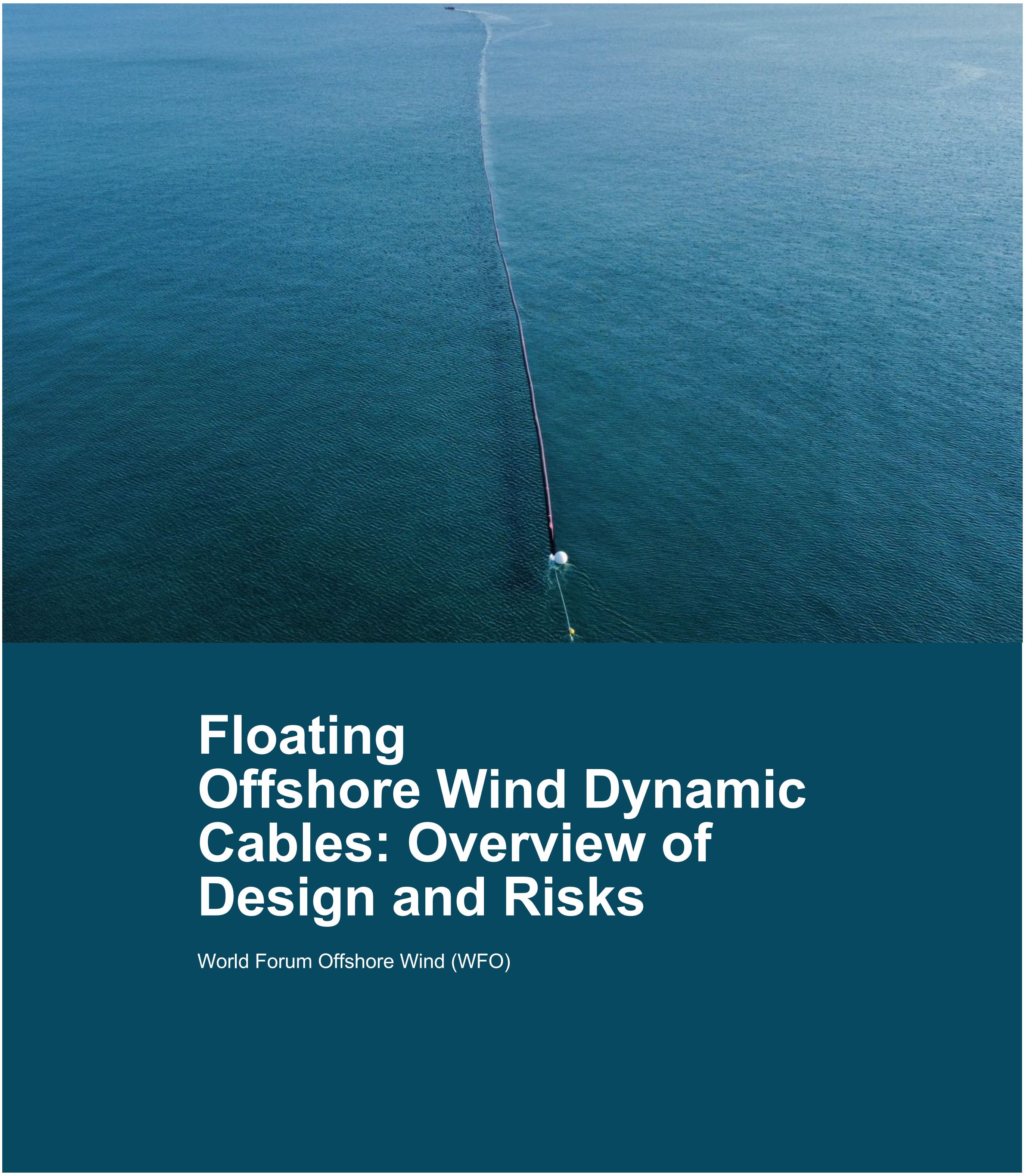

Floating Offshore Wind Dynamic Cables: Overview of Design and Risks

World Forum Offshore Wind (WFO)

Imprint

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Cover: Photo courtesy of RTE | Sébastien Xaxa. Pictured is the installation of the export cable's landfall duct for the EFGL floating wind project in March 2023, prior to dynamic cable laying.

Status: February 2024

Acknowledgments

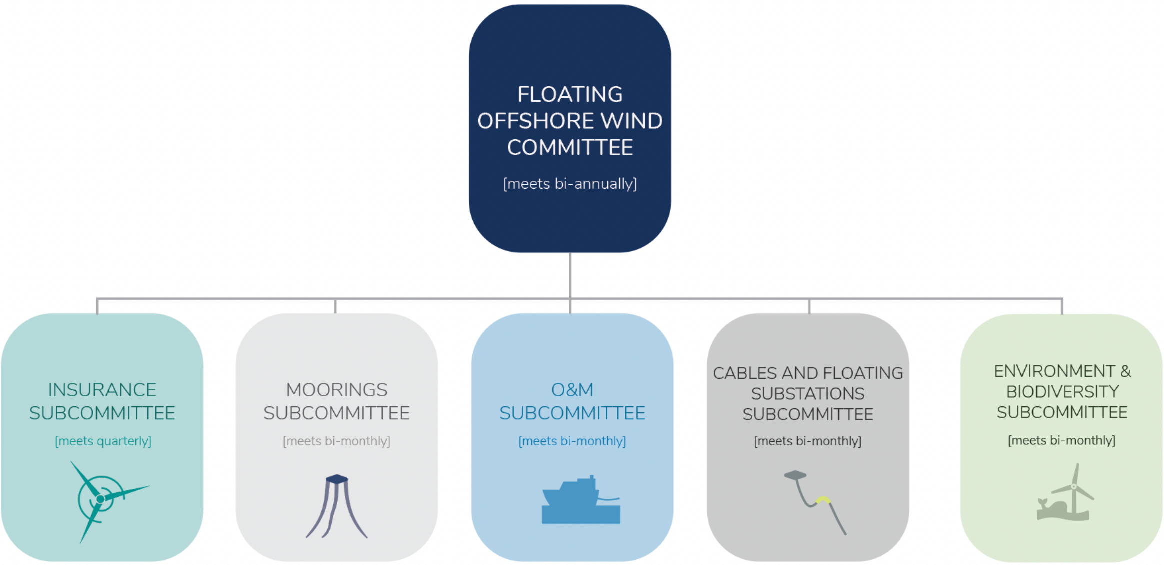
WFO's 120+ members represent the entire offshore wind value chain including but not limited to utility companies, manufacturers, service firms, consultancies and other non-profit organizations.

This document is the result of 1.5 years worth of monthly discussions between participating WFO members during meetings of WFO's Floating Offshore Wind Committee on the topic of floating wind dynamic cables. 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 the WFO Cables & Floating Substations Subcommittee 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 dynamic cables systems and therefore should not be generalised and are subject to evolve along with the industry.

Structure of the Floating Offshore Wind Committee



Foreword

A key component that will always get particular attention from lenders and insurers when reviewing floating wind projects is the dynamic umbilical cable. Two reasons for that come quickly to mind: 1) that is where the asset's revenue will - hopefully uninterruptedly - flow through and 2) electrical cables still remain an expensive source of insurance claims in offshore wind.

It was consequently a no-brainer for WFO's Floating Offshore Wind Committee to encourage the creation of a Cable and Substations Subcommittee to address all questions and issues that could eventually slow down commercial-scale deployment as well as clarify - not to say demystify - issues that could easily be solved with the most suitable best practices and guidelines, from design to installation and O&M.

We are blessed at WFO to have members representing all types of industries and expertise. In this very case, we were able to witness that cables are not only a critical issue for cable manufacturers and specialist engineers but also for offshore contractors and T&I specialists, for floating foundation designers and suppliers, for lenders and insurers and of course for developers.

I thank and congratulate all our members' experts who have been particularly proactive in assisting our Subcommittee Chair in drafting what is once again a landmark document and particularly relevant white paper for the floating wind industry. I already look forward to their next publication.

Bruno G. GESCHIER
Chairman of WFO's Floating Offshore Wind Committee
Chairman of FOWT's Scientific and Technical Committee
Founding Chairman of WindEurope's Floating Offshore Wind Task Force (now Work Group)

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1 Introduction – define current landscape

Global offshore wind installations are on track to reach 305 GW by 2030 and 480 GW by 2033.[1] Countries increasingly see the offshore wind sector as a key facilitator of their long-term climate goals. Mature markets in Europe are planning more projects via auctions and new markets in Asia and the Americas are establishing regulatory frameworks for offshore wind. Relevant suppliers can look forward to growth opportunities; however, they will have to keep up with the evolving profile of offshore wind farms characterised by deeper waters and larger turbines. When it comes to subsea cables, major suppliers are upgrading their manufacturing capabilities and refining their business models by specialising in certain products and services.

The subsea cables of future offshore wind farms have to achieve two main technology advancements:

1. Higher voltages of inter-array and export cables
2. Design optimization of dynamic inter-array and export cables for floating offshore wind

Risk mitigation in the design, manufacture and installation of subsea cables needs to be well-demonstrated even though standards may not yet include higher voltage brackets and floating wind specifications. Insurers are particularly concerned with the technology readiness of cable systems given the consequence of cable failure as well as a history of issues at various bottom-fixed wind farms.[2] Damage repairs for a single cable can easily cost millions of euros in addition to the lost revenue caused by wind farm's unavailability.[3] As a result, developers are now facing a hardening market with a tightening of terms and conditions, limitations of cover, shrinking capacity for challenging placements and increasing rates for floating offshore wind.[4]

As the industry works to prevent dynamic cable failure occurrence and downtime in case of failure, this White Paper will introduce the major floating wind cable specifications and their risks & mitigation measures, highlighting the importance of a holistic engineering approach that considers the impacts of the mooring system and maintenance solution on dynamic cable design.

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[1] *Westwood Energy. Installed capacity = estimate for fully installed wind farms with first power.*

[2] *The ORE Catapult ELECTRODE project concluded that in the UK, cable failures make up 75-80% of insurance claims while only making up 5-10% of the project cost. See section 3 for a breakdown of these failures.*

[3] *In the UK, the average downtime for a bottom-fixed wind farm inter-array cable repair is approximately 40 days and for an export cable approximately 60 days. Inter-array cable damage costs between $1.8M to $12M, and export cable damage costs between $10M to $30M (ORE Catapult, 2021).*

[4] *Offshore Wind Consultants at the 3rd Annual Floating Wind Europe conference in Hamburg, 4-5 April 2023.*

1.1 Dynamic cable configuration and global layout

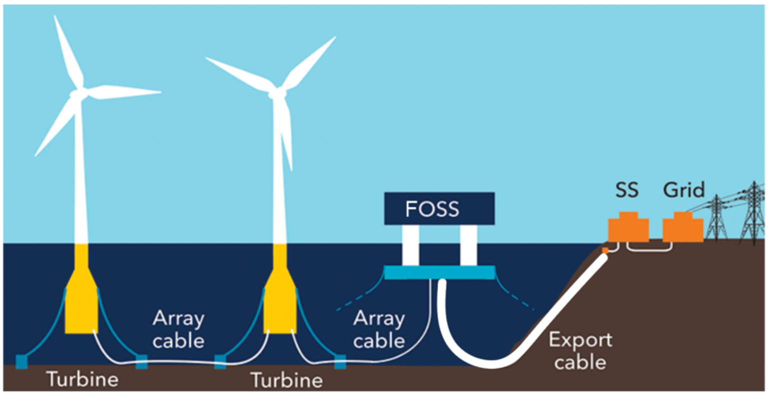

Figure 1. Layout of floating offshore wind turbine (FOWT) and floating offshore substation (FOSS). A combination of these technologies is likely for commercial projects in deep waters. Between the floating substation and the shore, the export cable is mainly static, either HVAC or HVDC. Source: DNV.

