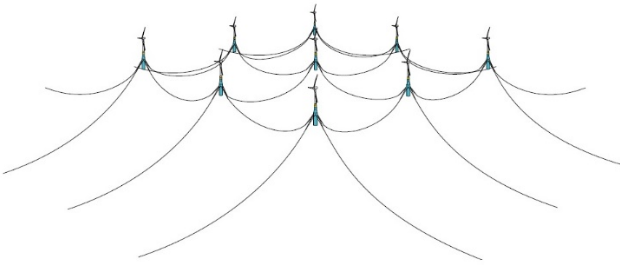


Figure 27. *Shared Mooring Concept*[32]

3.4.2 Tensioners

Tensioning systems to facilitate, quicken and improve the safety of installation and adjustment of mooring line tension will be particularly important as the industry scales up. Temporary chain shortening clutches used in oil and gas apply a vertical pulling force that is 40% of the equivalent load generated by horizontal reaction forces used to pull in drag embedment anchors. Repeated heaving and slacking of the clutch builds up load in the mooring chain until the required tension is achieved. The equipment can also be used for two-way cross tensioning of opposing anchors, or three-way tensioning with the addition of a link plate, thereby reducing the number of operations. These activities can also be performed by smaller, less-advanced vessels, further reducing the total installation cost.

New innovations include tension and length adjustment equipment permanently installed in the lower portion of the mooring line, e.g. ground chain. The passive side of the ground

[31] OMAE2016-54476: Efficient Multi-Line Anchor Systems for FOWTs, Fontana et al 2016

[32] NREL Presentation: NOWRDC Symposium, Hall et al 2021

chain is connected directly to the adjuster whilst the active side passes through the device facilitating adjustment. One tensioner can be used for a 3-line system, offering CAPEX savings, and allows for the use of smaller vessels, thus providing OPEX savings. Overarching safety benefits are also gained as mooring line adjustments can be made at a distance from the turbine at any time throughout the life of the system.

