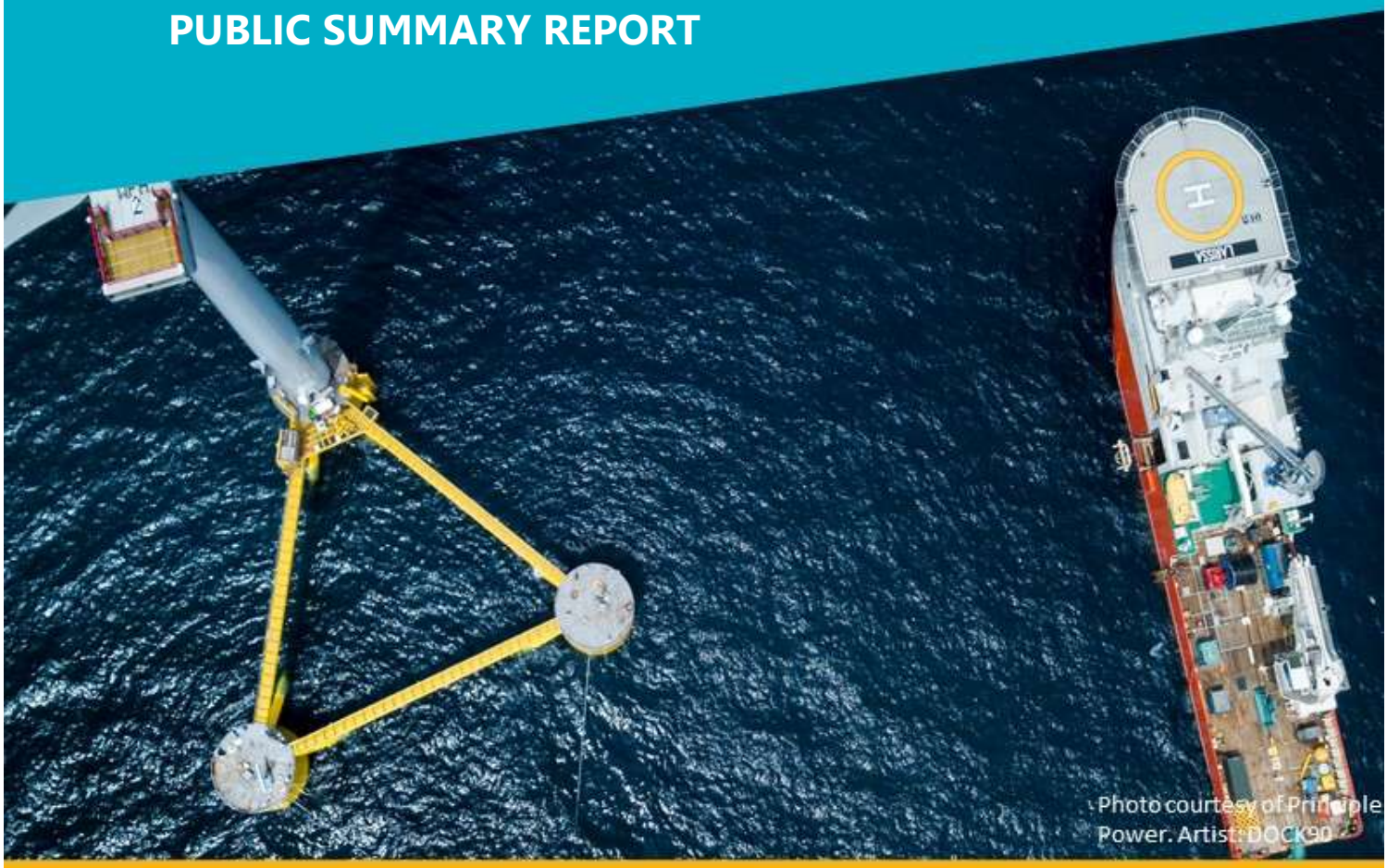
FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

DYNAMIC CABLE INSTALLATION RISKS AND FAILURE MITIGATION

PUBLIC SUMMARY REPORT



Author: Sonny Cain and Vivien Maertens

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EXECUTIVE SUMMARY

This report builds on the findings from Work Packages (WPs) 2 and 3 of the 'Dynamic Cable Installation Risks and Failure Mitigation' project and its Work Package 4 'Installation Risk Assessment & FMECA'. This work extends the assessment of offshore wind installation risks by incorporating direct stakeholder feedback, industry validation and a structured review of lessons learned. The objective is to determine how previous findings align with current industry experience, identify the most effective risk mitigation opportunities, and prioritise actions that can deliver tangible improvements across future projects.

The stakeholder engagement confirmed that many of the key installation risks identified in WPs 2 and 3 remain significant challenges within the offshore wind sector. Recurring themes include supply chain constraints, vessel and resource availability, interface management, weather-related delays, and operational inefficiencies during marine installation activities. Industry feedback also demonstrated that several WPs 2, 3 and 4 outputs are directly actionable, providing a strong foundation for targeted risk reduction strategies.

The analysis highlighted significant opportunities to improve both supply chain performance and marine operations through enhanced planning, greater standardisation, improved communication across project interfaces, and earlier integration of installation considerations within project development. Lessons learned from industry stakeholders further reinforced the need for proactive risk management approaches that address root causes rather than project-specific symptoms.

A prioritisation exercise was undertaken to identify the opportunities most likely to deliver meaningful reductions in installation risk. High-impact opportunities are concentrated within supply chain optimisation, improved logistics coordination, better visibility of resource availability, and the adoption of more efficient marine operational procedures. These areas offer the greatest potential for reducing delays, improving project certainty and enhancing overall installation performance.

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- Axis Capital
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- Tadek Ocean Engineering
- Windstaller Alliance
- ORE Catapult would also in particular like to thank Malcolm Bowie of First Energy Development Ltd, who was contracted as an advisor to the project and supported a number of different work packages, including the FMECA.

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NOMENCLATURE

API	American Petroleum Institute
BOW	Bottom-fixed Offshore Wind
CAM	Condition Appropriate Mode
CPS	Connection and Pull-In System
DC	Dynamic Cable
DCI	Dynamic Cable Interface
DP	Dynamic Positioning
DSS	Distributed Strain Sensing
DTS	Distributed Temperature Sensing
FAT	Factory Acceptance Test
FMECA	Failure Mode, Effects and Criticality Analysis
FOWT	Floating Offshore Wind Turbine
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HLS	Horizontal Lay System
HV	High Voltage
ITP	Inspection and Testing Plan
IVB	Independent Verification Body
MBR	Minimum Bend Radius
NCR	Non-Conformance Report
OEM	Original Equipment Manufacturer
O&G	Oil and Gas

ORE	Offshore Renewable Energy
OSS	Offshore Substation
OTDR	Optical Time-Domain Reflectometry
RDS	Reel Drive System
ROV	Remotely Operated Vehicle
RPN	Risk Priority Number
SAT	Site Acceptance Test
SC	Static Cable
SIMOPS	Simultaneous Operations
SIT	System Integration Testing
SWL	Safe Working Load
TAM	Task Appropriate Mode
TRL	Technology Readiness Level
VLS	Vertical Lay System
W2W	Walk-to-Work
WTG	Wind Turbine Generator