Fixed or floating, a typical commercial-scale offshore wind farm consists of an inter-array cable connecting the turbines to an offshore substation and an export cable connecting the offshore substation to shore (Figure 1 above). Inter-array cables are usually rated at a lower voltage than export cables.

In a fixed offshore wind farm, the cables are static and mostly buried in the seabed. Nonetheless, a short portion of the cable right at the exit of the turbine or substation foundation (also fixed) is exposed to the water column and subject to loads (e.g. seabed movement, wave action, tidal current, scour). This portion is thus equipped with a cable protection system (CPS) to provide protection against these external threats leading to mechanical overbending. A variety of components make up the CPS depending on the project conditions: bend stiffener, bend restrictor, i-tube, j-tube. In the last couple of years, CPS issues affected up to ten fixed offshore wind farms,[5] contributing to the aforementioned hardening insurance market.

1.1.1 Cable configuration

In floating offshore wind, the dynamic sections of the cables are longer as they hang in the water column from the floater or floating substation, typically in a lazy-wave shape (Figure 2 below). Ancillaries help maintain the cable shape in the water column (lazy wave or other) and protect the connection points from overload and fatigue. The equipment consists of bend stiffeners, buoyancy and ballast modules, tether and anchor systems, touch down and abrasion protection and bend restrictors (Figure 2 below). The cable then transitions down touching the seabed tangent to it (and in most topologies installed to date, the cable is not buried). W-shaped configurations are being promoted for very deep waters where it would be costly to run the cable all the way to the seabed and back up again (Figure 3 below). Instead,

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[5] *Ørsted has openly mentioned CPS issues at some of their offshore wind farms in their Q1 2021 interim report.*

the cable is run between FOWTs high up in the water column in a ‘w’ shape, which is achieved with placement of clamped buoyancy and ballast modules.

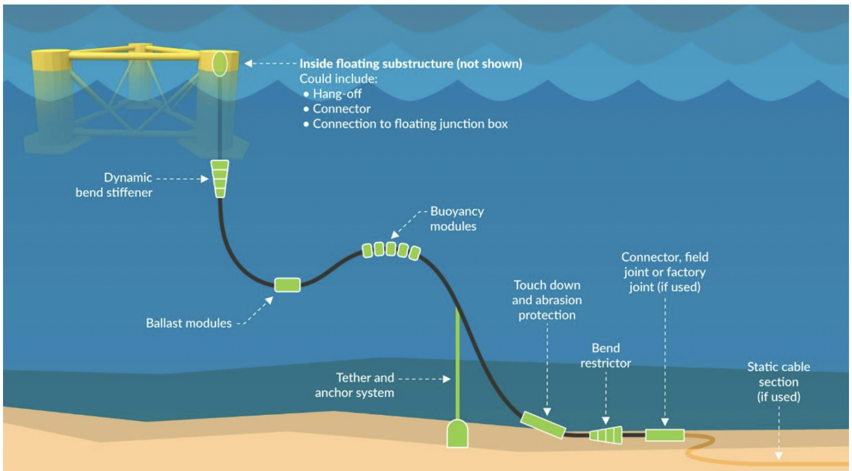
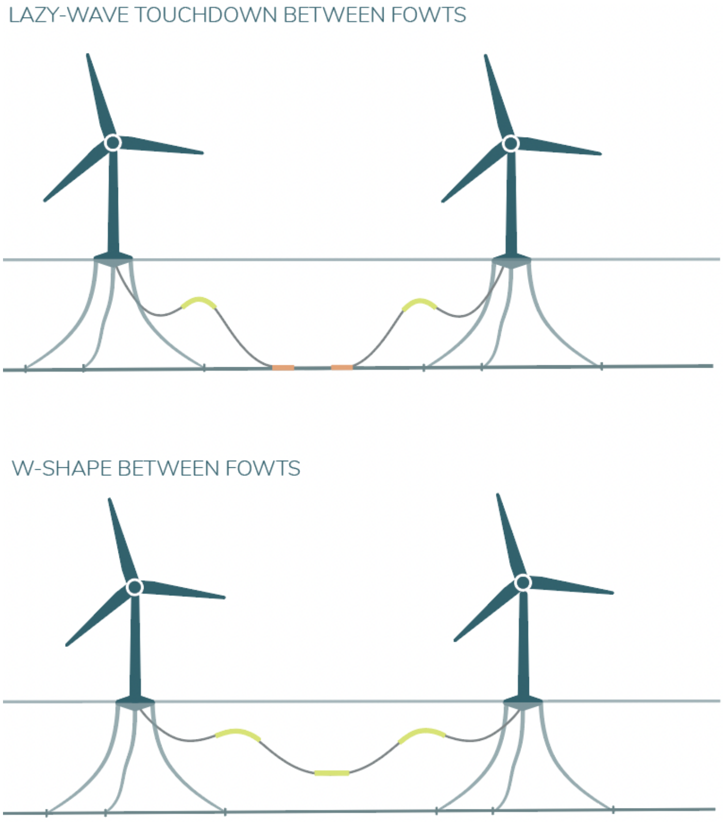


Figure 2. Ancillary equipment on the dynamic cable. An actual system would not use all these elements at the same time. Dynamic bend stiffeners protect the cable at the exit of the floater. Ballast/buoyancy modules and tethers are used to fix the cable shape in the water column. Equipment at the seabed protects the cable against abrasion and bending. Finally, connectors can be used at the floater and between cable sections.The horizontal distance between the floating substructure and the touchdown point depends on the water depth and cable configuration of the project. Source: BVG Associates/ORE Catapult.


LAZY-WAVE TOUCHDOWN BETWEEN FOWTS

W-SHAPE BETWEEN FOWTS

Figure 3. Two types of cable configurations. Lazy wave: attached buoyancy modules provide lift at midwater cable section. W-shape: Buoyancy modules also used to suspend entirety of cable so it does not touch the seabed. Although not pictured here, a dynamic cable can be used without accessories between the hang-off and touchdown (known as a catenary configuration, which would be best for benign, deep water conditions).

The inter-array cables between turbines are connected to each other in one of three ways:

1. A single continuous length of dynamic cable between turbines
2. Dynamic lengths at each turbine connected to a static length in between using either field joints or connectors, or
3. A single cable assembly using dynamic cable at each end with a length of static cable in between, assembled using factory joints (so manufactured and installed as a single length of cable)[6]

The final choice depends on the trade-off between the relative costs of static and dynamic cables, the additional costs of using field joints or connectors, and the introduction of additional potential points of failure at field joints or connectors. Configurations that can ensure electrical continuity of the rest of the wind farm in case of a failure at one FOWT is an additional consideration for a project's financeability and insurability.

1.1.2 Cable global layout

The global layout selection is a multi-disciplinary process involving the cable manufacturers, installers, suppliers and project developers. For each project, it is necessary to evaluate the pros and cons of reducing the total length of cable, using active or passive components and connectors, burying the cables between FOWTs etc. The existing floating wind farms have their turbines linked in a daisy chain, meaning that each turbine is linked to the adjacent turbines by one cable (Figure 4 below). The inter-array cable of one or multiple turbine(s) (often at the ends of the array) connects directly to the substation (if used) and/or export cable, transporting the power from all the other turbines to the grid. Larger wind farms using daisy chain would require varying cross-section sizes of cable to optimise the transport of energy and the project cost.

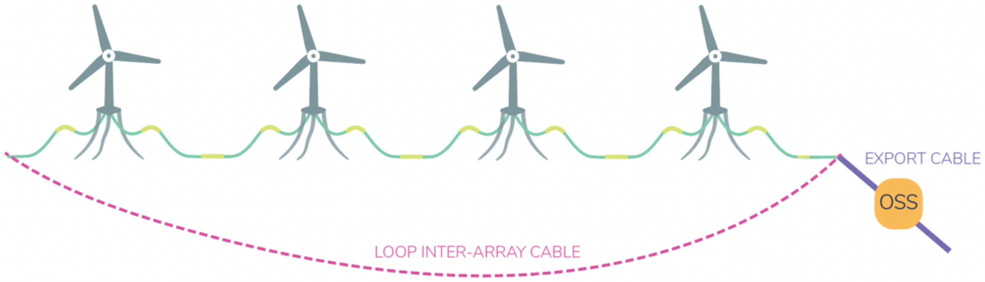


Figure 4. Simplified illustration of daisy chain array. OSS = offshore substation. Sources: WFO, information from Siemens Subsea.

While a daisy chain set-up with lazy-wave cables is most feasible with existing technology, this layout implies operational risk; a fault at one FOWT can affect the whole array, causing significant downtime and putting the other FOWTs at risk depending on the return path and sizing. The wind farm's repair concept would also influence the significance of the risks in a

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[6] *Text extracted from BVG Associates' Guide to a Floating Offshore Wind Farm (funded by ORE Catapult).*

daisy chain configuration: assuming a tow-to-port repair strategy, the FOWTs would have to be disconnected and the cables stored either on the seabed or on a temporary buoy. In such a case, the downtime risk to the other FOWTs is high. An onsite repair concept could reduce the necessity of a quick connection-disconnection system.[7]

Other types of global cable layouts such as fishbone and star (Figure 5 below) could provide more redundancy and flexibility to the system as well as reduce the number of cables (a benefit for larger, expandable projects). These set-ups could include subsea hubs and connectors, but this is technology that is not yet developed. The industry is currently estimating where subsea connectors make sense for floating wind given their current cost and early technology development status.

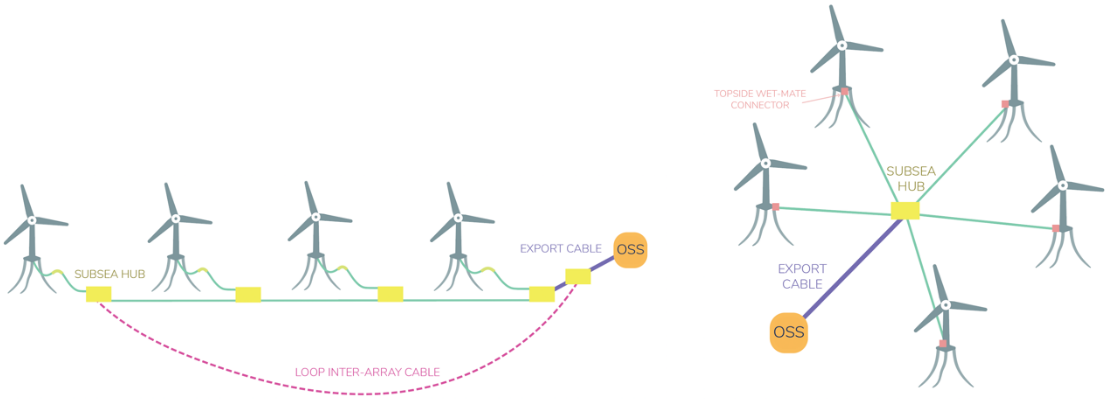

Figure 5. Simplified illustration of fishbone (left) and star (right) global configurations. In reducing the amount of equipment compared to a daisy chain, the installation of the cables is simplified. However, handling subsea hubs and connectors pose other risks. Source: WFO, information from Siemens Subsea.

