D3.1 Review of the state of the art of dynamic cable system design

INNOSEA / JDR / RAMBOLL / IREC / COBRA / UL DEWI / WINDEUROPE

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0 ABBREVATION LIST

Abbreviation	Description
CA	Consortium Agreement
CFS	Certificate on Financial Statement (audit report)
EC	European Commission
EC - GA	(European Commission)-Grant Agreement
EIB	Exploitation and Innovation Board
EPR	Ethylene Propylene Rubber
EU	European Union
FLS	Fatigue Limit State
FOWT	Floating Offshore Wind Turbine
GAGA	General Assembly / Grant Agreement
GC	Gran Canaria
IAB	International Advisory Board
IPR	Intellectual Property Right
LCOE	Levelized Cost of Energy
LRFD	Load and resistance factor design
PC	Project Coordinator
PMO	Project Management Office
PR	Periodic Report
SLS	Service Limit State
T&I	Transport and Installation
ULS	Ultimate Limit State
WoB	West of Barra
WP	Work package
WTG	Wind turbine generator
XLPE	Cross Linked Polyethylene

1 EXECUTIVE SUMMARY

This document defines the current dynamic cable state of the art for floating wind projects currently installed or being engineered which will ensure specifications and requirements to be developed within the WP3 account for current industry status. This document consists of a comprehensive literature survey, industrial engagement through the strong network of contacts with the COREWIND consortium and collation of findings to deliver a documentary summary report. This report also addresses key challenges, priorities and opportunities for cost optimization through alternative installation practices.

1.1 Cross section

Initial designs are proposed within section 2.4. These have been determined as reasonable for the COREWIND based on participant experience given the little data available publically for review at the time this report has been compiled. Designs may be revised during the subsequent WP3.2 configuration modelling based on evaluations of minimum cable characteristics such as bend stiffness.

Largest opportunity for cost saving is to extrapolate minimum attributes required for ancillaries so that they are tailored to the applications outlined in D1.2 which have been deemed representative of floating windfarm sites by WP1. Standardisation of this hardware across the commercial-scale field should lead to significant cost savings.

Priority for Corewind models is to develop cost-optimised 66kV cable configuration solution and ancillaries for cost benchmark and reduction purposes. Where this is balanced with the mooring line cost optimal solution, it is important to note that as cost associated with the cable are typically less significant than the mooring line, a relaxed mooring line system may in fact lead to greater overall cost savings while absorbing marginally greater cable system costs.

1.2 Dynamic Cable configuration

Dynamic Cable configuration is strongly linked to actual voltage and associated cable cross section, floater excursion / dynamic motions and environmental conditions (particularly marine growth). A set of configurations is defined each having its own advantages and disadvantages thus projects specific constraints will drive the selection.

Currently dynamic cable design is performed independently from station keeping system, further investigation is proposed combined mooring/dynamic cable configuration assessment with goal being to go up to determine the maximum dynamic cable capabilities / cable design requirements to relax mooring design / benefits of relaxed mooring design against less costly cable design / configuration. This task is planned within COREWIND project.

1.3 Installation & Inspection

Installation of Dynamic Power Cables

The installation of dynamic power cables can be separated into two parts which occur one before the other but not in a specific order. Recommended for offshore units with many interarray cables nearby is a “first-end pull-in”-operation. The pull-in operation itself is known from fixed-bottom turbines and consists of the pull-in and the running of the cable towards its destination point, the switchgear. While the rest of the cable is still stored on the CLV (dry-storage) its first end is pulled in and attached on temporary hang-offs on the floater. The CLV lays the cable towards the pre-laid static cable and connects them depending on the kind of transition joint used, on the ship after pull-up or underwater by using a ROV. As the cables are connected the electrical connection takes place on the FOWT by using pluggable dry-connectors for each phase. Depending on logistical and/or technical parameters, the cable may be laid in one piece including the transition joint. The pre-laid cable is wet-stored on the seafloor or attached with buoyance modules to guarantee an easy pick-up process at a later date for the pull-in operation into the floating structure.