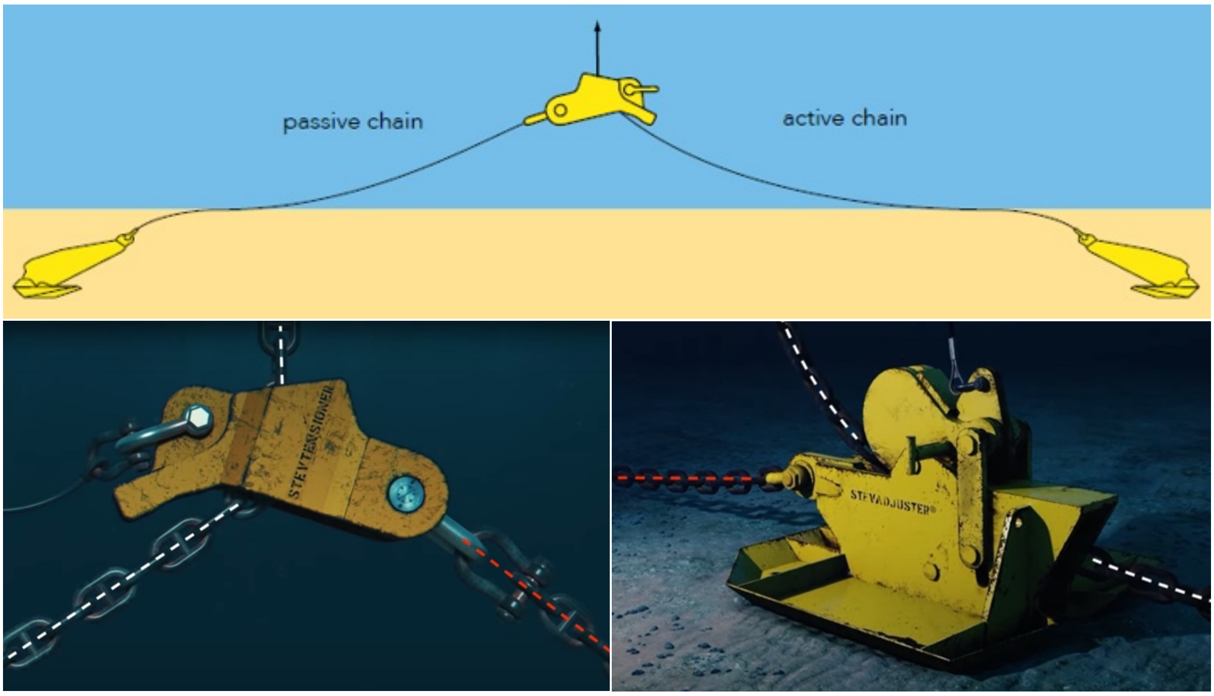


Figure 28. *Stevtensioner® (top & left) & Stevadjuster® (right) (courtesy of Vryhof)*
White dotted line is the active chain and red dotted line is the passive chain

3.4.3 Connectors

As mentioned in Section 3.2, WFO's O&M Subcomittee identified the need for quick connection-disconnection equipment and it is likely these will be employed at the top end of the mooring line. High load ball and taper gripping connectors were first used for quick mooring connection with anchor piles and SEPLAs on offshore oil and gas structures. Their employment on FOWTs may remove the need for expensive chain jacks/fairleads and eliminate the requirement for ROV or diver interventions. Furthermore, their combination with articulated or universal joints may counteract OPB issues.

Disconnectable turret systems, inspired by FPSO mooring buoy designs, are a simple method of keeping mooring lines and power cable in suspension whilst FOWTs are off station. Seabed congestion and potential damage is therefore avoided as double handing, i.e. set-down and pick-up from the seabed, is not required. This enables shorter power disconnection times during O&M but also facilitates quick power connections during installation, which is attractive from an insurer/project developer's perspective. This concept could be extended to be a permanent part of the mooring and dynamic cable system to enable genuine plug-and-play connections, similar to FPSO submerged turret mooring systems, but may be too costly to become feasible.

Figure 29. *Ballgrab® & Uni-Joint (courtesy of First Subsea)*

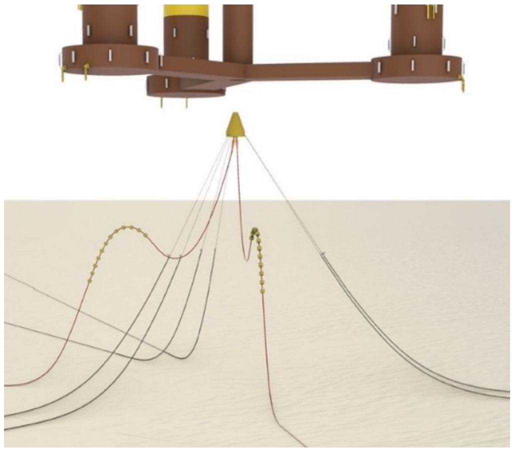


Figure 30. *DTR System (courtesy of SBT Energy)*

3.4.4 Analysis Software

Analysis software is used to simulate realistic behaviors of a floating wind system in order to achieve optimal designs of components and their ensuing behavior in shallow water or deep water conditions. Many companies are developing their own digital solutions that model different parts of the system and relevant met-ocean conditions (e.g. subsea architecture, anchorage and electrical equipment), combining cross-disciplinary indicators. The National Renewable Energy Laboratory (NREL) based in the U.S. has an open-source tool named OpenFAST which simulates the coupled dynamic response of wind turbines using hydrodramic, aerodynamic, control system dynamic and structural dynamic models[33]. All of these user-friendly solutions aim to help clients find the optimal configuration of a wind farm or, more appropriately for the current state of the industry, of novel platform concepts before further commercialization. However, more work is needed to achieve a fully integrated package for one turbine and its station-keeping system that does not sacrifice on accuracy, let alone across multiple units. Interfacing software with real-time data from sensors on assets in the water can help improve the accuracy of structural load and condition modelling, with the final intention being to accelerate design optimization and validation (Section 3.3.3).