1.2 Standards, Recommended Practice and Guidance

The power cable industry is very standardised with codes covering land cables, subsea cables and umbilicals.[8] However, it was not until December 2019 that an international standard covered subsea power cable design, manufacturing and testing for voltages up to 60 kV (IEC 63026). Since then, certification bodies are working to further specify recommended practice for dynamic, high-voltage subsea cables. For instance, in 2022, CIGRE published recommendations for mechanical testing of submarine cables for dynamic applications in the context of the growing floating wind industry (CIGRE TB 862). A summary of the main codes and standards relevant to the qualification of dynamic cables can be found in the table below.

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[7] *WFO's O&M Subcommittee White Paper on Onsite Major Maintenance explores related solutions.*

[8] *Umbilical: bundle of cables that link surface and seafloor oil and gas equipment for controls, power or heat.*

Table 1. Compilation of codes and standards relevant to the qualification of subsea/submarine power cables (AC and DC). Source: ORE Catapult 2022, COREWIND 2020, WFO research.

Code	Title
CIGRE TB 490	Recommendations for Testing Long AC Submarine Cables with Extruded Insulation for System Voltage Above 30 to 500 kV
CIGRE TB 623	Recommendations for Mechanical Testing of Submarine Cables
CIGRE TB 722	Recommendations for Additional Testing for Submarine Cables
CIGRE TB 862	Recommendations for Mechanical Testing of Submarine Cables for Dynamic Application
IEC 63026	Submarine Power Cables with Extruded Insulation and Their Accessories for Rated Voltages from 6 kV (Um = 7.2 kV) up to 60 kV (Um = 72.5 kV) –Test Methods and Requirements
DNV-RP-F401	Electrical Power Cables in Subsea Applications
ISO 13628-5	Subsea Umbilicals
API Spec 17E	Specification for Subsea Umbilicals
IEC 60840	Power cables with extruded insulation and their accessories for rated voltages above 30 kV (Um= 36 kV) up to 150 kV (Um = 170 kV) - Test methods and requirements
IEC 60502-2 and -4	Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) -- Part 2: Cables for rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV) Part 4: Test requirements on accessories for cables with rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)
IEEE Standard 400.2, 3, and 4	400.2 - IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) 400.3 - IEEE Guide for Partial Discharge Field Diagnostic Testing of Shielded Power Cable Systems 400.4 - IEEE Guide for Field Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current (DAC) Voltage
CIGRE TB 852	Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to and including 800 kV
IEC 60228	Conductor of Insulated Cables
IEC 61892-4 Edition 2.0 2019-04	Mobile and fixed offshore units – Electrical installations – Part 4: Cables
ISO 13628-5	Petroleum and natural gas industries — Design and operation of subsea production systems — Part 5: Subsea umbilicals
DNVGL-RP-0360	Subsea power cables in shallow water
DNVGL-ST-0359	Subsea power cables for wind turbines
Cigré ELECTRA 189	Recommendations for testing long length submarine cables
Cigré ELECTRA 171	Recommendations for mechanical testing of submarine cables
Cigre ELECTRA 77	Recommendations for mechanical testing of submarine cables

In an industry-wide survey on inter-array AC cables, the Carbon Trust concluded that:

1. Generally, existing standards cover dry-static cables at 132 kV

2. Significant improvements are required to existing testing standards of wet-static 132 kV inter-array cables
3. Additional tests need to be incorporated to cover dynamic 132 kV inter-array cables[9]

In a separate study, the Carbon Trust also concluded that only 6 publications of 62 reviewed were directly applicable to dynamic subsea power cables (ORE Catapult counts 8 in their report).[10]

The industry would greatly benefit from specific dynamic cable standards and load classes for offshore wind. Indeed, although CIGRE TB 862 has been released to close a gap on the structural analysis of submarine cables for dynamic applications, no similar guidance is available to discuss the thermal-electrical analysis of the power cable. For example, there is a need to test at higher temperatures than already recommended to know how the insulation system is affected. Additional studies are needed to evaluate the feasibility of scaling existing products to larger cross-sections, ensuring that the metallic barriers can experience bending without fatigue or breakage.[11] Lastly, qualification tests need to account for various loadings from shallow to deep-water environments. Large scale installations will require a more standardised approach to design and testing (vs. the project-specific approach of today).

There is also a gap at the level of ancillary equipment. As of now, there are no floating wind-specific standards for the qualification of these components. However, floating offshore wind cable systems require a variety of components along the cable length. This equipment is adapted from the oil & gas experience but differs in size and fatigue load regime. For instance, bend stiffener connectors for floating wind will need to have multiple latch and unlatch cycles to satisfy the disconnection requirements of FOWTs. Other examples are how equipment needs to be suited for shallower water depths, or no longer needs to accommodate the strain caused by the internal pressure of flexible pipes. Component-level testing can qualify the ancillaries for floating wind specific loads. The loading from the ancillaries to the cable must be accounted for in the design to meet cable-specific limits.

Overall, there is still a lot of innovation in the area of ancillary equipment, going from product integration (e.g. integrating the dynamic bend stiffener and connector) to new technologies altogether (e.g. wet-mate connectors). At the moment, research programmes are including accessories in the fatigue testing of cables.[12] The ORE Catapult technology qualification framework will work with a bend-stiffener, and other products are to be considered in future iterations of the programme. These efforts can improve the qualification track of ancillary equipment for floating offshore wind.

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[9] *Cables & Floating Substations Subcommittee June 2023 (presentation by Carbon Trust on its High Voltage Array Systems Project).*

[10] *Dynamic cable failure rates, Carbon Trust Floating Wind JIP Phase V Summary Report (2023); ORE Catapult Dynamic Cable Technology Qualification Framework and Case Studies (2022).*

[11] *Cables & Floating Substations Subcommittee June 2023. In addition, according to the Carbon Trust, greater cable diameter was found to induce higher hydrodynamic load ranges, and consequently higher stress ranges inside the cable, leading to reduced fatigue lifetime.*

[12] *Cables & Floating Substations Subcommittee November 2022 (presentation by Hellenic Cables and CRP Subsea on the MaRINET2 study).*

2 Consider design basis

Experiences from the oil & gas sector with umbilical cables and Direct Electric Heating (DEH) subsea flowlines are supporting the design of floating wind dynamic cables.[13] WFO's Floating Offshore Wind Committee has cited the Gjøa floating oil & gas platform comprising a 1.5 km dynamic cable section and the upcoming JANSZ IO subsea compression unit consisting of a field control station powered by a dynamic section in North West Australia as cases with valuable learnings for floating wind.[14]

2.1 Mechanical design

Compared to their static counterparts, the dynamic inter-array and export cable lengths must withstand higher loadings from being exposed to wave and current induced dynamic tension, bending and twisting cycles in the water column (Figure 6 below). Platform induced motion in response to wind turbine interactions and the mooring system's compliance also directly impact the dynamic cable. While environmental loads come from all directions, two particular directions have the most impact on the cable design: near (where the hang-off moves closer to the touch-down point, compressing the power cable) and far (where the hang-off moves away from the touch-down point, stretching the power cable) (Figure 7 below).[15] Induced wear at the touchdown point could also be a governing condition depending on the location and seabed sweep.

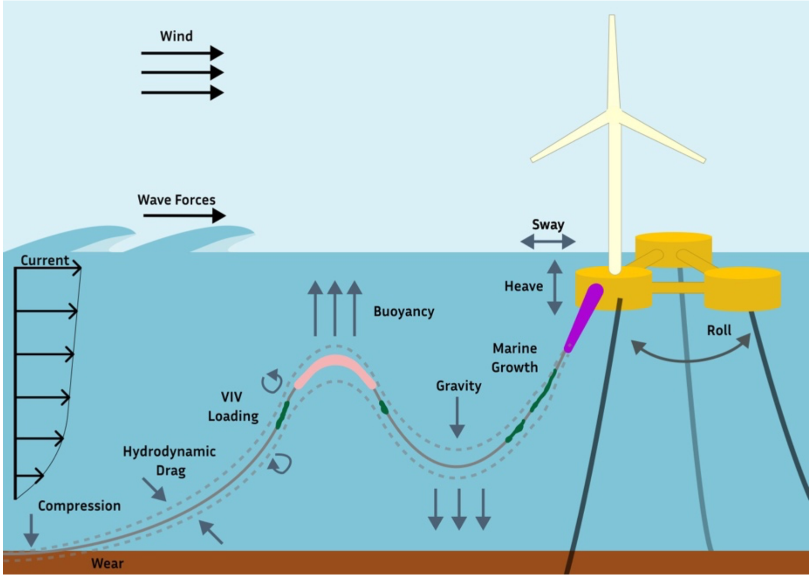

Figure 6. Loads acting on dynamic power cables. VIV = vortex-induced vibration. Source: AMOG.

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[13] *ORE Catapult Dynamic Cable Technology Qualification Framework and Case Studies (2022); Cables & Floating Substations Subcommittee June 2023.*

[14] *The Gjøa dynamic cable section was equipped with buoyancy units to maintain its lazy-wave shape. The upcoming JANSZ IO project will have a 145 kV dry-design import cable. The cable itself has a 3-copper core with an insulation around each core.*

[15] *Moorings Subcommittee November 2023.*

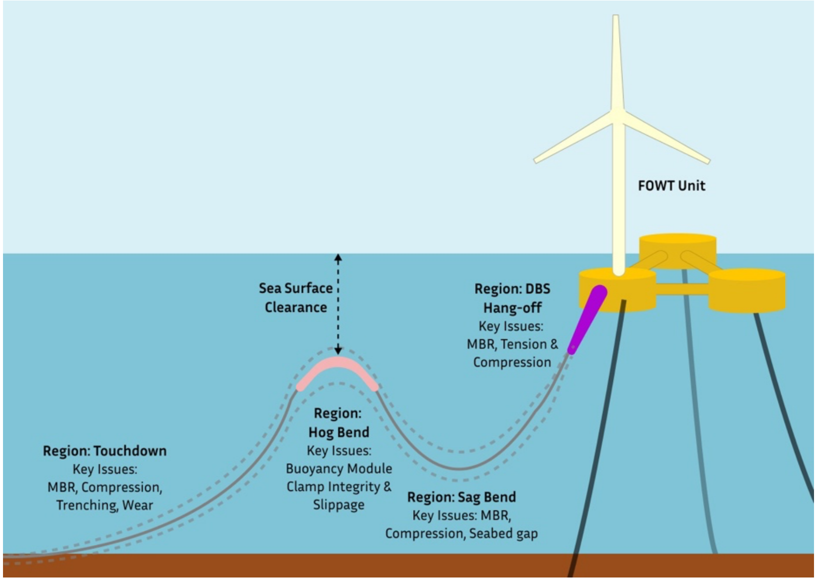

Figure 7. Design parameters of dynamic cable. Source: AMOG.