Generally, the procedure of the pull-in operation is relatively time intensive and requires valuable space inside the structure. To enable a faster and more efficient connection new technologies are being developed, like the Hybrid Wet Mate Connector [31] which can be seen in Figure 1.3-1.

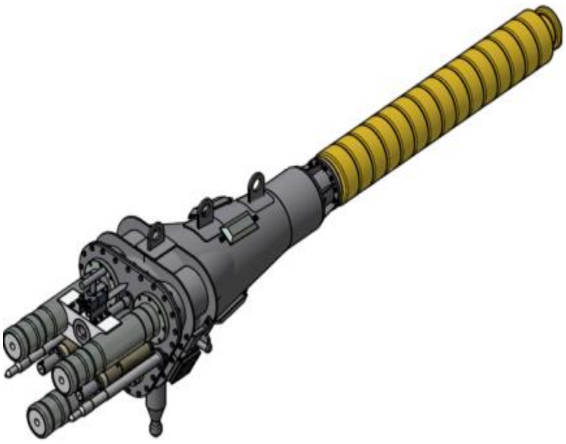


Figure 1.3-1 – MacArtneys 11kV Hybrid Wet Mate Connector Solution, Right: Male Connector, Left: Female and Male connector; Source: [31]

Since its maximum voltage of 11kV is too low, more research has to be done in the field, also to lower the high costs. Generally, this connection type enables an easy connection process. It eliminates the need to pull the dynamic cable into the floater and to run it through the structure. For this pluggable connection a ROV can be used. This shortens the time needed for connection and hereby making it possible to operate in waters with limited time windows. Additionally, the three phases do not have to be connected individually nor separately from the optical fiber cables. For a more detailed review of wet mate connectors, please check [32]. Another possible future innovation comes with self-connecting and disconnecting cables. This would avoid the time intensive connection via the transition joint either on the ship or with a ROV on the seabed [17].

Inspection & Monitoring

As seen in 5.2.2 maintenance work is mainly based on an inspection schedule. After installation, tests and inspections are conducted in an as-laid inspection to record the first condition of the laid cable. It should be kept in mind, that damages occurring during installation are often the direct cause of failure in the later service life. To ensure a long operational life, despite danger through the dynamic environment (review 5.2.3) there are three types of long-term inspections which differ from the trigger of the maintenance work. The most efficient method is the condition-based maintenance, where the condition of the cable is automatically monitored mostly via optical fiber cables in the interstices of the power cable. Through the recorded data, a remaining life time can be estimated, and the offshore repair work can be planned in advance. Common monitoring techniques are the Distributed Temperature Measurement System (DTS), explained in 5.2.5.1, and the Distributed Acoustic Sensing (DAS), covered in 5.2.5.2. If the estimated life time is not in an acceptable range, it is most likely to replace the dynamic cable in its entirety due to its relatively short length.

With advancing information technology, like the Internet of Things (IoT), pervasive networked sensors are becoming more common in manufacturing operation. This will likely happen in the offshore wind sector as well.

Real time monitoring and data recording becomes more accurate, data software will help to detect subtle changes in parameters, so that repair work can be even more accurately scheduled [17]. In section 5.2.4.2, Partial Discharge Measurement was presented as an offline inspection method. Due to the required high-voltage to identify minor damages it is not yet used for continuous monitoring on dynamic cables. But research is aiming for an online PD measurement in the future. Next to PD monitoring, online OTDR monitoring and the related DSS (Distributed Strain Sensing) are promising techniques to monitor the cables condition in the future. For a more detailed view into DSS please check [33]. All these monitoring techniques are being developed or are already in use to measure fatigue on the cable, which is crucial for dynamic power cables.

2 INTRODUCTION

2.1 INTRODUCTION

Floating offshore wind is still a nascent technology and its LCOE is substantially higher than onshore and bottom-fixed offshore wind, and thus requires to be drastically reduced.