1 INTRODUCTION

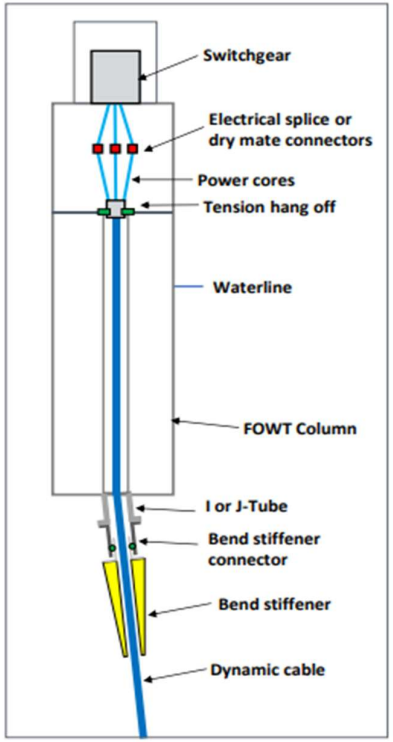
1.1 Overview of Dynamic Cable Systems

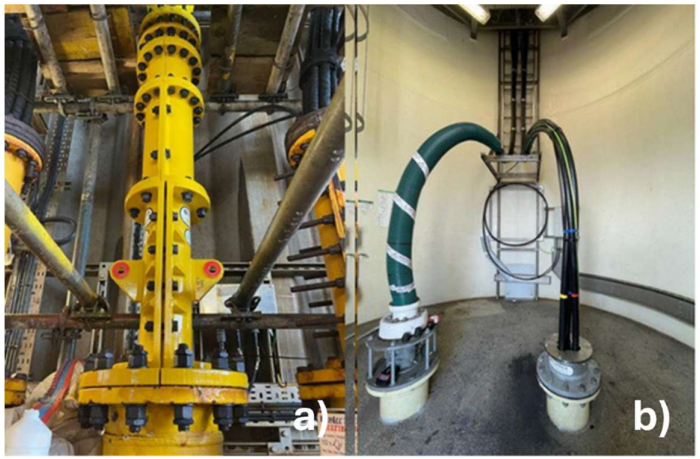
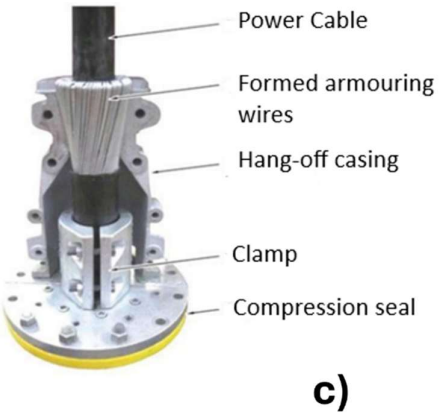
Dynamic array and export cables are among the most technically challenging components of floating offshore wind (FOW), as they must accommodate continuous floater motions, environmental loading and complex interfaces with moorings and ancillary components. Their design, installation and integrity management are therefore critical to commercial-scale deployment.

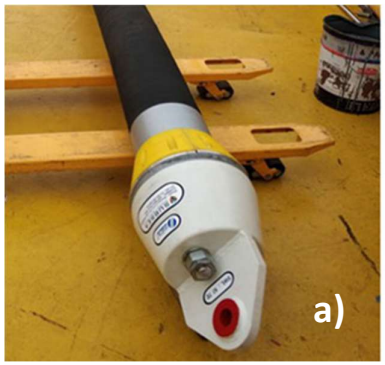
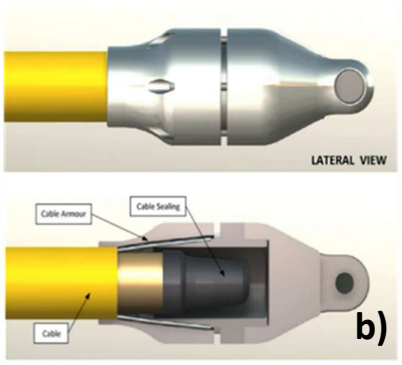
- **Dynamic cable systems** differ significantly from static subsea cables, being heavier, stiffer and more susceptible to damage during handling and installation. Floater entry points are particularly sensitive to overbending, kinking and misalignment.
- **Ancillary components**, including buoyancy modules, bend stiffeners and clamps, represent recurring sources of failure, alongside issues such as sheath abrasion and procedural errors.
- **Installation** commonly uses reels, carousels, Vertical Lay Systems (VLS), Horizontal Lay Systems (HLS) and Reel Drive Systems (RDS). Onshore pre-termination is generally preferred to reduce offshore complexity and improve schedule certainty, although mobilisation, deck handling and subsea pull-ins remain risk-intensive.
- **Installation risks** are strongly influenced by weather, vessel motions, equipment capability and crew competence, requiring rigorous qualification and effective interface management.
- **Integrity management** remains relatively fragmented, typically relying on ROV inspections and discrete tension or angle measurements. Fibre-optic sensing, digital twins and AI-based fatigue prediction offer potential for more predictive approaches, but full-length integrated monitoring is not yet mature.
- **Standards and guidance** remain a significant gap. Oil & gas experience provides a valuable foundation, but existing frameworks are not always well suited to floating wind. Stakeholders highlighted opportunities for greater harmonisation of connectors, bend-radius requirements, emergency-release procedures and fatigue monitoring, while avoiding excessive standardisation.
- **Commercial deployment** will require continued innovation in cable and ancillary-component design, robust qualification and testing, improved installation practices, early supply-chain collaboration and progressive standardisation. Lessons from demonstrators and test sites should be systematically captured to improve reliability, insurability and scalability.

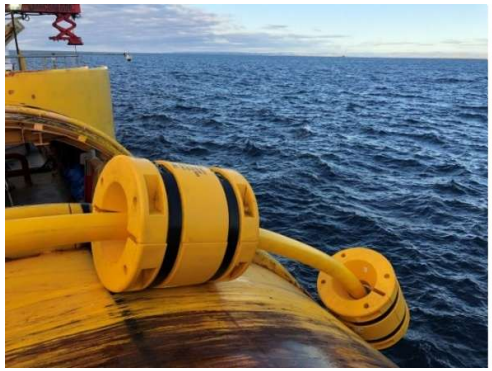
1.1.1 Interfaces and Ancillary Components

The interfaces and ancillary components of dynamic cable systems are particularly relevant to installation risk, as they govern how the cable is connected, supported, guided and protected during installation and operation. Components such as connectors, hang-off systems, bend stiffeners, buoyancy modules and I/J-tubes introduce additional handling, alignment and installation requirements and can create critical interfaces between the cable, floater and other offshore systems. Failures or damage to these components can have significant consequences for cable integrity and installation schedules. This section therefore focuses on the components and interfaces that have the greatest influence on installation methods, risks and practical execution.

Interface		Summary
Connectors		Connectors serve as the interface between dynamic cables and offshore electrical infrastructure, such as substations or floating platforms. They facilitate the connection and disconnection of power and signal transmission lines, ensuring reliable electrical and data communication.

I/J Tubes	 	I/J cable tubes provide protective enclosures for sections of the dynamic cable, particularly at transition points where they connect to other structures or equipment. These tubes shield the cables from external forces and environmental conditions. Typically, their dimensions range from two to three times the diameter of the dynamic cable. FOW application demonstrations of (left) I-tube and (right) J-tube.
Hang-Offs	 	Hang-offs secure and support dynamic cables as they are suspended from fixed or floating structures like platforms or vessels. They are essential for managing cable strain and maintaining stability under varying conditions. These assemblies typically include multiple components, a collar grips the cable's exterior, while the armour wires are separated and anchored to a flanged assembly. a) Hang-off for Oil and Gas (O&G) riser; b) Hang-off within a fixed Wind Turbine Generator (WTG); c) Hang-off with armouring termination

Pull-in Heads	  	Pull-in heads assist in drawing dynamic cables into position during installation, guiding them safely from the offshore location to the termination points. They are typically sized based on tensile load requirements, with one standard size expected to suit most projects. However, in deep-water applications, variations may be necessary due to increased tensile loads associated with longer cable lengths. Pull-in head examples of a) Subsea Energy Solutions; b) PCS Italiana; c) Power CSL.
Bend Stiffeners	 	Bend stiffeners control the cable's curvature by reinforcing connection points. Made from polyurethane elastomers, they offer high elongation at break, corrosion resistance, and a lightweight structure. Each bend stiffener is custom-designed to protect the cable's MBR. In deep-water applications, they must be significantly larger to accommodate the increased cable length. Bend stiffener examples of (left) SURF Standard DBS and (right) SURF split DBS