Existing floating offshore wind projects are in water depths from 60-200m,[16] which are considered at the shallow end for floating systems. Seemingly contradictory, these shallow conditions are more challenging for floating systems because the floating systems response to waves affects a larger percentage of the cable's length than in very deep water. The cable has a smaller water column to accommodate changes associated with marine growth, loss of buoyancy in accessories etc. Compression and seabed movement must be minimised, and sufficient clearance of the hog bend must be maintained for vessel access. The issues surrounding mid- to deep-water environments[17] will be uncovered as the technology matures and new projects get built in deeper sites. The need for longer cable lengths, withstanding pressure, the influence of sagging and more complex installation processes are some of the foreseeable challenges.

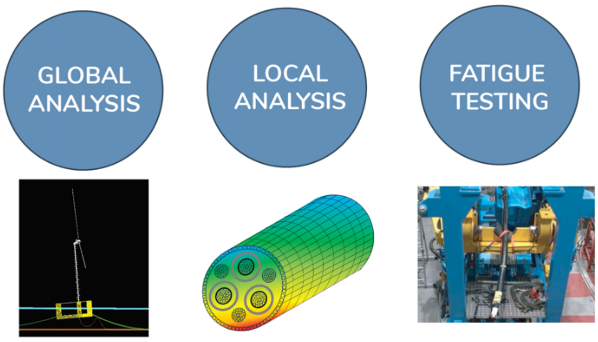

Figure 8. Three main testing and simulation activities for the design of dynamic cable systems. Together these activities define extreme loads, fatigue loads and fatigue life of the system. Images from AMOG, University of Manchester, ORE Catapult.

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[16] *This range is loosely defined in the WFO Floating Offshore Wind Moorings Subcommittee. Existing demonstrator projects are in water depths of range 30m-300m.*

[17] *As loosely defined in the Moorings Subcommittee: mid-water depth is 300m-1000m; deep-water depth is >1000m.*

During the design phase, the cable is configured in a compliant shape which minimises the chances of snatch loading. A global model is first used to determine the cable's levels of loading in three modes: bending, twisting and tension for representative environmental conditions. The cable's ability to tolerate short-term extreme loading (from infrequent large storms or hurricanes) and long-term fatigue (from persistent sea-states) is checked. The dynamic cable loading can be affected by its compass angle relative to the prevailing environmental loading.[18] The global model will typically include the mooring system design such that horizontal offset limits of the FOWT can be investigated. This is accompanied by an interference analysis evaluating the possibility of collisions with neighbouring subsea infrastructure like mooring lines. Such occurrences are considered not permissible under any conditions.

For a more efficient design process, the mooring system simulation is decoupled from the cable design.[19] Once the governing load cases of the mooring system are identified, they are applied to the decoupled cable model. From there the cable configuration is developed. It is important that feedback from the cable configuration design is used to update the mooring system design process and eventually find the optimal solution that meets all design limits. Preliminary quasi-static analysis of the cable can be incorporated into the workflow early on to exclude unfavourable configurations. More variables would then have to be used to identify the best cable configuration for the project (detailed site conditions, floater information, ancillary equipment information).

The offset surge, heave and angular displacement of the floater allowed by the mooring system has an impact on the cable response. Generally, larger offset gives larger tension on the cables. Ultimately, the best moorings & cable configuration for a floating wind project will be driven by site-specific conditions, where water depth, cable cross-section size, the use of ancillaries, mooring system redundancy etc. will all influence the power cable static and dynamic behaviour. The important takeaway is to integrate moorings and power cable design early on to respect each other's design limits.

In addition to a global model, local models estimate the levels of stresses in the metal components of the cable. Cables consist of helical metallic components and polymer layers which are more forgiving against bending loads than a standard cylindrical pipe would be (Figure 9 below). Generally, the metallic layers are more susceptible to failure from dynamic loading and thus they are the focus of mechanical engineering investigation. The stresses can be highly non-linear with the loading due to inter-layer friction and can be affected by water depth and thermal effects.

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[18] *According to results from the Carbon Trust's project on dynamic cable failure rates, the cable azimuth should be designed away from the prevalent wave directions.*

[19] *Moorings Subcommittee November 2023.*

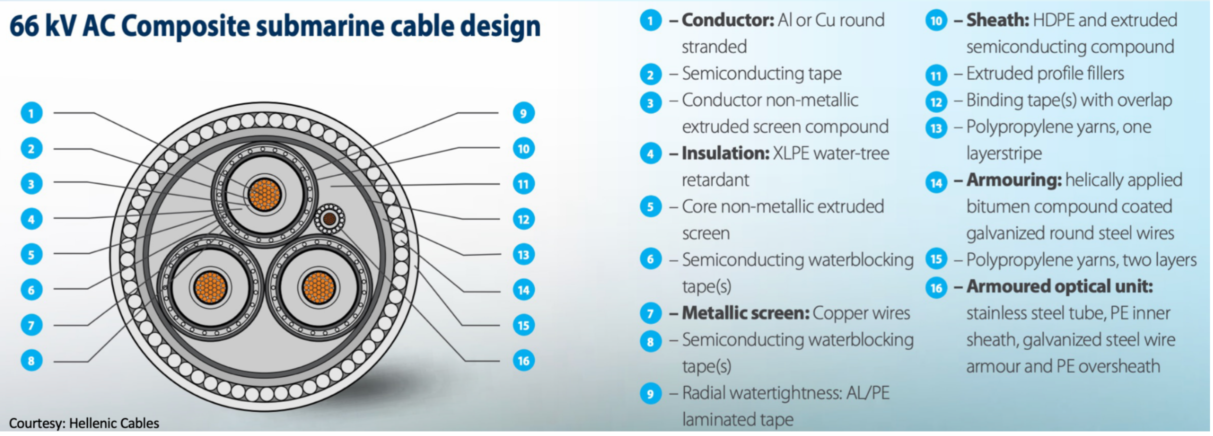

Figure 9. Composite subsea cable design. Dynamic inter-array cables require two layers of armouring for additional fatigue resistance (instead of a single layer for static cables). Source: Hellenic Cables.

Finally, to add a level of robustness, physical samples of the cables are often mechanically tested to confirm their expected performance (e.g. a fatigue test in a dynamic rig). For the design and testing of the high-voltage dynamic cable for the Gjøa oil & gas platform in Norway, emphasis was placed on the radial water barrier (copper sheath), highlighting the criticality of this technical innovation for floating wind cables. Similarly, water ingress was identified as a challenge for the JANSZ IO subsea compression unit.[20]

Cable structures often have the most fatigue sensitive areas at the top and bottom as these areas can be subject to high bending loads. Interfaces to mitigate the cable loading (e.g. I-tube and bend stiffener at the hang-off, other CPS at the seabed transition) should be selected based on the level of expected dynamic behaviour which is driven by the severity of met-ocean conditions and the cable's proposed mechanical properties. In particular, accessories need to be developed to sustain the higher-voltage and heavier export cable design.

2.2 Electrical design

2.2.1 Inter-array cables

Due to the relatively short lengths, all inter-array cables are AC (3 phase generally). The voltage rating of the dynamic inter-array cables in today's floating wind projects is 36 kV or 66kV.[21] In the next few years, the voltage of offshore wind inter-array cables (static and dynamic) is expected to increase to 132 kV to accommodate higher power turbines and reduce electrical losses.[22] Dynamic inter-array cables are mostly 'wet' design, which is in contrast to a 'dry' design traditionally used for static cables. In a 'dry' design, the sheath (item 10 in Figure 9) is typically an impermeable 'lead pipe'. Wet designs do not have such a metallic layer to withstand the impact of water. As a result, wet designs are much more tolerable of dynamic

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[20] *Cables & Floating Substations Subcommittee May 2023.*

[21] *Based on dynamic cable voltage information from the 4COffshore database of the following projects: Floatgen, WindFloat Atlantic, Kincardine, Hywind Scotland, Hywind Tampen, Provence Grand Large, EFGL.*

[22] *BVG Associates/ORE Catapult; Cables & Floating Substations Subcommittee June 2023 (presentation by Carbon Trust on its High Voltage Array Systems Project).*

motion and do not suffer mechanical fatigue damage like the dry design. Other materials can be used to protect against water; for example, the 33kV inter-array cables at the Kincardine offshore wind farm contain a polyethylene sheath with additional water-blocking tapes.[23] Wet designs can be cheaper, lighter and occupy less volume. However, they are more susceptible to ageing issues and have limited track record to date, though this is rapidly changing.

Figure 10. Model of 66 kV dynamic inter-array cable for the Provence Grand Large wind farm. Source: Prysmian, EDF Renouvelables.

2.2.2 Export cables

Connecting a project site to shore generally involves an export cable from a substation. For long distances, export cables have less transmission loss if they are DC (HVDC High Voltage Direct Current). For small to medium distances, AC (HVAC High Voltage Alternating Current) is a more efficient choice. If the substation is a bottom-fixed structure, export cables can be static cables. For floating substations, export cables need to be dynamic. High power dynamic export cables currently do not exist and are the one remaining missing piece of the FOWT cable industry to develop and qualify. Currently, the industry is closer to qualifying high-voltage AC cables than DC.

Existing floating wind projects are small enough in power and relatively near shore to not require a wildly different sized export cable to inter-array cable. To satisfy future project requirements, manufacturers are working to qualify *dynamic* export cables of up to 220 kV. As a point of comparison, current *HVAC static* export cables are typically rated at 220 kV and *HVDC static* export cables used for larger and more distant offshore wind projects are rated at 320 kV.[24] A recent European research project call focuses on AC and DC export cables up to 525 kV, including dynamic cables.[25] Already in 2023, 525 kV HVDC cables with extruded XLPE insulation have been ordered for multiple large onshore and offshore wind farms across Europe.[26]

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[23] *Figure 2.1 of the Kincardine Offshore Wind Farm Cable Plan (KOWL-PL-0004-009).*

[24] *BVG Associates/ORE Catapult.*

[25] *Cables & Floating Substations Subcommittee October 2023 (link to call).*

[26] *WFO Cables & Floating Substations Subcommittee meetings, NKT cites some of its orders in an article about 525 kV XLPE HVDC cables.*

2.2.3 Ageing Issues

Moisture, temperature and electrical stress in the insulation system age the cable. There are two main electrical failure modes for dynamic cables: water and electrical treeing of the insulation. When moisture penetrates the insulation in the presence of the AC electric field, the insulation area is weakened[27] and water trees grow. This leads to the formation of electrical trees at the tips of the water trees, the latter which then fails the cable insulation (by short circuit). Electrical trees are hollow gas channels (caused by ageing of the insulation and potential imperfections in manufacturing) that accelerate the partial discharge process leading to potential premature failure. To prevent water tree initiation, a lead waterproof barrier on the outer surface of the insulation is used (= dry design). As a lead waterproof barrier is not possible for wet designs, other protective materials are needed, e.g. water tree retardant fillers in insulation materials.