3.4.5 Remote Survey

Floating offshore wind turbines are unmanned installations. Performing inspections on hundreds of units at distance and in harsh weather conditions poses logistical and safety challenges. The industry presents an opportunity to develop marine autonomous systems like Unmanned Surface Vehicles (USV) or Remotely Operated Underwater Vehicles (ROUV or ROV) to carry out necessary inspection work, namely visual assessment of mooring line and dynamic cable system integrity, and of marine growth at key interfaces of the line.

[33] COREWIND D2.1 : Review of the state of the art of mooring and anchoring designs, technical challenges and identification of relevant DLCs, 2020 (section 6.2)

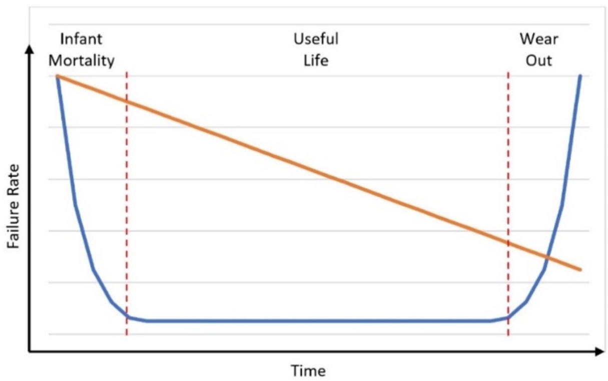
3.5 Reporting Systems

The greatest opportunity for improvement is presented when things go wrong and it is assumed that the application of new designs, technologies and materials in FOWT mooring systems will result in unanticipated failures via new modes and novel mechanisms. Sharing details of these events will hugely benefit our nascent industry and speed up the energy transition. However, commercial and intellectual property concerns present a significant barrier to achieving this.

Mooring Integrity Management is a theme running throughout this paper and data analysis is the basis of its success. Procedural-based controls are required for handling information properly between designers, manufacturers and operators, and transparency is therefore essential. But this is one area where oil and gas has been less successful: failure rate data is not in the public domain and since the 2014 OTC 25273 study, information remains incomplete.

As laid out in Section 2.5, limited insurance cover is available for the floating wind sector with reduced coverage, increased deductibles and higher premiums compared to bottom-fixed wind, the latter of which is currently experiencing significant claims. Developers will need to demonstrate risk mitigations but insurers may decline coverage. Finance could be difficult to secure on projects using unproven technologies or exhibiting limited track-record. An early conservative approach is therefore advocated; however, the pressure to reduce LCoE through innovation and rapid transition to full-scale arrays is the paradox lying at the heart of the industry.

To overcome this contradiction, the floating wind industry needs to take a radical approach, but a consensus between all stakeholders is required. To promote the sharing of information, insurers might consider taking a 'no-fault' approach whereby designers, manufacturers, developers, installation contractors etc. sign up to an independent reporting system that shares all mooring integrity management data (not just failure events). The early phases of any project will be of most interest, with the optimal time to share data being in the short- to medium-term. In this way, the industry could learn quickly together as anonymised results may be shared widely, insurers would be protected in the long run, and all would benefit from lower premium levels. If successful, declining insurance cover in later years could offset early risks to insurers, as demonstrated by the orange line superimposed on the below bathtub curve.



4 Conclusions

Only time will tell which technologies, amongst the current proliferation of FOWT concepts, may come to dominate our nascent industry. Station-keeping systems will vary according to foundation type selected, prevailing environmental conditions, geographic location and regulatory frameworks. There is therefore no 'one-size-fits-all' solution. However, a robust integrity management philosophy and associated process, covering all stages of the mooring life-cycle and developed in detail during the initial design phase, will be essential for securing finance and insurance cover across all projects.

In recent years, international classification societies have developed floating wind-specific standards, but these currently reflect a limited understanding of mooring system behaviour, requiring harmonisation and on-going development in line with growing operational experience. Design bases will vary between projects with choices on issues such as line configuration, materials and anchors shaping procedures relating to installation, repair, maintenance and decommissioning. As discussed in this paper, considering the trade-offs between early design choices and later project phases, e.g. impact of the top connection or anchor on installation, is encouraged to achieve savings in both CAPEX and OPEX whilst also assuring long-term system reliability. Integrity management during all phases remains critical for monitoring structural health of the mooring system, assessing its 'fitness-for-service', and determining its current condition versus the as-designed, as-built and as-installed condition.