Buoyancy Modules	 	Buoyancy modules help maintain neutral or positive buoyancy for dynamic cables, preventing excessive tension and stress while ensuring stability in marine environments. Their size increases significantly in deep-water applications due to the additional cable weight. Buoyancy module examples of (left) CRP Subsea and (right) Balmoral.
Ballast Modules	  	Ballast modules provide controlled negative buoyancy to stabilise cables and ensure proper submersion. They counteract the positive buoyancy of both the cable and buoyancy modules, helping to maintain positioning. Like buoyancy modules, their size increases in deep-water applications to handle the added cable weight and mitigate the effects of marine growth. Ballast module examples of (left) CRP Subsea [1] and (middle and right) Subsea Energy Solutions [2]

1.1.2 Failure Mode Identification for Dynamic Cables

Figure 1 summarises the number of identified failure causes for each cable component, grouped by risk rating. The Bend Stiffener accounts for the largest number of distinct failure causes overall, including one High-rated item alongside six rated Medium. Connectors have fewer identified failure causes but both are rated High risk, the only component where every failure cause falls into the highest risk category. Buoyancy Modules and Ballast Modules present fewer identified failure causes by comparison, rated Medium and Low respectively.

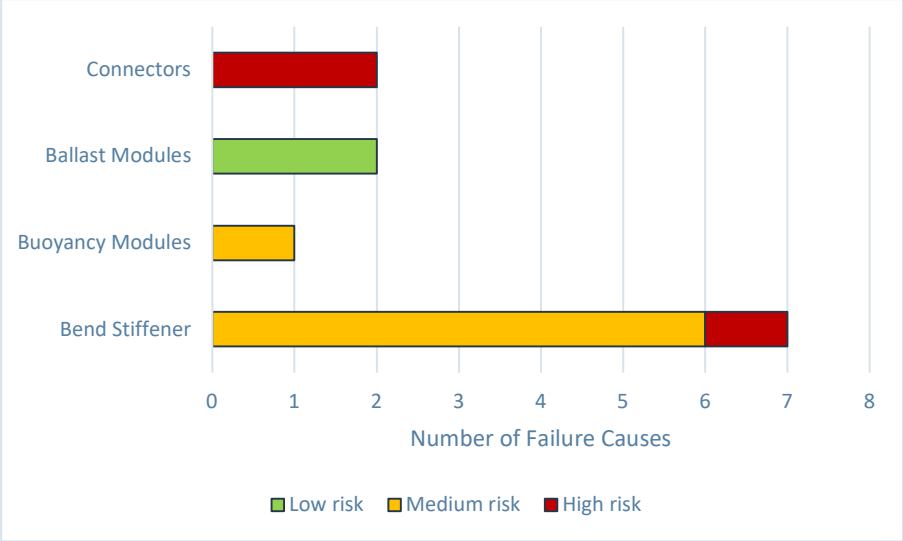


Figure 1 Failure modes per component

This distribution suggests risk is concentrated in two areas: the Bend Stiffener, by volume of identified failure causes, and Connectors, by risk severity. Both warrant closer design and fatigue review attention relative to the buoyancy and ballast systems.

2 OVERVIEW OF INSTALLATION EQUIPMENT AND TECHNIQUES

2.1 Installation Equipment

2.1.1 Storage and Handling

Reels

Reels are cylindrical structures used to wind and store lengths of cable, offering a compact and controlled means of managing cable spools during transport and installation. They are typically used for shorter cable lengths and allow some tension control during laying operations, since a back tension must be provided to guard against slack wraps.

Reels are generally more suitable for projects involving lower overall cable weights and volumes due to their limited storage capacity. They offer greater mobility and are easier to integrate on smaller vessels, making them ideal for shallow-water applications or when handling shorter dynamic cables. However, their capacity constraints can make them less practical for large-scale FOW projects, due to the volume required for the large terminations. Figure 2 shows two different examples of cable reels used in industry.



Figure 2 Two separate reel drive examples by (left) Maritime Developments Limited [24] and (right) Huisman [25]

Carousels

Carousels, by contrast, are large rotating platforms capable of storing and deploying substantial cable volumes. They are better suited to handling longer, heavier dynamic cables such as the long collector cables required for the connection to the substation but equally can store numerous short cables.

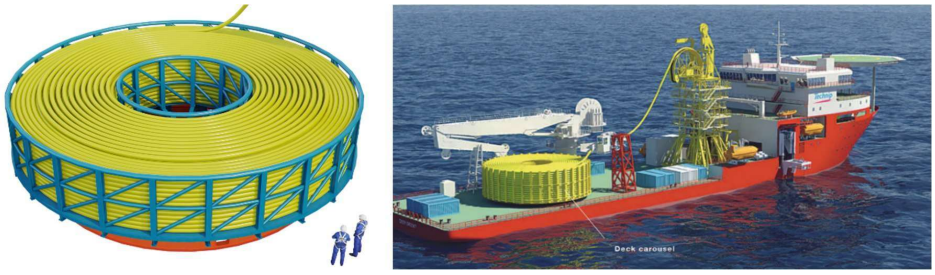


Figure 3 Back-deck cable carousel examples by (left) Maritime Developments Limited [3] and (right) Wartsila [4]

Unlike reels, carousels can manage larger cable diameters and higher overall loads, making them essential for deep-water installations where extended cable lengths are required. Carousels are integrated with tensioners and other cable management equipment to ensure consistent handling and to prevent damage during loading, transport and installation. While they offer greater capacity and are ideal for large-scale deployments, their size requires larger installation vessels and more

complex logistical planning. The choice between reels and carousels depends on factors such as cable length, diameter, project scale, water depth and vessel capacity.

2.1.2 Cable Laying

Equipment Type		Summary
Tensioners		Tensioners are mechanical devices used to apply and maintain controlled tension on the cable during deployment and retrieval. They prevent slack, which can lead to kinks and damage, and ensure that the cable is laid in a controlled manner.
Chutes		Chutes guide the cable from the deck to the subsea environment, ensuring a smooth transition and reducing mechanical stress. They are typically made of materials with low-friction surfaces to minimise abrasion and are designed to accommodate various cable bending radii.
Vertical Lay System (VLS)		In a VLS, the cable is lifted over the top chute, pulled down into a vertical tensioner and deployed. The gap under the tensioner allows buoyancy modules and clamps to be attached to the cable during deployment.
Horizontal Lay System (HLS)		The HLS is a smaller version of the VLS, where the overboarding chute is the last point of contact with the cable. The tensioner is often oriented at an angle of 30 degrees, creating space for the work platform where ancillary equipment can be attached underneath the chute.

2.2 Installation Preparation

2.2.1 Pre-lay Operations

As part of the pre-lay operations, initial site surveys are conducted to identify and map potential obstructions or debris, seabed irregularities and geological conditions. Pre-lay surveys typically use multi-beam echo sounders, side-scan sonar and sub-bottom profilers to gather high-resolution data; Figure 4 shows examples for the former two. Based on survey findings, a pre-lay grapnel run (PLGR) may be performed to clear debris such as fishing gear, abandoned cables and other obstructions from the designated cable route.

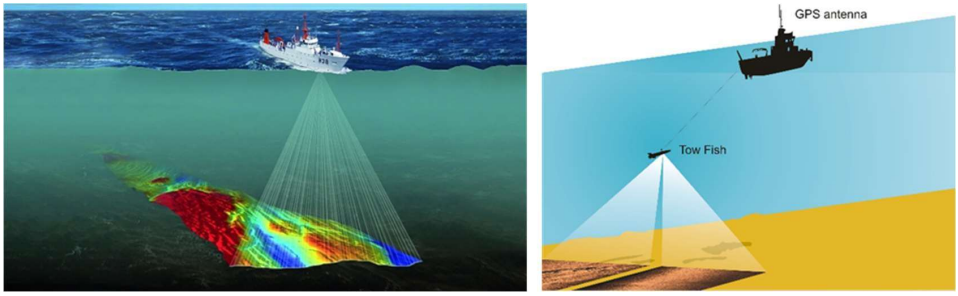


Figure 4 (left) Schematic of multi-beam echo sounder [5]; (right) Side-scan sonar [6]

Once the route is cleared, boulder removal may be carried out using specialised subsea ploughs or ROVs equipped with mechanical grabs. For sections of the route requiring smoothing, trenching or dredging may be employed to create a stable cable bed. In areas where cables must cross existing infrastructure (e.g., pipelines or other cables), protective measures such as mattressing or rock placement are used to prevent damage and maintain allowable clearance.