The COREWIND project aims to achieve significant cost reductions and enhance performance of floating wind technology through the research and optimization of mooring and anchoring systems and dynamic cables. These enhancements arisen within the project will be validated by means of simulations and experimental testing both in the wave basin tanks and the wind tunnel by taking as reference two concrete-based floater concepts (semi-submersible and spar) supporting large wind turbines (15 MW), installed at water depths greater than 100 m and 200 m for the semi-submersible and spar concept, respectively. Special focus is given to develop and validate innovative solutions to improve installation techniques and operation and maintenance (O&M) activities. They will prove the benefits of concrete structures to substantially reduce the LCOE by at least15% compared to the baseline case of bottom-fixed offshore wind, both in terms of CAPEX and OPEX. Additionally, the project will provide guidelines and best design practices, as well as open data models to accelerate the further development of concrete-based semi-submersible and spar FOWTs, based on findings from innovative cost-effective and reliable solutions for the aforementioned key aspects. It is aimed that the resulting recommendations will facilitate the cost-competitiveness of floating offshore wind energy, reducing risks and uncertainties and contributing to lower LCOE estimates.

COREWIND aims to strength the European Leadership on wind power technology (and specially floating). To do so, the project consortium has been designed to ensure proper collaboration between all stakeholders (users, developers, suppliers, academia, etc.) which is essential to accelerate commercialization of the innovations carried out in the project.

2.2 OBJECTIVE

The purpose of this document is to define the current dynamic cable state of the art for floating wind projects currently installed or being engineered which will ensure specifications and requirements to be developed within the WP3 account for current industry status. This document will consist of a comprehensive literature survey, industrial engagement through the strong network of contacts with the COREWIND consortium and collation of findings to deliver a documentary summary report. This report will also address key challenges, priorities and opportunities for cost optimization through alternative installation practices.

3 DYNAMIC CABLES REVIEW

This chapter details factors which are considered within cable design.

3.1 Cable Cross Section

System installers and operators must work together to identify priorities for windfarm system design which influence cable design and ensure reduced Levelized Cost of Energy. This will include identifying a balance between CAPEX (equipment cost) and the OPEX (operation and maintenance). A cable optimized only for installation may not retain an acceptable power loss across the system during operation.

Important factors for cable design include:

- Function (Energy needed to be transported with minimal losses)
- Survival duration in the environment under loading within the application
- Cost
- Reliability
- Ease of collection, transport, installation and decommission
- Maintenance and Risk Management during operation
- Environmental Impact

3.1.1 Windfarm Application Details for Cable Design

Details on windfarm layout are critical for cable design.

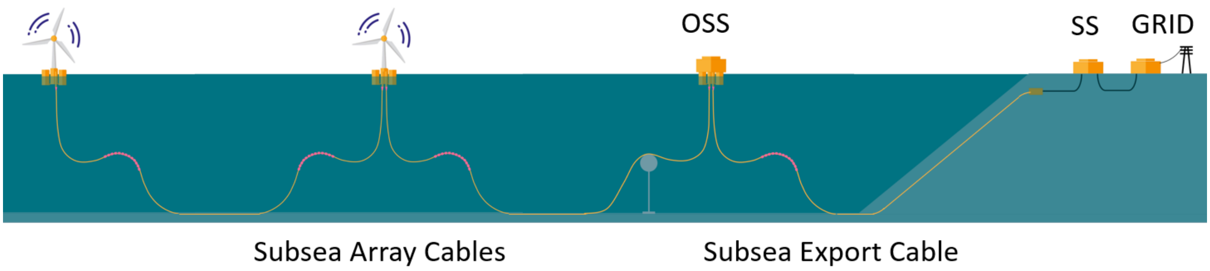


Figure 3.1-1 – Dynamic Windfarm Layout Example

Traditional windfarm layout contains a number of turbines connected by cables which form a 'string' of turbines. In larger windfarms there may be multiple strings. These strings feed into an offshore sub-station (OSS). Cables which run between turbines in a string up to the offshore sub-station are known as array cables. The cable(s) which lead from the offshore substation to land are termed export cables. Typically, the power is then transferred to an onshore sub-station (SS) before it enters the grid.