Redundancy and associated consequence class is an important issue when considering continuous energy production, i.e. enabling the floater to maintain its position and function should failure occur. The provision of alternative load paths through additional lines (n+1 concept) is generally considered the preferred option. However, increasing the capacity or size of equipment (strengthening), effective change-out/sparing strategies, employing load reduction devices and utilising digital twins to facilitate predictive maintenance may also be suitable approaches to improving availability. Though not extensively discussed in the Moorings Subcommittee, the interaction between the mooring system and dynamic power cable is an area of particular interest and significance in guaranteeing continuous energy production. The newly formed Cables & Floating Substations Subcommittee, whose inaugural meeting is scheduled during May 2022, should explore this area in more detail with findings shared, discussed, and developed across all FOWC Subcommittees.

Innovation is considered key to driving down LCoE but is also a potential constraint on the exponential growth required to achieve global net zero ambitions. Accelerated technology qualification to high TRLs at commercial scale is essential. However, developers must provide sufficient levels of comfort to their investors and insurers by quantifying the additional risk between LEG 1 and LEG 2, demonstrating technical risk mitigations, and perhaps in some instances adopting the risk themselves. Early failures in serialised, highly optimised and/or non-redundant mooring systems may dramatically curtail future developments. Therefore, initial conservatism is warranted with enhanced inspection and monitoring activities recommended during early years.

This paradigm presents a unique opportunity for the floating offshore wind industry to take a novel approach compared to that which came before, and data sharing is fundamental to this process. While common failure modes and degradation mechanisms are well understood from offshore oil and gas experience, there is limited transferability with respect to floating offshore wind. New threats are either unknown or less well-understood and consequently not easily prevented by existing IM practices. The greatest opportunity for improvement presents itself where things go wrong; however, information sharing should not be limited to failures alone. Moreover, all integrity management data should be made available so that the whole industry can learn quickly together. Direct measurement through continual monitoring, periodic measurement or visual inspections are preferred, although new procedures and digitalisation will complement any developments. Importantly, intellectual property and commercial contractual constraints also need to be relaxed or modified to facilitate data sharing. The Committee identified that an independent, anonymised reporting system which benefits all stakeholders deserves further investigation and may therefore form part of its future work.

Capability of the supply chain to meet mooring system component demand is another major challenge for the industry. Currently, there is a limited capacity in the manufacturing sector for both the forecast volume and dimension of mooring chain. However, the ability for synthetic rope output to ramp up is deemed relatively feasible which, together with its perceived operational advantages and growing trend toward compliant mooring systems, could push for the adoption of alternative layouts, e.g. hybrid buoyant semi-taut spreads with smaller footprints. Furthermore, implementing an n+1 approach may provide an opportunity to manufacture smaller lines with consequent benefits to handleability and installation. However, trade-offs later in life should be considered, for instance the monitoring needs that would likely increase to cover the number of lines. Finally, the importance of working with experienced suppliers that have equipment/technology track record can pose a challenge to markets implementing local content targets. Building localised floating wind supply chains will require large investments and sustainable knowledge transfer mechanisms from established industry players to boost the development of suitable, local production facilities.

The nascent floating offshore wind industry stands at a crossroads. Rapid transition from small-scale/demonstrator projects to commercial scale arrays is urgently required to achieve global net zero ambitions and reduce LCoE. Lessons derived from oil and gas experience will be important, but transferability is limited and therefore a unique opportunity to take a novel approach arises. Innovation will be key but early failures in serialised systems may impact project finance and insurance availability, potentially restraining growth. Initial work conducted by the Moorings Subcommittee has determined the Integrity Management process' holistic, iterative characteristics can support the industry's path into technological maturity through the rigorous monitoring of risks and associated implementation of mitigation measures at all project phases alongside an improved system for data-sharing. Future efforts will focus on areas of particular interest and significance, supporting our main Chair's earlier call to "…bring even more relevant information to the market."