2.2.2 Transport

Reels are commonly transported using multipurpose cargo vessels, many of which are equipped with heavy-lift cranes for loading and unloading. This makes reel transport relatively flexible and well suited to long-distance transit.

Carousels, due to their size and weight, are less commonly transported. Where required, they are typically skidded onto wide-beam vessels or semi-submersible barges. This operation is more complex and less flexible than reel transport but may be justified when handling very large cable volumes.

2.2.3 Cable Pre-termination

The nature of FOW means that it is critical to get the power and communication between OSS/Shore/adjacent FOWT online as soon as possible, as the warranty and powering of the turbine are on the critical path. Therefore, it is assumed that the power cable will be pre-terminated to minimise the delay plus cost of a vessel alongside for personnel to perform any splicing operation. An example of such pre-termination process is shown in Figure 5.

In addition, due to the criticality of timing, as much preparation as possible will be performed in port to ensure that the pull-in operation, hang-off and connection to the switchgear are performed as soon as possible to minimise the time of a vessel alongside the FOWT.



Figure 5 Dynamic cable pre-terminated for the Provence Grand Large FOW project [7]

2.2.4 Load-out

Load-out marks the final stage of onshore preparation, where the dynamic cable is transferred into the installation vessel's storage system. The choice of port depends on:

- The size and draft of the installation vessel
- Availability of heavy-lift cranes and quayside infrastructure
- Proximity to the manufacturing facility
- Interfaces with the overall offshore schedule

Most dynamic cables are stored in carousels at the manufacturer's site and can be efficiently transferred into vessel-mounted carousels, minimising intermediate handling. However, this requires ports with sufficient quay strength and lifting capacity. Reels, by contrast, provide greater flexibility, as they can be lifted and transported to alternative ports of opportunity. The main constraint is their heavy lift weight, which restricts suitable ports to those with large cranes. Figure 6 shows two examples of cable reel load-outs.



Figure 6 (left) Onshore cable load-out at TechnipFMC's Newcastle facility [8]; (right) Load-out of cable reels onto a cable lay vessel [9]

2.3 Installation Process

2.3.1 Deck Operations

While subsea operations during power cable installation typically focus on vessel positioning, cable tension and maintaining MBR, these parameters are less influenced by vessel selection than deck operations. Factors such as deck layout, crane positioning and reach relative to the overboarding chute, significantly affect handling efficiency and operational safety. Operations involving long terminations, fixing clamps and buoyancy modules are particularly challenging on congested or compact decks, especially where directional changes are required, compared to vessels with open layouts and a straight firing line.

Carousel Pull-Out

Underdeck carousels (Figure 7) are constrained by hatch size, which affects recovery of end terminations, particularly those with long bend stiffeners, with risks including hatch edge contact and MBR exceedance. Lifting is typically carried out by crane, requiring careful control of block swing radius and awareness that the cable can shift across carousel layers during the lift.

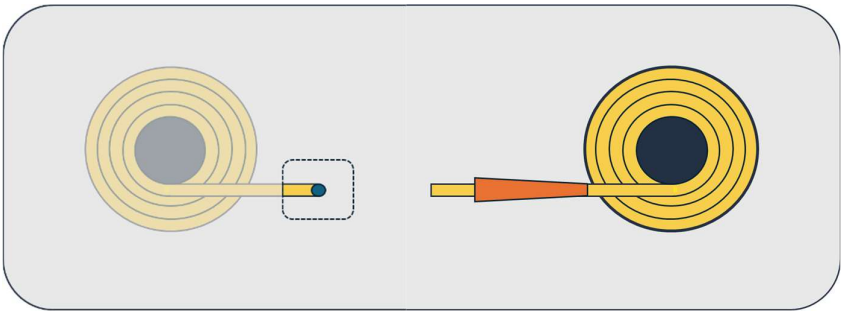


Figure 7 Sketches of a cable pull-out from a cable carousel (left) below-deck and (right) above-deck

Reel Pull-Off

Reels (Figure 8) are usually spooled with the bend stiffener as the final item, so maintaining back tension above the recommended threshold is essential to prevent slack wraps and cable damage. This requires careful coordination between reel payout, winch pull and crane lift, or alternatively, use of a Chinese finger grip to preserve tension while the termination is lifted independently, a method preferred near a diverter chute. Reel fleeting angle also needs consideration during deck layout, as a tight angle can cause misalignment or high localised loads.



Figure 8 Cable being pulled from a reel [10]

Cable Lay System Operations

Initiating the cable into the lay system involves guiding the termination through the tensioner, with careful management of outboard clearance to allow the termination and bend stiffener to pass safely before the tracks close. Handling the second end presents distinct challenges, typically requiring crane or winch support to lift the termination, with accessing equipment at sea subject to formal risk assessment due to the potential for injury.

Crane operations are among the most hazardous activities on board, given the risk of load swing and the need to maintain a near-vertical wire angle throughout lifting. Winch operations carry a related risk: a tensioned line under load poses a significant hazard to personnel and equipment in the event of failure, requiring strict control of load paths and robust operational procedures.

Subsea Lay and Wet Storage

Once a dynamic cable is secured to a floating turbine, it is laid along the seabed toward the next connection point, managing the transition from the dynamic segment to the static seabed section while maintaining minimum bend radius throughout. Pre-lay and wet-storage operations involve ROV-supervised placement of anchors, clump weights and cable terminations, with continuous monitoring of touchdown position and bend radius. Achieving precise positioning of tether bases and terminations, while maintaining bend radius, tension and cable integrity, is a key operational challenge.

Recovery of a wet-stored cable is particularly complex in shallow water, where changes in tension during lifting can cause the seabed-contact section to slide, and cross-haul operations between vessel and platform winches carry meaningful risk of damage due to shallow working angles. These operations typically involve multiple simultaneous activities and require detailed planning, coordination and communication across all parties involved.

Pull-In and Hook-Up

Pull-in operations, whether at the first or second end, are highly sensitive to weather and vessel positioning, with risk of exceeding minimum bend radius present at several stages. The final stages of pull-in carry particular risk around touchdown contact and limited tolerance for misalignment, since platform motion restricts the scope for corrective adjustment.

Personnel are generally required onboard for final hang-off and electrical connection, even where earlier stages can be managed remotely. The transfer of the cable end from the installation vessel into the platform's guide tube is considered the highest-risk stage of the hook-up sequence, being highly sensitive to point loading, buoyancy effects, tether configuration and vessel positioning relative to prevailing wind and wave direction.

2.3.2 Risk Identification

Table 1 summarises the key hazard themes identified across the five phases of dynamic cable installation: storage, mobilisation, deck handling, cable laying, and hook-up. Hazards range from environmental degradation and handling risk during storage, through mechanical and coordination challenges on deck, to the more complex interface, positioning and subsea risks associated with laying and final connection to the floating structure. These themes provide the framework for the more detailed risk assessment set out in the following sections.