Energy is generated at each turbine through rotating machinery which forms a 3-phase pattern. The 3 core cable mates with this system (with a voltage step where needed). Alternating current (AC) is used for power transmission across the windfarm. Within a string the cable between wind turbine 1 and 2 has a much lower power transmission requirement (power generated by turbine 1) than the power transmission between turbine 2 and 3 (which is collective power generated by turbine 1 and turbine 2). Although the power transmission required of array cables within a string is not equal, it is often cost effective to have a single array cable design therefore windfarm cables are generally sized to carry the maximum power generation of all turbines joined within the string generating the greatest power.

In larger windfarms backlink array cables can also be fitted to join two neighbouring strings together. In an emergency case where a fault has occurred within the farm which severs the circuit in one string, power from this string may be transmitted through this back-link cable and through the intact neighbouring string. Power transmitted through this backlink is often restricted by the array cable design in the string which has been optimised for normal operation driven by CAPEX reduction initiatives.

Export cables may be the same design as the array cables provided the export length is short and the total windfarm size is relatively small. In large high capacity fields, it is not unusual to have a separate design for the export cable given it is required to transport much greater power than smaller cables within windfarm strings. Retaining an AC 3 core cable design can be beneficial as the OSS size is minimized based on equipment required which results in reduces OSS installation costs. This also means that as the bulk of the equipment will be on the onshore substation, the equipment overall is generally easier to install and maintain which results in lower maintenance costs. Cable length is limited by maximum allowable charging currents (associated with the cable's inherent capacitance) which occur during power transmission. As charging currents are a function of frequency, by reducing the frequency of AC power transmission (often referred to as Low-frequency AC) at the OSS (e.g. 50 Hz down to 12.5 Hz), the export cable can be extended proportionally. Where the distance to the shore is large, it can be more efficient to transmit power using direct current (DC). This results in a single core DC export cable which may be cheaper and easier to install, however the conversion equipment required at the OSS from AC-DC results in the size of the offshore substation becoming much greater which results in higher build and maintenance cost.

To develop a lowest possible cost solution the windfarm cable design needs to be customised for the specific project and site requirements due to the high number of possible variations.

The overall mechanical loading imparted to the cable during installation and operation must be considered. Wind farm location details including layout, operational design life, climate, water movement induced by waves and currents, water depth, marine growth at the end of life, environmental restrictions (e.g. temperature or electromagnetic field), and traffic information all contribute to cable and cable ancillary hardware design.

Routing of the cables is also particularly important to review regarding proximity to heat sources, crossing of cables, and minimum separation distance management to ensure the cable can be used to its full potential. Geotechnical data is often studied to assess the stability of the cable on the seabed and likelihood of buried cables being exposed over the lifetime of the product. Entrances to the offshore structures must be carefully selected to ensure cables are sufficiently protected from over bending or fatigue, and vibrations from structures are acceptable. Consideration should always be given to the resonance of a moving systems.

3.1.2 Cable Electrical Ratings

Cables are electrically classified into different Voltage Designations commonly presented as U_0 / U (U_m).

<table>
<tr><td rowspan="4">Image source: JDR Cable Systems

</td><td>U_0</td><td>Rated R.M.S. Voltage between each conductor and screen</td></tr>
<tr><td>U</td><td>Rated R.M.S. Voltage between any two conductors
$\mathbf{U}=1.73\mathbf{U_0}$</td></tr>
<tr><td>U_m</td><td>Maximum R.M.S. Voltage between any two conductors</td></tr>
<tr><td>R.M.S</td><td>Root Mean Square (equivalent DC Voltage)
=peak/√2 for sine wave</td></tr>
</table>

Table 3.1-1 – Voltage Designation Definitions

U_0	/	U	U_m
0.6	/	1	(1.2)
1.8	/	3	(3.6)
3.6	/	6	(7.2)
6	/	10	(12)
8.7	/	15	(17.5)
12	/	20	(24)
18	/	30-33	(36)
26	/	45-47	(52)

U_0	/	U	U_m
36	/	60-66-69	(72.5)
64	/	110-115	(123)
76	/	132-138	(145)
87	/	150-161	(170)
127	/	220-230	(245)
160	/	275-287	(300)
190	/	330-345	(362)
220	/	380-400	(420)

Table 3.1-2 – Standard Voltage Designations as per IEC 60183 [76]

Worldwide ratings can vary, particularly within American standards, so it is important to check to which standard the cable is designed and qualified to. Voltage rating affects core size chiefly in the increased thickness of insulation required for greater voltages.