Appendix - Governing Standards for FOW

Tables courtesy of ORE Catapult's Floating Offshore Wind Centre of Excellence

IEC TS 61400-3-2			
General	IEC 61400-1 IEC 61400-3-1	Corrosion Protection and Control System	IEC 61400-1 (CS) IEC 61400-3-1 (CS) ISO 19904-1 (CP) ISO 12944-9 (CP)
Environmental and Soil Conditions	IEC 61400-1 IEC 61400-3-1 ISO 19900 ISO 19901-1 ISO 19901-4 ISO 19904-1 ISO 19906 API RP 2FPS	Stability	IMO res. MSC.267(85)
Materials and Construction	ISO 19901-7 ISO 19905-1	Fatugue Limit State	IEC 61400-1 IEC 61400-3-1 ISO 19904-1
Safety Levels and Safety Concepts	IEC 61400-3-1 ISO 19904-1	Ultimate Limit State	IEC 61400-3-1 ISO 19904-1
Design Methods and Loads	IEC 61400-1 IEC 61400-3-1 ISO 2394 ISO 19900 ISO 19901-2 ISO 19901-4 ISO 19901-7 ISO 19904-1 ISO 19906 API RP 2FPS API RP 2T ITTC Guid. 7.5-02-07-3.8	Transport and Installation	IEC 61400-3-1 ISO 19904-6
Stationkeeping System and Anchor	ISO 1901-4 ISO 19901-7 ISO 19904-1 APR RP 2T	Commissioning, Surveys and O&M	IEC 61400-3-1 ISO 19901-6 ISO 19904-1
Mechanical and Electrical Equipment	IEC 61400-1 IEC 61400-3-1	Serviceability and Accidental Limit State	ISO 19904-1
Wind Turbine	IEC 61400-1		

IEC TS 61400-3-2 Framework

ABS 195			
General	ABS Class Rules ABS FPI Rules ABS MOU Rules ABS RA Notes	Corrosion Protection and Control System	API PR 2SK (CP) API PR 2T (CP) NACE SP0176 NACE SP0108
Environmental and Soil Conditions	ABS FPI Rules ABS OWT Guide IEC 61400-1 IEC 61400-3-1 ISO 2533 API RP 2MET	Stability	ABS FPI Rules ABS MOU Rules
Materials and Construction	ABS FPI Rules ABS MOU Rules ABS OI Rules ABS Mat Rules ABS OWT Guide ABS Chain Guide ABS FA Guide ABS Fibre Notes ACI 213R ACI 301 ACI 318 ACI 357 ACI 395 ASTM C31 ASTM C39 ASTM C94 ASTM C172 ASTM C330 AISC St. Const. Manual	Fatugue Limit State	ABS FA Guide ABS PMS Guide ABS Fiber Notes API RP 2T
Design Methods and Loads	ABS FPI Rules ABS MOU Rules ABS Mat Rules ABS MV Rules ABS LRFD Guide ABS PMS Guide ABS Semi Notes ABS Fiber Notes ABS Anchor Notes ABS Pile Notes ABS FOWT Notes IEC 61400-1 IEC 61400-3-1 IEC 61400-3-2 ISO 19904-1 ISO 19906 ACI 318 ACI 357 AISC St. Const. Manual API RP 2A API RP 2MET API RP 2N API RP 2T API Spec. 9A	Ultimate Limit State	ABS USA Guide ABS Fibre Notes
Stationkeeping System and Anchor	ABS FPI Rules ABS OI Rules ABS Mat Rules ABS OWT Guide ABS Chain Guide ABS Fiber Notes ABS Anchor Notes ABS Pile Notes API RP 2A API RP 2SK API RP 2T API RP 9B API Spec. 9A	Transport and Installation	ABS FPI Rules ABS Anchor Notes ABS Pile Notes
Commissioning, Surveys and O&M	ABS Class Rules ABS FPI Rules ABS MOU Rules ABS Mat Rules ABS CSurv Rules ABS Chain Guide ABS NDI Guide ABS RBI Guide ABS MRMT Guide ABS Fiber Notes ISO 19903	Mechanical and Electrical Equipment	ABS MOU Rules IEC 61400-3-1
Other	ABS MOU Rules[1] IEC 61400-24[2]	Wind Turbine	IECRE OD-501
		Safety Levels and Safety Concepts	ISO 19904-1