Table 1 Installation phase and associated key hazard themes

Installation Phase	Key Hazard Themes
Storage	• Environmental exposure and degradation (UV, weather, moisture ingress) • Handling and storage practice (coiling, support, point loading) • Storage integrity and traceability (reel stability, long-term condition monitoring)
Mobilisation	• Vessel stability and motion
Deck Handling	• Mechanical damage during cable preparation and routing • Dropped objects and load handling on deck • Working at height and restricted access • Coordination of simultaneous operations (SIMOPS)
Cable Laying	• Mechanical loading of the cable (tension, compression, deformation) • Deployment control (payout rate vs. vessel motion) • ROV operations (access, reliability, environmental effects) • Seabed interaction, touchdown monitoring accuracy and SIMOPS coordination
Hook-up	• Cable positioning and termination integrity (pull-in alignment, stiffener arrangement, bend radius) • Structural and mechanical loading at connection points • Subsea operations hazards (ROV and diving) • Personnel transfer, working at height and electrical connection hazards

3 STANDARDS REVIEW

Several established standards and regulatory frameworks govern the installation of submarine power cables, and these have become central references for FOW projects. Many originated in the O&G sector, particularly for subsea umbilicals and flexible pipelines, but the underlying principles of fatigue management, safe handling and lifecycle integrity are directly applicable to dynamic electrical cables.

Different standards bodies and industry groups contribute across the project lifecycle illustrated in Figure 9. American Petroleum Institute (API) specifications and International Organization for Standardization (ISO) standards focus primarily on the design and manufacture of umbilicals and flexible pipe systems, offering transferable requirements for cable strength, fatigue qualification and ancillary components. DNV standards provide a more comprehensive framework, spanning design, installation and operational aspects specific to offshore renewables. CIGRE technical brochures and International Electrotechnical Commission (IEC) standards add further detail on high-voltage testing, electrical qualification, fault detection and long-term monitoring, ensuring that reliability is maintained throughout service life. Supporting offshore execution, International Marine Contractors Association (IMCA) guidance provides recommended practices for vessel operations, lifting and cable handling during installation. Lifting Operations and Lifting Equipment Regulations (LOLER) set legal requirements for safe planning and inspection of lifting activities, while the Provision and Use of Work Equipment Regulations (PUWER) ensure that all equipment used in cable manufacture, testing and installation is suitable, maintained and operated safely.

Together, these frameworks form a structured body of practice that aligns with the major phases of dynamic cable installation, shown schematically in Figure 9. The following sections review the standards most relevant to each phase: Design and specification, manufacture and fabrication, pre-installation testing, installation practices, and monitoring and inspection.

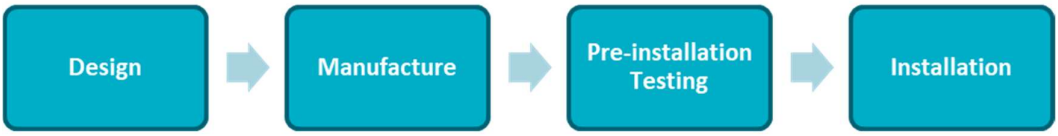


Figure 9 Phases of the dynamic cable installation process

3.1 Technical Standards and Guidance

The review identified 24 standards and regulatory frameworks relevant to subsea cable design, testing and installation, spanning API, ISO, DNV, CIGRE, IEC, IMCA and UK statutory regulations (LOLER, PUWER). These collectively address marine operations, cable handling, bend radius control, ancillary equipment and offshore vessel requirements across five installation phases: design & specification, manufacture & fabrication, pre-installation testing, installation practices, and monitoring & inspection.

Coverage is uneven across phases: most standards address design & specification (the majority of the list applies here), fewer address manufacture & fabrication (API 17L1, IEC 63026, IEC 60840, DNV-ST-0359, CIGRE TB 862), and monitoring & inspection is the thinnest category, covered mainly by DNV-RP-0360, DNV-ST-0359, ISO 13628-5 and CIGRE TB 610. Installation practices draw primarily on DNV-ST-0119, DNV-RP-0360, DNV-ST-0359, CIGRE TB 610/883, LOLER and PUWER.

Table 2 highlights how each of the principal standards relevant to subsea cable design and deployment applies to dynamic power cable installation. Collectively, the standards address key considerations such as marine operations, cable handling, bend radius control, ancillary equipment and offshore vessel requirements.

Table 2 Matrix of identified standards for the dynamic cable installation and their applicability to design & specification; manufacture & fabrication; pre-installation testing; installation practices; and monitoring & inspection

Code	Design & Specification	Manufacture & Fabrication	Pre-Installation Testing	Installation Practices	Monitoring & Inspection
API 17E	*x*				
API 17L1	*x*	*x*			
DNV-RP-F401	*x*		*x*		
DNV-ST-0119	*x*			*x*[1]	
DNV-RP-0360	*x*		*x*	*x*	*x*
DNV-ST-0359	*x*	*x*[1]	*x*	*x*	*x*
IEC 63026	*x*	*x*	*x*		
IEC 60840	*x*	*x*	*x*		
ISO 13628-5	*x*				*x*
CIGRE TB 610	*x*		*x*	*x*[1]	*x*
CIGRE TB 862	*x*	*x*	*x*		
CIGRE TB 883	*x*		*x*	*x*	
LOLER				*x*	
PUWER				*x*	

[1]*Partially covered in the standard*

3.2 Health and Safety

The installation of dynamic submarine power cables in FOW projects presents a unique combination of risks associated with heavy lifting, vessel operations, subsea deployment and rapidly changing environmental conditions. A robust framework of health and safety standards provides the foundation for safe marine operations, supplemented by industry-specific guidance and best practices during installation.

3.3 Regulatory and Standards Framework

Several international and national standards govern health and safety in marine and subsea operations:

- **ISO 45001** [11] provides the overarching occupational health and safety framework, requiring risk assessment, worker participation and continual improvement.
- **PUWER** [12] ensures that all work equipment, including cable lay spread, winches and burial tools, is suitable, maintained and operated by competent personnel.
- **LOLER** [13] sets requirements for lifting operations, including cranes, A-frames and cable deployment equipment. It requires SWL marking, competent supervision and thorough examination by independent inspectors.
- **IMCA R 004** [14] covers ROV classification, tools and safe operating procedures. It applies directly to pre- and post-lay cable surveys, trenching support and touchdown monitoring.
- **IMCA M 220** [15] provides guidance on DP vessel operations through ASOG [16], Condition Appropriate Mode (CAM) and Task Appropriate Mode (TAM). This ensures DP redundancy during high-risk phases such as overboarding and touchdown.
- **DNV-ST-N001** [17] defines marine warranty standards for operations such as cable laying and burial. It mandates risk assessments, contingency planning, monitoring of vessel responses and environmental thresholds.
- **G+ Good Practice Guidelines** [18] address safe personnel transfer offshore, covering gangways, push-on transfers and emergency response, all of which are relevant during mobilisation and offshore operations.
- **G+ Guidance on Manual Handling** [19] highlights ergonomic risks, particularly in spooling, cable handling and deck operations.

Together, these frameworks establish the minimum baseline for safe operations while enabling project developers and contractors to adopt best practice.

3.4 Risk-Specific Safety Measures

3.4.1 Equipment Handling

Dynamic cables and associated ancillaries are heavy and tensioned components requiring careful management. LOLER [13] requires lifting equipment such as cranes, shackles and slings to be certified and periodically examined. PUWER [12] requires winches, tensioners and cable engines to be inspected and maintained. IMCA R 004 [14] provides guidance on the safe and correct usage of ROVs for subsea operations, particularly umbilical and cable handling.

3.4.2 Vessel Operations and Positioning

IMCA M 220 [15] requires cable lay vessels to operate in CAM during critical phases, ensuring station-keeping integrity in the event of a single failure. DNV-ST-N001 [17] requires risk assessments (HAZID, HAZOP, FMECA) and contingency planning for drift-off or power loss. Clear communication protocols and SIMOPS planning are required where multiple vessels operate in proximity [20].

3.4.3 Weather and Environmental Criteria

Cable installation is highly sensitive to sea states, winds and currents. DNV-ST-N001 [17] and IMCA M 220 [15] require weather-restricted operations to be based on metocean forecasts. IMCA R 004 [14] highlights visibility requirements for safe navigation and ROV operations. Table 3 summarises typical operational limits applied in FOW cable installation projects.