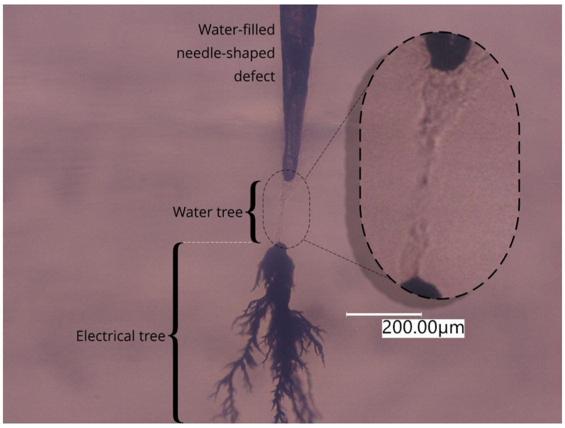

Figure 11. Microscopy evidence indicating an electrical tree in low-density polyethylene (LDPE) sample initiating from a water tree (highlighted) that originated from a water-filled, needle-shaped defect, manually applied to the insulation. Source: University of Manchester.

At the moment, the track record of high-voltage wet designs for both static (> 132 kV) and dynamic cables (> 66 kV) is very limited. Higher voltages increase the electrical field strength and the likelihood of water tree initiation, thus shortening service life. These cables also have to withstand higher design stress (7.5-8 kV/mm versus 3-5.5 kV/mm for dry design).[28] Preventing moisture on the insulation of the power chord is critical especially for larger conductor sizes.

Laboratory wet testing will be key to pre-evaluate the effects of the water on the insulation, water pressure and any stress-induced electrochemical degradation on the conductor materials. Combined mechanical and electrical testing methods need to be explored further to properly address dynamic cable failure mechanisms. Recent research already shows how mechanical strain and tensile strain impact the growth of electrical trees and the cable time-to-failure.[29]

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[27] *The water tree saturates the polymer and creates low density regions in the insulation. There are two types of water trees: bow-tie and vented. Cables & Floating Substations Subcommittee October 2023, University of Manchester research.*

[28] *University of Manchester research.*

[29] *Cables & Floating Substations Subcommittee October 2023, University of Manchester research.*

2.3 Installation and handling

In floating wind, there are two procedures for installing dynamic cables depending on whether the floater is already deployed at its final location. The first strategy where the floater is already moored on site implies dry-storage of the cables (as they arrive on the vessel's carousel) and the second implies wet-storage of the cables at the project site prior to arrival of the floater. For each strategy, there are specific processes that require detailed planning to minimise risks:

Dry storage installation

1. **Smooth critical path** for proximate installation activities within a given weather window (like the arrival of FOWT, mooring hook-up, cable connection…).
2. **Jointing of the dynamic umbilical** with the static cable that is already on the seabed

Wet storage installation

1. **Waterproofed sealing** at the free end of the cable
2. **Rigging and rope** to enable safe recovery
3. **Recording of cable position** to be shared with all nearby offshore operations. Risks of damage during wet storage need to be taken into account for each project site

In dry storage, the installation vessels need to be coupled in their work, which in case of any delay could significantly increase the project CAPEX because of day rates. Wet storage allows the operator to de-couple the arrival of the floater with the cable installation vessel which de-risks a lot of installation vessel waiting time.

Analyses are performed to ensure the integrity of the cable during installation. The installation analysis for floating wind should, as a minimum, be based on the following variables:

1. Vessel station-keeping characteristics and motion responses
2. Effects of vessel-induced motions
3. Friction between cables and i-tubes (hang-off area)
4. Clash with mooring lines
5. Cable minimum bending radius
6. Maximum sidewall pressure and maximum tensile load[30]

2.4 Substation – floating or subsea

Commercial offshore wind projects require a substation to ensure the efficient transmission of power. Because of the deeper waters of floating wind sites, alternative substation designs

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[30] *OWC presentation on dynamic cable installation at Leadvent's 3rd Annual Floating Wind Europe Conference (4-5 April, 2023).*

are emerging: floating and subsea. Oil & gas experience is likewise relevant for these designs.[31]

Beyond a certain water depth, floating substations start to make sense considering the excessive cost involved in a bottom-fixed structure.[32] One study[33] is comparing the cost-benefit of developing floating versus subsea substations, answering to what extent water depth is a driver of the final decision for a given project. Depending on the distance of the substation to shore, HVAC (short distance) or HVDC (long distance) export cables are used. For longer distances (>100 km), energy could be transported as hydrogen as opposed to electricity.[34]

There are obvious technology gaps for both floating and subsea substations. Besides the use of high-voltage dynamic cables and connectors, the insulation (subsea) and station-keeping (floating)[35] requirements as well as the unique installation and maintenance procedures are some of the challenges. A redundant mooring strategy at the floating substation is paramount for energy security as a loss of the substation inevitably results in loss of production from the whole field. The consequence of failure increases if living quarters are to be included. At the same time, however, it will be necessary to avoid contact between the mooring lines, inter-array cables and export cables (termed the "spaghetti ball problem") by establishing a minimum distance between connection points. Distributed buoyancy systems and alternating the heights of adjacent sag and hog bends can be used to keep cables separated. It may be that parallel line contact between cables could be acceptable in extreme conditions, however point contact that could occur between moorings and cables would be unacceptable.

Using a similar floater design and mooring layout for the FOWT and floating substation could mutualise construction infrastructure and the installation methodology, allowing flexibility in the sequence of activities (e.g. start/stop between FOWT and substation installation).[36] However, as mentioned earlier in the paper, decoupling the cable installation and floater installation schedules with a cable pre-lay will require careful thought on the wet storage. Developers of floating substation concepts are currently conducting modelling exercises as well as tank testing to observe dynamic responses and towing behaviour in specific configurations and environmental conditions.

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[31] *Example resources: Petrofac presentation on floating substations; Baker Hughes presentation on subsea substations; Aker Solutions in Cables & Floating Substations Subcommittee May 2023.*

[32] *Different ranges have been identified across the Cables & Floating Substations Subcommitte meetings: one study identifies ~60 metres as the cut-off range from fixed to floating substation for 2 sites in the UK. Another study mentioned 120-150m.*

[33] *ORE Catapult is comparing the costs of floating and subsea substations.*

[34] *WFO's Offshore Wind to Hydrogen Committee is exploring the use of existing pipeline infrastructure to transport hydrogen from faraway offshore wind farms. A step further would be to transport the hydrogen in ships.*

[35] *Specifically dynamic motions and accelerations (Fatigue Limit State), survival state conditions (Ultimate Limit State), vibration, heeling, space & weight constraints, availability requirements.*

[36] *Cables & Floating Substations Subcommittee July 2023 and November 2023.*

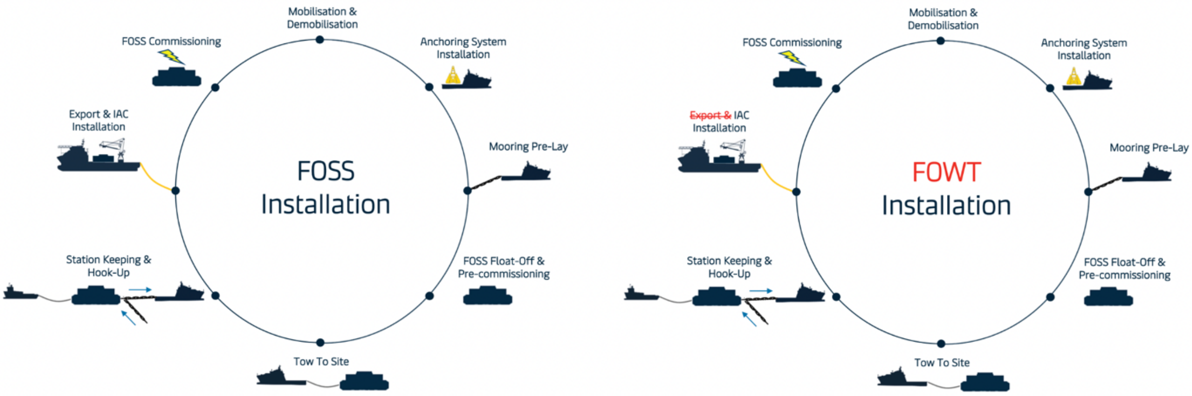

Figure 12. Example installation steps for FOSS and FOWT. The FOSS example includes 12 mooring lines distributed across 4 clusters with drag-embedment anchors. This simplified diagram can already show the different equipment necessary. Source: Maersk Supply Service.

Currently, no standard for floating substations exists. DNV is leading a JIP to update its standards ST-0145 for offshore substations and ST-0359 for subsea power cables (HVAC and HVDC).[37] The vision of the project is to enable scaling of floating wind with an acceptable level of commercial, technical and health & safety risk, through suitable standards and guidelines for floating offshore substations. In completing Phase 1 of the project, it was identified that HVDC and HVAC dynamic cables as well as HVDC equipment are the most novel technology elements. In addition, the principal gap for the design process is the lack of guidance of the cost-benefit of reducing the motion characteristics for the floater versus reinforcing the equipment and cables for increased floater motions. Finally, Phase 1 also concluded that the same safety class shall be used for floating offshore substations as for fixed.

Similar optimisation challenges apply to the FOWT, where floater motions enabled by the station-keeping system create loads on the dynamic inter-array cable that need to remain within the latter's design envelope.

Subsea substations are being considered a serious choice for floating wind projects as well, with a recent pilot project being announced in January 2024. The pilot substation in question will be hosted at a test centre in Norway using a star configuration, 66kV wet-mate connection system and subsea switchgear.[38] This offshore wind farm architecture is intended to have benefits over the traditional daisy chain pattern, for example in isolation of power transmission in case of failure or scheduled repair.

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[37] *Reference report : https://www.dnv.com/Publications/floating-substations-joint-industry-project-phase-1-249148*

[38] *Aker Solutions press release : https://www.akersolutions.com/news/news-archive/2024/aker-solutions-to-pilot-floating-wind-power-hub/.*

2.5 Site-specific environmental data

Dynamic cables must be able to withstand the environmental factors of the project's site. Marine growth on the cable can add weight to the cable, but the way this happens depends on the ecology of the site, e.g. the type of marine organism, its growth rate etc. Existing standards for marine growth are based on data logs from the North Sea, which may be irrelevant for other floating wind sites in the world. As such, efforts to collect robust site-specific data are necessary to support the dynamic cable designs that will correspond to the various floating offshore wind areas. Additional questions on the effective prevention and removal methods, recyclability of the ecological matter will only be answerable with project experience. In addition to marine growth, thermal insulation properties of the seabed, scouring, and water current influence the material and ancillary equipment choice for dynamic cables.