1 Helicopter deck, guards and rails, piping, bilge system, ventilation, firefighting

2 Lightning protection

ABS 195 Framework

BV NI572				
General	BV NR445 BV NR571 BV NR578	ISO 19902 API RP 2A API RP 2T	**Safety Levels and Safety Concepts**	BV NR493
Environmental and Soil Conditions	BV NR493 BV NI 605 IEC 61400-3 ISO 19901-1 ISO 29400	EN 1997 IMO MODU Code IMO MSC/Circ.884 IMO A765(18)	**Wind Turbine**	BV NI 525 IEC 61400-1 ISO 76 ISO 281 ISO 6336 series
Materials and Construction	BV NR216 BV NR426 BV NR445 BV NR467 BV NR576 BV NI 594	API RP 2T ISO/IEC 17021 ISO 9001 ISO 19903 EN 106 EN 1992 AISC Steel Construction Manual AWS D1.1	**Mechanical and Electrical Equipment**	IEC 60092 series IEC 61892 series IEC 61400 series IEC 60092-401 IEC 61400-24 IEC 61892-6
Corrosion Protection and Control System	BV NI 423 BV NR445 BV NR493 BV NI 605 ISO 9226	ISO 11306 ISO 12944 NORWOK M-501 ASTM G1	**Stationkeeping System and Anchor**	BV NR493 BV NR578 BV NI 604 BV NI 605 API RP 2T
Design Methods and Loads	BV NR426 BV BR445 BV NR467 BV NR493 BV NR571	BV NR578 BV NI 611 IEC 61400-3 API RP 2T ISO 19901-2 ISO 29400 EN 1993-1	**Transport and Installation**	BV NR526 ISO 29400 API RP 2A IMO MSC/Circ.884 IMO A765(18)
Fatugue Limit State	BV NR493 BV NR578 BV NI 604	BV NI 611 API RP 2T	**Commissioning, Surveys and O&M**	BV NR445
Stability	BV NR445 BV NR578 ISO 29400	IMO MSC/Circ.884 IMO A765(18) IMO Res MSC.267(85)	**Ultimate Limit State**	BV NI 615 API RP 2A
Other	BV NR445[1] BV NR467[2]	1 Mooring support, hull attachments, heli deck, bilge system 2 Lifting appliance foundations, bulwarks, guard rails	**Serviceability and Accidental Limit State**	BV NR445

BV NI572 Framework

LR GN for Offshore Wind Farm Project Cerification				
General	IEC 61400 series		**Stability**	IMO MODU Code LR Ship Rules[1]
Environmental and Soil Conditions	IEC 61400-1 IEC 61400-3 IEC 61400-12-1	IEC 61400-12-2 ISO 19900 ISO 19901-1 ISO 19901-2 ISO 19902 ISO 19903 ISO/IEC 17025 API RP 2A-WSD	**Fatigue Limit State**	IEC 61400-1 IEC 61400-3
Materials and Construction	ISO 9001 BS EN 10204		**Transport and Installation**	IEC 61400-22 IECRE OD-502
Safety Levels and Safety Concepts	IEC 61400-3		**Commissioning, Surveys and O&M**	IEC 61400-22 IEC 61400-3 IECRE OD-502
Design Methods and Loads	IEC 61400-1 IEC 61400-3	IEC 61400-22 IECRE OD-502 ISO 19904-1 LR Ships Rules[1] LR Craft Rules[2] DNVGL-ST-0119	**Wind Turbine**	IEC 61400-1 IEC 61400-3
Stationkeeping System and Anchor	IEC 61400-3 API RP 2SK LR Ship Rules[1] ISO 19901-4	ISO 19902 1 LR Rules and Regulations for the Classification of Ships 2 LR Rules and Regulations for the Classification of Special Service Craft	**Other (Grid Compliance and EIA)**	IEC 61400 series IECRE OD-502 ISO/IEC 17020 ISO/IEC 17025