Table 3 Environmental Criteria for Dynamic Cable Installation

Parameter	Typical Operational Limit	Application
Significant Wave Height (Hs)	1-2m	Overboarding, touchdown monitoring, burial operations
Wind Speed	10-15m/s	Crane lifts, cable handling, DP station-keeping
Current Velocity	0.5m/s	ROV operations, touchdown monitoring
Visibility	Good visibility, no squalls or fog	Navigation, ROV visuals, personnel transfers
Weather Window	Duration + contingency (site-specific)	Restricted operations and marine warranty approvals
Note: These values represent typical offshore practice. Project-specific limits must be established through detailed metocean assessment, vessel capability studies and equipment specifications.		

3.4.4 Emergency Preparedness

DNV-ST-N001 [17] requires contingency plans for equipment failure, power loss or severe weather interruption. IMCA M 220 [15] requires defined response protocols for degraded DP status, with operations suspended in “yellow” status and terminated in “red”. G+ guidelines [18] require Man Overboard drills and redundancy in transfer systems.

3.5 Gap Analysis

Although existing international and industry standards provide a strong foundation for subsea power cable design, testing and installation, several gaps remain when these are applied specifically to FOW dynamic cables. Standards from IEC, DNV, ISO, API, CIGRE and IMCA together address design, manufacture, testing, marine operations and equipment validation, but their coverage is often adapted from O&G or static cable practice. The key gaps include:

- **Dynamic fatigue qualification:** Most standards specify short- to medium-duration cyclic testing (e.g., 50,000 cycles in DNV-RP-F401 [21]). In contrast, only CIGRE TB 862 [22] prescribes extended full-scale dynamic fatigue trials representative of FOW service conditions. A harmonised requirement for long-duration testing under combined bending, torsion and axial loading is lacking.
- **Fault detection and monitoring:** Current standards reference DTS, DSS, OTDR and ROV inspection (IEC 60840 [23], CIGRE TB 610 [24], CIGRE TB 722 [25], IMCA R 004 [14]) but these methods are derived from static cable practice. Robust, standardised approaches for real-time monitoring and predictive fault detection in dynamic sections are not yet established.

- **Ancillary equipment validation:** API 17L1 [26] defines safety factors for bend stiffeners, buoyancy modules and clamps, adapted from O&G flexible risers. Standards tailored to the geometry, cyclic motion and load profiles of FOW ancillary equipment are absent.
- **Installation and operational practices:** Marine operations standards (DNV-ST-N001 [17], IMCA M 220 [15], IMCA M 264 [27], PUWER [12]/ LOLER [13], DNV-ST-0378 [28]) provide safety frameworks for vessel operations, lifting appliances and handling systems, but do not fully codify the unique requirements of dynamic cable deployment in FOW. These remain treated as guidelines rather than harmonised subsea cable standards.
- **High-voltage dynamic cables:** IEC 63026 [29] covers medium-voltage submarine cables, while IEC 60840 [23] and IEC 62067 [30] extend to high- and extra-high-voltage static applications. No IEC standard currently addresses the qualification of dynamic HV submarine cables (>66 kV), despite their growing importance in FOW projects.

4 FMECA AND RISK ASSESSMENT

A Failure Mode, Effects and Criticality Analysis (FMECA) and a risk assessment were carried out in WP4 of this project, using a methodology that considered both operational and component-related risks, whilst recognising that the majority of risks arise from operational activities rather than purely from design. This approach enabled a detailed criticality analysis, supporting the identification and prioritisation of high-risk components and operations that require greater attention.

The FMECA's risk values range from 1 to 5 (based on severity, with 1 the lowest and 5 the highest risk) for each entry within the various installation phases. Medium risks and above are defined as risk values above 2.5, whereas high risks are defined as risk values above 3.5. Next, the number of risk incidents for each entry of the different installation phases was counted, with a focus on medium and high risks. This count of risk incidents is shown in Figure 10 for each phase of the cable installation process for medium and above risk values (> 2.5).

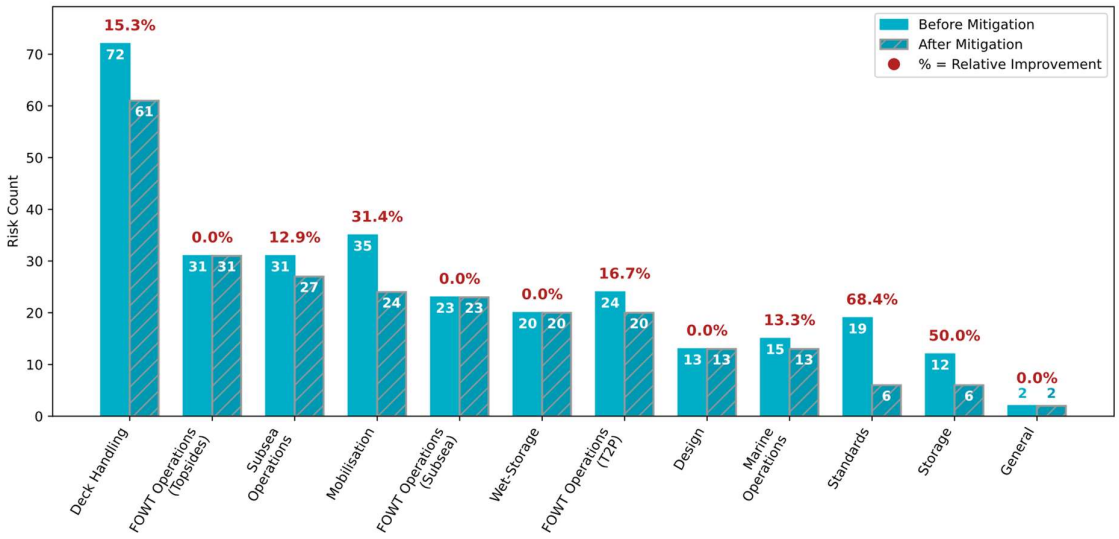


Figure 10: Counts of risk incidents for each phase of the cable installation process for medium and above risk values (risk values > 2.5), comparing the counts of risks before mitigation to afterwards and displaying that corresponding relative improvement

Figure 11 shows the same analysis for high-risk values (> 3.5). Both graphs compare the counts of risk incidents before to after mitigation and display the relative improvement between the two, sorted from highest to lowest count of risk incidents for the after-mitigation installation phases.

After categorising the risks, the next step of the FMECA was to evaluate the criticality of the identified risks to support prioritisation across the various cable installation phases. As existing industry codes and standards do not address all phases with the same level of detail, a criticality assessment helped determine key priorities and the installation phases most exposed to risk. The criticality assessment featured a Risk Priority Number (RPN) to highlight areas where additional work is required to reduce overall risk. The RPN is defined by the equation: Consequences x Probability x Detection. The values for Consequences, Probability and Detection range from 1 to 5 (based on their severities, with 1 the lowest and 5 the highest). The resulting RPNs of above 25 are defined as significant priority phases, whereas RPNs of above 40 are characterised as issues requiring urgent attention. Next, the entries with assigned RPN values during different installation phases were counted, considering only medium (RPN > 25) and high-priority phases (RPN > 40). It is worth noting that this is a subjective assessment, and the threshold for prioritisation may vary between reviewers.