Pilot projects therefore play a key role in building up knowledge on these issues by observing the real-life behaviour of the system in its environment.[39]

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[39] *An example study is the environmental monitoring report of the Floatgen demonstrator by BW Ideol.*

3 Address commercial challenges

3.1 Bottom-fixed offshore wind cable failure modes and mechanisms

To reflect on the experience of the bottom-fixed wind industry, the root cause of cable failures discovered during operation is broken down as follows:

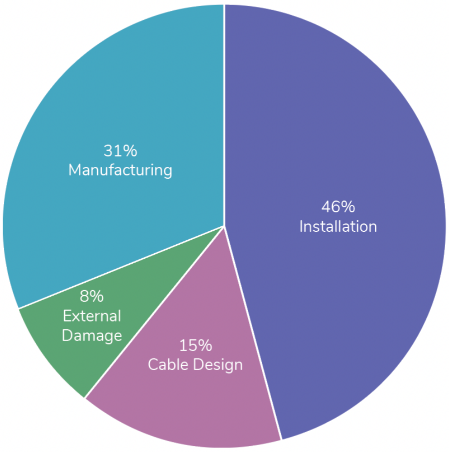

Figure 13. Recorded failure modes for bottom-fixed wind export and inter-array cables in the UK that were discovered during operation. The origin of the failures is attributed to installation (46%), manufacturing (31%), faulty design (15%) and external damage (8%). Source: ORE Catapult, 2021.

The Carbon Trust estimates the average failure rate envelope of static offshore wind subsea cables to be between 1.9 x 10^{-3} failures/km/year and 2.13 x 10^{-2} failures/km/year.[40]

To properly mitigate the risk of cable failures from the above pie-chart, a high-voltage subsea cable expert suggests that projects should consider the points below:[41]

- **DEVELOPMENT:** Ensure a more comprehensive site surveying in the development phase with the aim to design cables better suited for the environment and installation methodology (e.g. thermal resistivity readings, seabed mobility).
- **MANUFACTURING:** Allocate budget for cable design and manufacture witnessing by an experienced subsea cable expert to identify issues early on. To mitigate the risk of serial defects, the cable design, fabrication facilities and their manufacturing need to be surveyed.
- **INSTALLATION:** Pay closer attention to joints and accessories during installation by hiring a skilled installation (sub-)contractor and in particular an expert on high-voltage

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[40] *Dynamic cable failure rates, Carbon Trust Floating Wind JIP Phase V Summary Report.*

[41] *Insurance Subcommittee November 2023 : PRIMO Risk & Control presentation.*

cables to survey the operation. The expert should complement the work of the Marine Warranty Surveyor, the latter being typically responsible for a) prior to installation, ensuring the cable is suitable for spooling and installation; the vessels, related equipment and contractors are adequate and b) surveying the installation phase, but not surveying the quality of jointing works.

- **EXTERNAL DAMAGE**: Ensure good survey data (coming back to the DEVELOPMENT phase), have good knowledge of shipping traffic, perform cable burial risk analysis (applicable mainly to bottom-fixed, but buried export cable lengths are also expected in floating wind).

Public communication of cable issues can help the industry solve them faster. Two examples of this are the sharing of faults at the fibre optic carrier tube and cable protection system:[42] developers sharing these high-profile problems increased awareness and is contributing to risk mitigation in the long run.

3.2 Installation faults as leading failure mode in bottom-fixed offshore wind

As seen in the Figure 13 pie-chart, installation makes up almost half of cable failures in bottom-fixed wind farms. This is mainly because the cables are at risk of mishandling and overbending. However, tracing the origin of a cable failure back to installation can be a challenge if the failure occurs at a later period during the operational phase. Similarly, a design issue may often manifest itself in an installation method etc.[43]

The following table groups installation failures into 5 categories:

Table 2. Examples of installation failure causes. Source: Renewable Construction Academy (RECOA).

Design	Cable design not complying with foundation (in floating wind context = the FOWT/substation), installation methodology, vessel capabilities; cable accessories not complying with installation methodology
Equipment	Installation equipment unvalidated or not appropriate for project given no availability of better tools; equipment performing poorly or failing
Planning	Timeline pressures or delays influencing operations; lack of contingency plan to bring back operations into acceptable quality
Engineering	Unclear cable handling criteria, environmental data; standards not met or defined; design changes not assessed or communicated; unvalidated/unproven methods (e.g. using the wrong standards)
People	Complacency, fatigue, poor communication and workmanship (e.g. lack of common terminology, lack of qualified resources or training)

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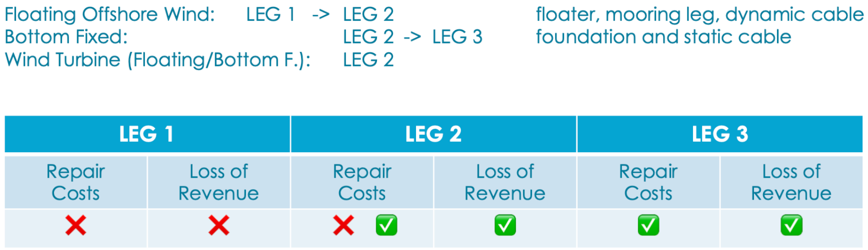
[42] *Insurance Subcommittee November 2023: OFTO report for FOC issue; Ørsted report for CPS issue.*

[43] *To provide nuance on such uncertainity, related data can be labelled (e.g. diagnosed vs. assumed failures) or the values provided with a confidence level.*

The first end pull-in where the inter-array cable gets pulled into the turbine foundation through the i-tube is a critical operation. The project must select vessels with appropriate reel/carousel, dynamic positioning system and deck space for the accessories.

There could be many transitions and stops/starts in the installation operation which create compound risks. Due diligence on the installation plan, working with experienced players, strong interface management between the cable and floater EPCIs (e.g. to avoid issues like the contractor installing the export cable unknowingly damaging the inter-array cable), as well as the presence of an experienced and qualified Marine Warranty Surveyor (MWS) can help mitigate these risks.

3.3 Insurance perspective on floating offshore wind



Floating Offshore Wind: LEG 1 -> LEG 2 floater, mooring leg, dynamic cable
Bottom Fixed: LEG 2 -> LEG 3 foundation and static cable
Wind Turbine (Floating/Bottom F.): LEG 2

LEG 1		LEG 2		LEG 3	
Repair Costs	Loss of Revenue	Repair Costs	Loss of Revenue	Repair Costs	Loss of Revenue
✗	✗	✗ ✓	✓	✓	✓

Figure 14. How the Construction All Risk/Delay in Start-Up and Operational All Risk/Business Interuption Insurances responds in case of loss or damage due to defect.[44] Most of the floating foundations and mooring line concepts still qualify for only LEG 1. The same goes for dynamic cables. Source: Ralf Skowronnek, WFO Floating Wind Insurance Subcommittee.

Lowering the probability of failure in dynamic cables (risk mitigation) and the reduction of their repair cost and downtime (loss mitigation) are key for floating offshore wind because it is expected that for a certain qualification period, technologies in floating wind including the dynamic export/inter-array cable and substation are regularly falling under the LEG 1 exclusion of coverage for defective parts.[45] This means that costs for losses due to defect including the related loss of revenue will remain with the project. As such, it is recommended to developers that they request a cable/accessory/connector design which is suitable for a cost-efficient and fast repair/replacement.

Failures at the inter-array cable on the end of the daisy chain that is adjacent to the export cable, the export cable itself and/or substation have higher impacts on business interruption. What insurers have echoed in the Subcommittee meetings is the need for redundancy and easy replaceability of the systems, for example, if possible, by using multiple, smaller cables.

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[44] *London Engineering Group (LEG) is a consultative body for insurers of engineering class. The group produces coverages clauses which vary in their exclusions with respect to engineering risks. In this case there are three ranging from lowest amount of coverage for loss or damage due to design defects (LEG 1) to highest (LEG 2,3).*

[45] *The WFO Floating Wind Insurance Subcommittee's latest suggestion is for projects to be aware of the repair costs and downtime because these will not be covered by insurers in case of damage due to defects at this point in the industry. This is a lower starting point than bottom-fixed wind, whose projects started with LEG 2 coverage.*

This is especially important if substations are being used as singular connection points for multiple renewable energy projects (wind, wave, tidal…).[46] In addition, floating wind standards could reflect the criticality of these parts by requiring certain technology readiness levels or designating higher consequence classes.

3.3.1 Redundancy

It would be expected that even in a daisy chain, risk mitigation measures in case of a failure are built into the cable design to preserve electrical continuity. As we move towards 16 MW + turbines with 132 kV inter-array cables, the CAPEX of the array cables becomes smaller versus the energy loss, making redundancy add-ons more attractive from a cost perspective and helping respond to insurer concerns without negatively impacting the wind farm's LCOE. Examples of such measures include a loop (dotted line in Figure 4) or using parallel array cables between turbines. Bottom-fixed offshore wind farms tend to have more than one export cable for redundancy.

At the level of the FOWT, redundancy at the mooring lines can help preserve station-keeping and hence dynamic cable integrity. For example, a redundant mooring strategy (i.e. 3 x 2 legs) implies less risk to the cable in case of a single leg mooring failure. A non-redundant mooring strategy (i.e. 3 x 1 legs) implies greater risks to the cable in the event of a single leg mooring failure and loss of floating system station-keeping. The risk of mooring line failure must be considered during the dynamic cable and overall system design.

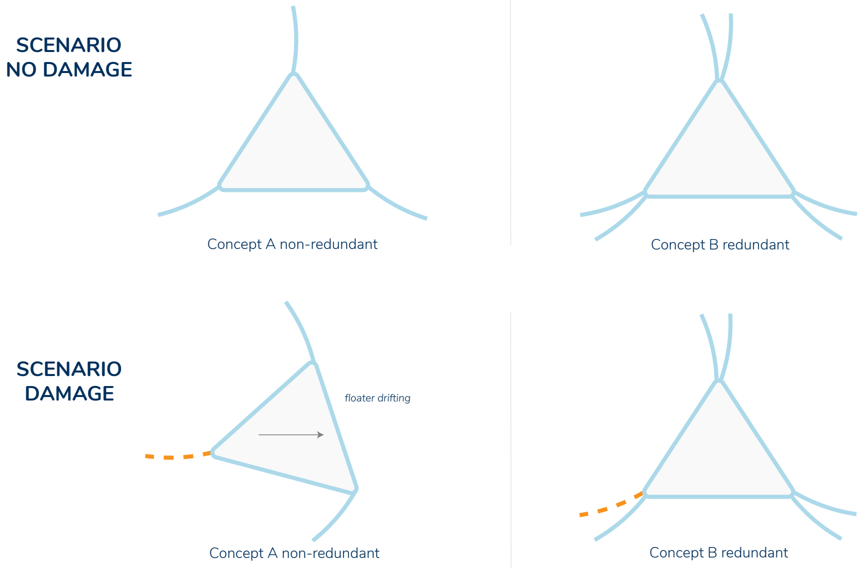

Figure 15. Illustration of mooring redundancy concept. Source: WFO.