LR Guidance Note Framework

DNVGL-ST-0119						
General	DNVGL-ST-0126 DNVGL-ST-0376 DNVGL-RP-A203 IEC 61400-1	Circ.1023– MEPC/Circ.3 92 Guidelines for Formal Safety Assessment		Corrosion Protection and Control System	DNVGL-ST-0076 DNVGL-ST-0126 DNVGL-ST-O438 DNVGL-OS-A101 DNVGL-OS-D202	DNVGL-OS-E301 DNVGL-RP-0416 DNVGL-RU-OU-0102 NORSOK M-001
Environmental and Soil Conditions	DNVGL-ST-0126 DNVGL-ST-0437 DNVGL-RP-C205 DNVGL-PR-C207	DNVGL-RP-C212 IEC 61400-1 ISO 19901-2		Stability	DNVGL-OS-C301 DNVGL-RP-C205	
Materials and Construction	DNVGL-ST-0126 DNVGL-ST-C501 DNVGL-ST-C502 DNVGL-OS-B101 DNVGL-OS-C103 DNVGL-OS-C105	DNVGL-OS-C106 DNVGL-OS-E301 DNVGL-OS-E302 DNVGL-OS-E303 DNVGL-OS-E304 DNVGL-RP-E304	DNVGL-RP-E305 ISO 13628-5 ISO 898-1 EN 1992-1-1 EN 1992-2 EEMUA pub #194	Fatugue Limit State	DNVGL-ST-0126 DNVGL-OS-C401 DNVGL-OS-E301 DNVGL-OS-E303 DNVGL-RP-E305	DNVGL-RP-F401 DNVGL-CG-0129 DNVGL-RP-C203 BS 7910
Safety Levels and Safety Concepts	DNVGL-ST-0126			Ultimate Limit State	DNVGL-ST-0126 DNVGL-RP-C202 EN 1993-1-1	EN 1993-1-8 Eurocode NORSOK N-004
Design Methods and Loads	DNVGL-ST-0126 DNVGL-ST-0437 DNVGL-ST-C501 DNVGL-ST-N001 DNVGL-OS-C101 DNVGL-OS-C103 DNVGL-OS-C105 DNVGL-OS-C106	DNVGL-OS-C401 DNVGL-OS-D101 DNVGL-OS-E301 DNVGL-OS-E303 DNVGL-OS-F201 DNVGL-OTG-13 DNVGL-OTG-14 DNVGL-RP-C103	DNVGL-RP-C104 DNVGL-RP-C201 DNVGL-RP-C205 DNVGL-RP-C208 DNVGL-RP-F205 IEC 61400-3	Transport and Installation	DNVGL-ST-0437 DNVGL-ST-N001 DNVGL-RP-N101 DNVGL-RP-N103	
Power Cable	DNVGL-ST-0359 DNVGL-ST-N001 DNVGL-OS-F201 DNVGL-RP-0360 DNVGL-RP-C203	DNVGL-RP-C205 DNVGL-RP-F105 DNVGL-RP-F107 DNVGL-RP-F109 DNVGL-RP-203	DNVGL-RP-F204 DNVGL-RP-205 DNVGL-RP-F401 ISO 13628-5 API Spec. 17J	Commissioning, Surveys and O&M	DNVGL-ST-0126 DNVGL-OS-E301 DNVGL-OS-E303	
Stationkeeping System and Anchor	DNVGL-ST-0126 DNVGL-ST-C501 DNVGL-OS-C105 DNVGL-OS-E301 DNVGL-OS-E302 DNVGL-OS-E303 DNVGL-OS-E304	DNVGL-RP-C207 DNVGL-RP-C212 DNVGL-RP-E301 DNVGL-RP-E302 DNVGL-RP-E303 DNVGL-RP-E305 DNVGL-RU-OU-0102	EN 1573 EN 1997-1 NORSOK M-001 NORSOK N-006 PTI DC 35.1	Mechanical and Electrical Equipment	DNVGL-ST-0076 DNVGL-ST-0359 DNVGL-ST-0378 DNVGL-OS-A101 DNVGL-OS-D101 DNVGL-OS-D201	DNVGL-OS-E301 IEC 61892-6 ISO 13628-5 EEMUA pub #194

DNV-ST-0119 Framework