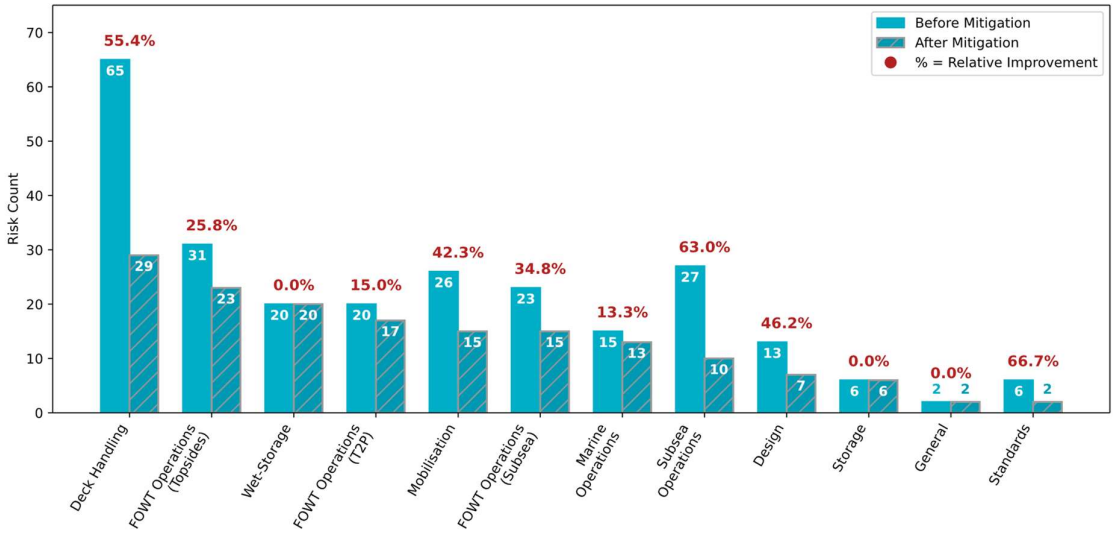


Figure 11: Counts of risk incidents for each phase of the cable installation process for high risk values (risk values > 3.5), comparing the counts of risks before mitigation to afterwards and displaying that corresponding relative improvement

Figure 12 compares the counts of risks which have RPN values for significant priority phases (RPN > 25) and issues requiring urgent attention (RPN > 40), both after risk mitigations have been applied. It also displays the relative difference between the two. The graph is sorted from highest to lowest counts of risks for significant priority phases (RPN > 25) of the after-mitigation installation phases.

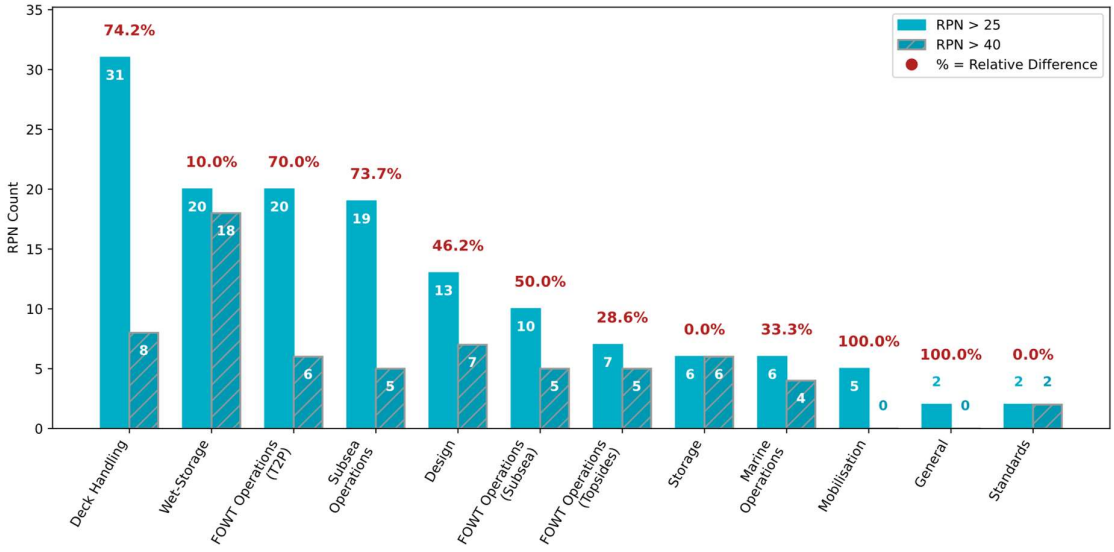


Figure 12: Comparing the counts of risks which have RPN values for each phase of the cable installation process for significant priority phases (RPN values > 25) and issues requiring urgent attention (RPN values > 40) after the risk mitigations have been applied, and the relative difference between the counts of risks occurring with these RPN values

The difficulty of detecting damage on the seabed during or after wet-storage, compared with the straightforward visual inspection possible during deck operations, resulted in higher priority ratings for seabed-related activities. Detection is the critical factor within this RPN calculation, as certain failure modes may be difficult or impossible to identify until the system is fully installed. In such cases, the associated direct or indirect rectification costs can be significantly higher, for example during post-installation cable testing. On the other hand, some failure modes can be identified easily and reliably,

and any required repair or correction can be carried out safely and straightforwardly, such as on a vessel deck or during load-out. Thus, a higher RPN value does not automatically indicate a higher level of risk; it can also reflect the difficulty of detecting or mitigating that risk. As a result, medium-level risks may receive a high RPN if they are challenging to identify or alleviate.

In order to determine what types of mitigations appear most often in the FMECA study and what recurring patterns exist, mitigation types have been identified and reported in Table 4. Mitigation types are defined as conceptual categories, each representing a distinct way in which risks are reduced (e.g., removing design constraints, controlling mechanical loads, reducing human error). These categories are derived through a systematic review of all mitigation statements and grouping actions that have the same underlying risk control mechanism. Each mitigation is assigned to one primary category to avoid double counting and to preserve clarity. The limitation to this approach is that some mitigations could plausibly span multiple categories but are assigned to one for analytical clarity.

Table 4 Mitigation Types with their descriptions, and counts of how often each type of mitigation appears across the full risk matrix from the FMECA study

Cat	Mitigation Type	Description	Count
A	Design-for-Installation / Early Design Integration	Design-stage mitigations integrating installation constraints into engineering design.	18
B	Installation Analysis / Modelling	Mitigations based on analytical or numerical modelling of installation behaviour.	13
C	Procedural Controls & Detailed Work Instructions	Mitigations relying on procedures, sequencing, and work instructions.	42
D	Inspection, Testing & Verification	Mitigations using inspection, testing, monitoring, or verification.	5
E	Manufacturer Guidance / Technical Specification Compliance	Mitigations achieved through compliance with manufacturer specifications.	5
F	Materials Management & Marking / Identification	Mitigations addressing logistics, storage, and component identification.	3
G	Communication & Early Engagement	Mitigations reducing risk through early communication and engagement.	3
H	Operational Planning / Weather, Dynamic Positioning (DP), Lift Planning	Mitigations focused on planning of weather, DP, lifting, and offshore operations.	5
I	Physical Protection / Additional Hardware	Mitigations involving physical protection or additional hardware.	6
J	Standardisation / Industry Guidance	Mitigations addressing gaps or ambiguity in standards or codes.	4
K	Training, Mock-ups, Competency Assurance	Mitigations reducing risk through training, mock-ups, and competency assurance.	2

5 LESSONS LEARNED FROM INSTALLATION EXPERIENCE

This section draws on stakeholder engagement and lessons from the offshore oil and gas sector, particularly the Sureflex Joint Industry Project's flexible pipe integrity database, to capture practical experience relevant to dynamic cable installation for FOW. It covers the full installation sequence: vessel and deck configuration, on-deck handling risks, subsea lay and configuration control, wet storage, pull-in and hang-off to the floating structure, and post-installation monitoring and assurance.

5.1 Vessel and Deck Configuration

Topic	Key findings / implications
Lay system	Vertical Lay System (VLS), preferably midships, is consistently favoured. Maximises the sea states in which installation and recovery can proceed.
Horizontal deck spread	Generally considered a secondary/compromise solution. Overboarding large ancillaries such as buoyancy modules and tether clamps is more difficult due to size, weight and localised point loading.
Cable storage	Vessel carousels can be inefficient for dynamic cables due to end-fitting and packing constraints. Deck-mounted reels are therefore more common.
Deck-mounted reel limitations	Constraints on cable length and weight, deck space and number of vessel transits required.
Tensioner	Cable squeeze/crush limits constrain allowable tension, which consequently limits the total cable-system weight that can be handled. Tensioner pad size, length and orientation can be adapted to the cable product.
Chute	Particularly challenging in deeper water. Low side-wall pressure limits for power cables can require larger chutes and more complex outboard sea-fastening arrangements.
Buoyancy modules	Generally require a moonpool vessel. Large ancillaries need to be positioned close to the installation point.
Cable loading	Significant FOW challenge because array installation is serial: multiple dynamic cables must be loaded, transported and installed sequentially.