3.3.2 Replaceability

Easy replaceability of components would mean factoring transport and logistics constraints. For instance, while designing with larger but fewer equipment may look favourable from a

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[46] *This is the case of the Pembrokeshire Demonstration Zone in the Celtic Sea, where substations are being considered as a multi-connection stop for renewable energy projects.*

cost perspective (CAPEX),[47] it could increase installation and repair costs through a reduced, more expensive choice of vessels. Insurance policies always have a deductible of 2-3 months, and so achieving the repair within this time can help projects to purchase and maintain their operational insurance coverage at a lower premium level. This is why during the risk evaluation and underwriting process, insurers are asking for details of spare parts, major component exchange and emergency response plans. Bad weather conditions and vessel availability are hard-to-control factors that can affect repair time. To best address this, projects can lean on other technology and commercial innovations, e.g. vessels that can operate in harsher sea states, condition monitoring that can enable preemptive repair in favourable weather conditions, or the collective procurement of spare parts and vessels between developers for a given project area.[48]

What can help minimise open market risks and delays in the case of a cable failure during operation (e.g. high prices for cables or lack of available vessels when turning to in-field players) is to include repair terms in the construction agreements, thereby clarifying responsibility for a fixed period early on. In addition, procuring of spares alongside the main product order (so prior to installation) can mimise cost and time risk for a project.

3.3.3 Project certification

At the moment of the insurance policy placement, insurers often do not have enough information about the selected technology, design, accessories, joints, safety factors, suppliers and future installation companies. Project certification is cited as a tool that can complement a project's several technical certifications and reduce the risks caused by new fabrication, installation and O&M methods.[49]

3.4 Supply chain readiness

The floating wind industry has yet to establish a baseline of standardised products and solutions for commercial scale, whether that be for the turbine and floater, moorings and cable ancillary equipment, installation and heavy maintenance approach etc. While each project's design will be heavily influenced by its geography (seabed, met-ocean, available ports…), a minimum convergence on technology design and dimension is necessary to clarify supply chain requirements and eventually reduce the LCOE through industrialised production. Below are some aspects of the supply chain identified by Subcommittee as critical to develop.

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[47] *The alternative of having multiple mooring lines per anchor (= alternative load paths approach) is to use single lines of larger size (= strengthening approach).*

[48] *Cables & Floating Substations Subcommittee meeting February 2023. However, it was found that it could be challenging to implement framework agreements if their set vessel prices are not as attractive as the market price (Moorings Subcommittee meeting March 2023).*

[49] *The WFO is liaising with the Joint Natural Resources Committee (JNRC) of the Lloyd's Maritime Association to improve the insurance industry's understanding of floating wind risks and identify ways to address them. Project certification has been discussed as a helpful tool.*

3.4.1 Testing and qualification capacity

Historically, cable manufacturers have been able to deliver products beyond the scopes of recommended practice.[50] The same is happening for today's floating wind cables as the manufacturers develop their own tests to qualify new products for specific projects.[51] They sometimes partner with other stakeholders (academic, private, public) to make use of funding, research capabilities and/or testing centres. Independent tank testing to respond to technology readiness and projection certification criteria may be more or less favoured depending on the project (its developer and risk appetite).

Industry efforts aim to guide established suppliers to qualify products in similar ways as well as educate new players. For instance, the Carbon Trust is working to identify the parameters for future tests of wet static and dynamic designs.[52] Similarly, ORE Catapult developed a technology qualification framework and will apply it to a floating wind dynamic inter-array cable cross section.[53] DNV will pursue a second phase of its Floating Substations JIP.

However, amidst all these efforts (more of which are unmentioned here), there is a bottleneck of testing houses to timely qualify the future high-voltage static and dynamic cables. Full-scale cable fatigue tests (combined mechanical, electrical, thermal) in such facilities can help determine fatigue life more accurately.[54] Cable ancillaries also need to be tested (component level testing) to suit required loads for floating offshore wind.

3.4.2 Cable installation market

In addition to qualifying the cable product, some cable manufacturers have their own cable installation vessels for the bottom-fixed offshore wind market. Depending on the fleet they have, companies can have EPC or EPCI ambitions (Engineering, Procurement, Construction, Installation) for export and inter-array cable contracts. Other cable manufacturers do not have any installation vessels and instead partner with third parties or simply sell the cable without getting involved in the installation. Different commercial set-ups are more or less attractive to project developers depending on the latter's size, experience and project requirements.[55]
However, just like for testing houses, there is a shortage of vessels that can support larger-diameter, longer cables and their ancillary equipment, the latter requiring specific installation methodology not covered by the efficient and scaled solutions for bottom-fixed wind. This along with port capacity will naturally limit how big equipment can get.

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[50] *Cables & Floating Substations Subcommittee June 2023, where a cable manufacturer explained how they developed a wet-design of a higher cable rating than what standards recommended a metallic water barrier for.*

[51] *Manufacturers adopt a cooperative approach with developers due to the very project-specific nature of dynamic cable systems. Example press release.*

[52] *High Voltage Array Systems Project presented in Cables & Floating Substations Subcommittee June 2023; Dyamic cable failure rates, Carbon Trust Floating Wind JIP Phase V Summary Report*

[53] *ORE Catapult Dynamic Cable Technology Qualification Framework and Case Studies (2022) presented in Cables & Floating Substations Subcommittee March 2023.*

[54] *Current testing approaches that make use of S-N curves of material coupons are likely to lead to conservative estimates (Dyamic cable failure rates, Carbon Trust Floating Wind JIP Phase V Summary Report).*

[55] *Experienced developers tend to take on the risk of the project through multiple contracts rather than pay EPCI contracts to take it (ORE Catapult).*

The suitability of these offshore wind vessels is another question: for deep water installation, the existing stern deployed cable lay approach may not be suitable. Rather, vertical lay may be required, which can open up the floating wind installation market to oil & gas vessel operators instead.

3.4.3 Balance between quality and cost

The practice of driving costs down through the supply chain, particularly during re-bidding phases, is criticized for potentially compromising quality and overlooking the track record of cable manufacturers. Indeed, the cable failures in the bottom-fixed wind industry are considered to have been driven by cost-reduction market pressures where design criteria and installation best practices have not been all accounted for. Floating wind projects must adopt the lessons learned of the bottom-fixed wind industry from the start, thereby allowing stakeholders to focus on the newer challenges: FOWT integrity, station-keeping, dynamic cable design, environmental impact…

Ultimately, floating wind's pre-commercial status means that initial investments are still required to support pilot projects and build an industrial supply chain. Additionally, the emerging non-price criteria in offshore wind auctions incentivize projects to consider environmental and socio-economic impacts in addition to costs. As such, current market designs need to reflect these aspects to best support the industry's path to commercialisation.

4 Adopt mitigation measures

4.1 Innovations

New technologies and new applications of existing technologies are essential to realising floating wind at a commercial scale. These products must achieve sufficient technological readiness levels (TRLs) to secure project financing and insurance coverage. The maturity of a technology is evaluated on a “readiness” scale, with levels progressing from a concept backed by desk research to a full-scale prototype test and finally field application. A typical scale used for subsea projects is API 17N.

While the innovations presented in the following section were discussed separately within the Subcommittee, there is an industry trend towards integrating cable protection systems, for example by combining the connector and dynamic bend stiffener.[56] Discussion between stakeholders is important to enable such combined solutions if it is of benefit to the project.

4.1.1 Connectors (emergency and planned)

When it comes to FOWT installation or major repairs requiring tow-to-port, it will be necessary to easily connect or disconnect the mooring and cabling system. This requirement is pushing for innovations in connection systems at the floater but also along the cables. During installation, the cable connection at the floater (also known as topside connection) needs to be quick as the turbine is running on limited auxiliary power to maintain its idle mode. During a tow-to-port of one FOWT, the disconnection procedure must ensure that the mooring lines and dynamic cables are safely stored in a way that can enable a quick re-connection to minimise downtime. The temporary storage of the mooring lines and cables can be combined near the surface[57] on a buoy or left on the seabed, the latter implying more risks for lay-down and recovery. Certain connectors can be used to link the cables in a way that preserves the electrical continuity between the surrounding turbines in a string.[58] Connectors can also be at the seabed depending on the cable configuration, i.e. whether it includes subsea hubs or a subsea substation.

Connection operations need to be simple and quick to suit various weather windows and minimise downtime. Like cables, connectors are differentiated between dry and wet designs (dry-mate or wet-mate). A dry-mate connector means that the connection operation can only happen above the water: if a connector lies on the seabed during normal operation, a disconnection requires lifting the connector and whatever it is connecting (e.g. two cables, one cable and a subsea substation) to the surface for disconnection. This is evidently a

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[56] *This is the case of the Kincardine bend stiffener and connector. Link.*

[57] *Examples presented during Moorings Subcommittee October 2022, Moorings Subcommittee October 2023.*

[58] *A few of existing floating wind projects use connector technology. Two projects use connectors that can connect two cable lengths together at the surface during tow-to-port of a FOWT; one cable provider developed a connector solution for the 66 kV dynamic inter-array cable it is supplying for an upcoming floating wind farm (3 turbines). These solutions are not straightforward/mature, and there needs to be close collaboration between different parts of the supply chain to reach the optimal solution for each project.*

demanding operation, especially if it concerns a high-voltage export cable and a subsea substation. Wet-mate connectors can be connected underwater, thereby enabling more options for global cable layouts.

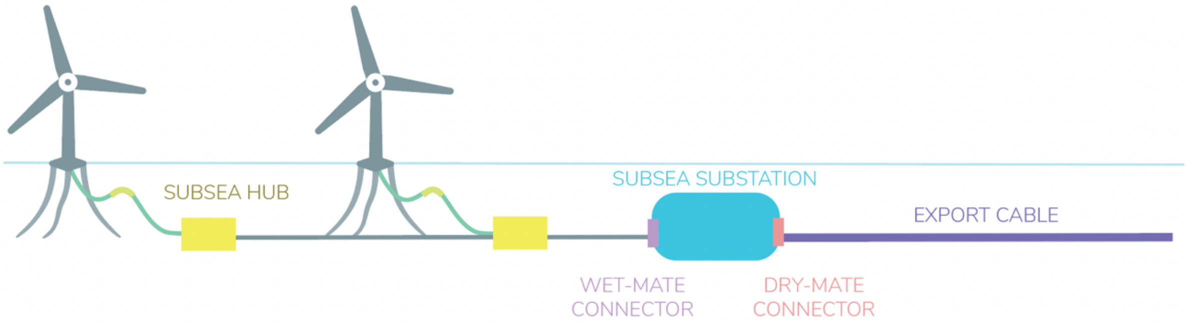

Figure 16. Example floating wind configuration using subsea connectors and substation. Source: WFO, information from Siemens Subsea.

Suppliers of connectors (who are cable manufacturers and specialised companies with experience in the oil & gas or offshore wind fields) are working to qualify high-voltage wet-mate connectors (72 kV) but are in early development. However, it is still not quite clear what connection solutions are required for the commercial scale environment. It is important to note that connectors create additional points of failure to the system.