5.2 On-Deck Mechanical Risks and Handling

Risk / stage	Main causes / considerations	Key controls / implications
Overbending	Vessel motion, payout deviations, support geometry and rehandling	Control cable geometry, support spacing and tension throughout handling.
Crush / squeeze	Tensioner loading and local contact pressures	Remain within OEM squeeze/crush limits; tensioner configuration may need product-specific adaptation.
Misalignment	Differences between design and actual support/interface geometry	Verify handling arrangements and interface geometry before and during operations.
Torsion / twist	Cable transfer, vessel motion and rehandling	Protect against torsion during reel transfer and subsequent handling.
Point loading	Added weight, local supports and ancillaries	Check local loads against OEM limits.
Anchor clamps / tethers	Excessive tightening loads	Control installation/tightening loads.
Ancillary handling	Transport and pre-installation handling of bend stiffeners and other equipment	Use suitable external protection and packaging.
Most demanding stages	Load-out/transfer, overboarding, touchdown, pull-in and recovery	These stages require particular attention to local bending, tension transients, support spacing and interface geometry.
Recovery / rehandling	Often more severe than initial lay	Requires dedicated planning and analysis rather than simply applying initial-lay procedures.
Installation records	Non-conformances, concessions and deviations	Maintain records and communicate manufacturing issues to the installation team before departure.

5.3 Subsea Lay and Configuration Control

Topic	Key findings / implications
Operational analysis	Detailed lay tables and live analysis support are essential, particularly for hook-up and wet storage.
Step tables	Translate dynamic analysis into instructions for vessel movements, tensioner/winch payout or haul-in, and the limiting factor at each step.
Integrated analysis	Cable behaviour should be assessed together with floater motion, mooring response and environmental conditions, rather than in isolation.

Design-life configuration	Configuration should be designed across the full life. Typically, the hog bend is positioned high in the water column at start of life to prevent sag-bend seabed contact at end of life.
As-installed configuration	Can differ from analysis in departure angle, catenary shape, touchdown location, slack and local curvature at the bell-mouth/bend stiffener.
Vessel heading	Fixed-heading operations are particularly weather-sensitive. Flexibility in vessel heading is preferable to avoid beam seas where possible.
Overbending	Can result from cable hogging between the installation vessel and floating turbine.
Subsea congestion	Potential interference with mooring lines, cables, floater structures, winch wires and ROV tethers.
Current effects	High currents increase entanglement risk and lead angles during cross-hauling.
Weathervaning	Limited vessel heading control near the floater can add procedural complexity.
Wet storage	Considered by some stakeholders to be the least understood FOW installation phase. Oil & gas lazy-wave umbilical experience is relevant, but shallower FOW water depths introduce additional challenges.
Near-miss / damage response	Potential measures include lower weather/lay-speed limits, additional hold points, revised support spacing or handling routes, and increased monitoring. Events should trigger re-validation of installation assumptions.

5.4 Pull-In, Hang-Off and Integration with Floaters

Topic	Key findings / implications
Pull-in	First- and second-end connections can be reliably engineered with adequate vessel-specific analysis and contingency planning.
Analysis requirements	Required analysis may exceed what many current offshore wind cable contractors typically provide.
Governing motion	Pull-in tends to be governed more by floating turbine motion than installation vessel motion.
Weather window	Once pull-in starts, time pressure increases the risk of exceeding design loads if operating near weather limits.
Lazy-wave configuration	Can help decouple installation vessel motion from the cable end during pull-in.
I/J-tube entry	Snagging before bend-stiffener connection is a recognised risk. Mitigations include vessel stand-off adjustment, sufficient bellmouth flare, adjustable floater inclination.

Bend-stiffener alignment	Identified by some stakeholders as the single biggest installation risk. Strongly dependent on ancillary qualification and system integration testing.
Interface locations	Bend stiffeners, bell-mouths, clamps and handling/support points are key risk locations where design-to-as-installed mismatches can occur.
Pull-in winch	Critical equipment. Requires fail-safe operation, multiple speeds, over-pull capacity and continuous tension recording.
Evidence package	Typically includes approved procedures/RAs, ITPs, calibration records, monitoring logs, progress reports and post-installation surveys.

5.5 Monitoring, Data and Assurance

Parameter / activity	Monitoring / assurance approach
Vessel position & speed	Continuous vessel monitoring.
Cable tension	Monitor at both vessel tensioner and floater winch.
Catenary / departure angle	Monitor cable geometry during installation.
Payout speed	Monitor against planned operating limits.
Touchdown location	Key indicator of expected cable geometry and tension.
Chute angle	Useful indicator of cable curvature and loading.
Cable exit angle	Monitor to identify deviations from expected configuration.
ROV monitoring	Provides visual confirmation of subsea configuration and potential interference.
Tensioner feedback	Considered one of the most reliable indicators of developing tension and geometry.
Insurance / warranty	Surveyor approval is generally based on the reviewed installation method. SAT logs or IVB reports may additionally be requested where project certification applies, but are generally not conditions of insurance cover.

5.6 Transferable Lessons from Other Industries

Topic	Key findings / implications for FOW
Oil & gas experience	Provides a useful starting point for FOW installation practice, but cannot be transferred directly in all cases.
Standards / frameworks	Relevant references include ABS subsea power cable and floating wind rules, CIGRE TB 862, the FOW CoE dynamic cable technology qualification framework and API specifications underpinning the Sureflex JIP.
FOW-specific interfaces	Termination methods and connectors specific to dynamic power cables remain areas requiring further definition.
Buoyancy module damage	Oil & gas experience with thruster-induced buoyancy-module damage is directly relevant to FOW.
Wet-storage damage	Oil & gas incidents involving mooring lines damaging wet-stored cables during floater hook-up provide relevant lessons for FOW.
Array scale	The larger scale of FOW arrays may increase the likelihood of similar incidents, increasing the importance of protective measures.
Qualification vs installation	Qualification limits need to be translated into procedures, operating limits and monitoring requirements. Qualification alone is insufficient to manage installation risk.
Integrity management	A structured gap analysis is recommended before applying oil & gas integrity-management frameworks, given differences between dynamic power cables and unbonded flexible risers.
Vessel/equipment transferability	Umbilical-installation vessels and equipment from oil & gas may not transfer directly to FOW dynamic cable installation.
Tensioner contact length	Potential challenge for dynamic cables due to generally lower squeeze capacity compared with static cables of similar size.

6 SUPPLY CHAIN DEVELOPMENT OPPORTUNITIES

Building on the lessons captured in previous WPs, subsequent sections map development needs across the DC supply chain, spanning installation contractors, ancillary and equipment suppliers, vessel operators, analysis providers, and developers/insurers, and translate these into a set of prioritised recommendations for the sector.

Development Area	Key Themes
Installation Methods and Procedures	• Cable pre-fabrication and loading efficiency • Installation sequencing and vessel heading flexibility • Cross-industry transfer of installation experience
Testing and Qualification	• Connection and pull-in system qualification • Factory acceptance testing of ancillaries and monitoring systems • Post-installation verification methods
Installation Equipment and Tools	• Lay spread configuration and vessel selection • Deck space and ancillary transport logistics • Interface design at guide tubes and tether connections
Interfaces and Standardisation	• Early contractor involvement in design • Coordination between equipment suppliers, hull vendors and developers • Standardisation of substructure and connection interfaces
Monitoring, Data and Digital Tools	• Gaps in local curvature and transient load measurement • Emerging monitoring technologies (curvature, acoustic emission) • Maturity of real-time monitoring at commercial scale

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