Finally, the connection scenarios described above are planned. A connector can also be used in an unexpected scenario, say during a mooring line failure, to free the cable from the floater and prevent further damage. This is known as emergency disconnection. Depending on the unlatching mechanism, the end of the dynamic inter-array cable and the accessories could require replacement. These break away systems are likewise not field-proven and further work is required.

4.1.2 Dynamic bend stiffeners

The purpose of a dynamic bend stiffener (DBS) is to add stiffness to the cable at the termination point, hence limiting curvature and bending stresses which improves the fatigue life of the cable. In floating wind, DBSs will be used at the floater. A 2021 study demonstrated positive effects of using a DBS on a 66 kV dynamic inter-array cable.[59] However, bend stiffeners are the most likely to impact the probability of the dynamic cable itself to fail in terms of how well it is designed, manufactured, or installed.[60]

There remain outstanding questions regarding the use of bend stiffeners in floating wind: concerns on temperature, the target size for a DBS (for inter-array and export cables) and connectivity are difficult to clarify given the different floater concepts competing in the market

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[59] *Hellenic Cables, CRP Subsea, University of Exeter participation in the MaRINET2 research programme (Cables & Floating Substations Subcommittee November 2022). The cable with DBS was on average 72.5% stiffer than the bare cable sample on the last cycle of loads. The cable with DBS maintained the bending moment more steadily for the duration of the fatigue testing vs. cable with no DBS.*

[60] *Dynamic cable failure rates, Carbon Trust Floating Wind JIP Phase V Summary Report.*

and ongoing development of high-voltage dynamic cables. In addition, the limited number of projects to draw empirical data leaves suppliers uncertain of DBS requirements.

High temperature at the cable inside the bend stiffener due to the latter's low material thermal conductivity (polyurethane) has been an issue in the oil & gas sector. The onset of floating wind has increased interest in addressing this problem, especially given the impact of higher temperatures on the electrical cables.[61] One bend stiffener manufacturer investigated a passive cooling solution that allows for water to flow through an insert made at the bend stiffener. A natural convection phenomenon lets the heated water escape through the insert, thereby lowering the temperature at the bend stiffener and cable inside of it.[62]

4.1.3 Buoyancy and ballast modules

Buoyancy and ballast modules hold the dynamic cable in its designed shape to reduce cable fatigue. Buoyancy modules are attached to points of the subsea cable to provide uplift, which reduces tension in the cables and maintains a wave configuration that decouples the floater motion from subsea connection. Suppliers of buoyancy modules in the bottom-fixed wind and oil & gas industries are developing products for floating wind dynamic cables. In these new iterations, they are improving bending protection in the design as well as clamping mechanism, thermal insulation, installation method, manufacturing process and recyclability.[63]

4.1.4 Monitoring solutions

Inspection frequency is a significant challenge in subsea risk integrity management. Inspection of a given sample of cables at fixed time intervals may not represent an optimal management of inspection costs versus mitigating failure risks. Class societies provide guidance on inspection frequency, but the offshore industry (oil & gas and renewables) is moving towards a risk-based strategy that compares the value of inspections versus their cost and the risks they are accounting for. Condition monitoring enables the project to collect data at a distance and inform risk mitigation measures like further inspection, marine growth removal or pre-emptive repair. A holistic consideration of condition monitoring and inspection strategies in combination can assist in optimising both inspection and monitoring costs throughout the life of the asset, while maintaining adequate levels of risk mitigation.

Distributed fibre optic solutions can infer the mechanical (strain, bending, heating, pollutants) and electrical (transience, harmonics) stress factors on the cable through measurements of the optical fibre. Solutions include:

DAS - Distributed Acoustic Sensing
DTS - Distributed Temperature Sensing

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[61] *Oil & gas risers are most of the time insulated, so the flexible outer-skin temperature where the DBS is is not so high. There is no such insulation for floating wind cables, and the insulation effect of the DBS polyurethane can increase the local temperature of the outer sheath of the cable. This is a problem for the PU itself and outer sheath of the cable (Cables & Floating Substations Subcommittee November 2022).*

[62] *Solution by EXSTO (Cables & Floating Substations Subcommittee October 2023).*

[63] *Cables & Floating Substations Subcommittee November 2023.*

DSS - Distributed Strain Sensing

Distributed fibre optic sensing does not require active sensors along the cable route. A device at one end of the cable pulses a laser through the fibre and the reflected light gives information on bending, amplitude, movement and frequency of the optical fibre.[64] While the number and placement of hardware depend on the wind farm configuration, the main benefit of fibre optic solutions is that one interrogator can be used to monitor the cables of multiple FOWTs.[65] However, there are limitations on how much cable length is covered by one device (50km-125km). In addition, the splicing of fibre optics can cause optical loss, which is why it can be beneficial to reduce the number of connectors along the cable.

Condition monitoring of the cable generates a lot of data that has to be properly filtered and analysed. Given the dynamic nature of the cables, it will be important for the operators to differentiate data points to properly quantify the cable design life. For example, certain sounds coming from the cable may be a normal part of operation and not necessarily signal an abnormality.[66]

There are other options to monitor the integrity of the cable such as accelerometers & gyroscopic rate sensors, ROV or AUV fly-by with camera and sonar detection methods. Monitoring of cable accessories can be done with sensors on the equipment.[67] This in addition to weather station data can help the project validate models against real-life conditions, creating digital twins to help identify issues and fatigue over the wind farm's life.

While the project would increase its CAPEX to incorporate various monitoring systems, the operational visibility gained is intended to improve the OPEX. A solution to reduce equipment cost could be to monitor only a few individual units within a system as indicators of the overall system health. In pursuing such an approach, the choice of selected analyses to represent the whole wind farm would have to be justified to insurers and classification societies. The potential OPEX reduction thanks to the flexibility gained for inspection/repair activities is theoretically sound; however, it is still uncertain as to how immediate fault intervention is guaranteed following a data report.

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[64] *The movement of the individual fibre does not perfectly correlate with the strain experienced by the whole cable. The specification of the fibre impacts this relationship: tight-buffered fibres that are mechanically connected to the cable improve the strain correlation, but these are only being researched at the moment. All commercially available fibres are loose-tube (Cables & Floating Substations Subcommittee November 2022).*

[65] *The DAS is placed on an end-turbine and a loop is installed on the next turbine so that the DAS can connect to the other cable and so on. For large wind farms, the DAS could be placed on the substation to monitor all the inter-array cables (Cables & Floating Substations Subcommittee November 2022).*

[66] *The BOPTIC project installed a DAS system on WindFloat Atlantic to identify strain variations along the cable route. The results will help validate cable design criteria and distinguish normal versus unexpected strain. Wave is the primary driver of cable movement, with higher strain observed at the points of fixation: hang-off, buoyancy modules, touchdown (Marlinks presentation at the Sirris Wind Energy Technology Summit in Ostend, 12 September 2023).*

[67] *Examples of buoyancy module monitoring presented in Moorings Subcommittee October 2023; Cables & Floating Substation Subcommittee November 2023.*

4.2 Holistic engineering for floating wind cables

It is natural to assume that failures in floating offshore wind will occur due to the use of new technologies and their production methods. As such, projects have to plan for failure. A few project management philosophies have been studied in the FOWC meetings to achieve lower probability of failure as well as lower downtime in case of failure. These processes underline the need for a holistic engineering approach, i.e. one that designs the system by considering its multiple parts together as well as the whole project life.

The first is **Mooring Integrity Management (MIM),** which is a process for ensuring a mooring's fitness-for-service over its entire life cycle. MIM programmes categorise risks based on their likelihood and severity, which then guide the use of inspection and monitoring to detect abnormal conditions or factors outside the original design envelope. Should an issue arise, intervention and repair procedures are enacted to protect the mooring system against accident or loss. Given the dynamic cable's dependence on the mooring systems' performance, i.e. the floater excursions it can work within and the impacts of pre-stretching, storm events and offsets etc., MIM can support the conceptual layout needs of the cable in the design phase.

Monitoring for predictive maintenance also invites a holistic engineering approach, where different parts of the FOW system are monitored and modelled based on their relevance to key failure modes, creating a systems-level digital twin. In simplified terms, a digital twin is a virtual representation of a real-world asset (in this case a FOWT or the wind farm). Modelling digital twins can enable operators to detect anomalies on time and plan necessary inspection or maintenance activities around favourable weather conditions. Some challenges with developing digital twins include understanding which parts of the system would benefit most from condition monitoring, managing huge amounts of data and sharing it between multiple parties, and finally evaluating the monitoring system itself.[68] Additionally, operators will have to assess whether they can make use of insurance claims for pre-emptive repairs when failures may not have yet actualised as defined in the insurance coverage clauses.

Lastly, in planning for failure, a **spare parts strategy** is important to mobilise replacement components quickly and minimise downtime. For cables, the decision to repair is often at odds with the option to replace because a repair is a longer, more demanding operation (i.e. a replacement can be plugged in more easily thanks to the presence of connectors). The cable connection technology impacts the cable spare parts exchange. It also impacts the feasibility of tow-to-port. In procuring spare parts, there is the question of what is economically feasible to have spares of: connectors? full length cables? The availability of the spares prior to construction is a question: would the project want them ready right at installation? Should they be handled directly by the installation contractor or the operational team (if separated)? The decision ultimately depends on the size and set-up of the project; for example, portfolio companies could create standardised parts to support multiple wind farms and have them available right from the installation phase.

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[68] O&M Subcommittee December 2023 with presentation on DNV RP-A204: Assurance of Digital Twins

5 Conclusion

Having captured the major floating wind cable risks and mitigation measures, this White Paper aims to promote best practices and guide developers in building their projects. Suppliers and research institutions can also take from the industry trends presented to adapt their strategies.

In summary, the following priorities characterise the industry's efforts to establish floating wind high-voltage dynamic cable technology:

1. The need to develop dynamic export cable standards – so that designs can function in a dynamic environment while preventing water ingress (a bigger issue for higher voltages).
2. The need to develop wet connector technology – this can help streamline floater hook-up and replacement as well as allow for different cable global layouts.
3. The need for a holistic engineering approach – in other words integrating design between the turbine, floater, mooring system and cable as well as mastering the complex installation procedure & maintenance strategy. Quality environmental data is crucial to this process.
4. The need for integrity management philosophy right from the design phase – so that common failure modes (of the cable but also mooring system) that affect power export/all FOWTs are avoided. Inspection & monitoring for predictive maintenance can help minimise failure occurrence and downtime in case of failure.

Cable manufacturers are progressing through their cable qualification timelines for both bottom-fixed and floating offshore wind. At the same time, industry projects are working to align these testing and qualification methods, identify floating wind-specific load cases for the cables themselves and their accessories, and ultimately update related standards. Data sharing between industry players is key to speed up the application of lessons learned.

Finally, project contracting models must prioritise other aspects in addition to reducing LCOE, e.g. by encouraging early (and if possible region-centric) supply chain commitments, prioritising safety, following design criteria and industry best practices, and reducing environmental impact. The Floating Offshore Wind Committee continues to explore these topics to keep the industry at pace with its technology developments as they evolve in their commercial contexts, i.e. go-to-market strategies, insurability perspectives, supply chain limitations, government regulation…

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