It is common to supply a standard voltage rated cable for a specific application. For the purposes of this report we will we will refer to 18 / 30 (36) as common term ‘33 kV’ as nominal system voltage for medium voltage (MV) and we will refer to 36 / 60-69 (72.5) as common term ’66kV’ as nominal system voltage for high voltage (HV).

3.1.3 International Standards for Electrical Cables

Until December 2019, no international standard covered MV subsea power cable design, manufacture and test therefore a combination of MV land cable and HV subsea cable and umbilical standards have been applied throughout the industry.

New Electrical Standard (December 2019)

- **IEC 63026** Submarine Power cables with extruded insulation and their accessories for rated voltages from 6kV (Um = 7.2 kV) up to 60 kV (Um = 72.5 kV) – Test methods and requirements.

Main Electrical Standards

- **IEC 60228** – Conductors of Insulated Cables.
- **IEC 60502-2** – Power cables with extruded insulation and their accessories for rated voltages – Part 2: Cables for rated voltages from 6k V (um=7.2 kV) up to 30 kV (Um = 36 kV).
- **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 61892-4 Edition 2.0 2019-04**: Mobile and fixed offshore units – Electrical installations – Part 4: Cables

Main Optical Standards

- **ITU-T G.652** – Characteristics of a single-mode optical fibre and cable
- **ITU-T G.651.1** – Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network

Additional Standards / Recommendations

- **ISO 13628-5** – Petroleum and natural gas industries — Design and operation of subsea production systems — Part 5: Subsea umbilicals
- **Cigré TB 490** – Recommendations for testing long length submarine cables.
- **Cigré TB 623** – Recommendations for mechanical testing of submarine cables.
- **Cigré TB 722** – Recommendations for additional testing for submarine cables.

Historical Standards / Recommendations

- **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.
- **DNVGL-RP-0360** – Subsea power cables in shallow water
- **DNVGL-RP-F401** – Electrical power cables in subsea applications
- **DNVGL-ST-0359** – Subsea power cables for wind turbines

Adherence to standards is often required to allow comparisons between designs and provide confidence as to suitability. However simple compliance to standards may be insufficient to guarantee reliable operation and strict adherence may inhibit the adoption of new improved technologies. Experts can offer guidance concerning adoption of new technologies and interpretation of standards.

3.1.4 Cable Industry Review

Europe was an early adopter of offshore windfarms, having significant experience in cable design, installation and investment in development, with the United Kingdom and Germany having the largest installed capacities. As the windfarm industry costs have reduced in line with windfarm development, and with the global political shifts towards renewable energy sources, international developments are underway. Recently China has rapidly invested in offshore wind industry and has quickly become a major participant with the 3rd largest installed capacity and is expected to dominate the market in future. In addition, with the progression of floating wind development facilitating deployment into deeper waters, countries with deep coastal areas such as USA, Japan and South Korea are also expanding into the offshore wind industry.

The main cable manufacturers for the Europe offshore wind industry are summarised in the table below. In addition, cable manufacturers world-wide, including those based in Asia, have been developing (e.g. Furukawa, ZTT, Hengtong Group, etc.).

30-66 kV Cable Manufacturers	132 – 220 kV Cable Manufacturers
JDR Cables	NKT Cables
Nexans	ABB Cables
NSW	Nexans
Prysmian (Including Draka)	Prysmian
NKT Cables	NSW
	Hellenic
	LS Cable & System
	JDR Cables

Table 3.1-3 – Main European Cable Manufacturers

Offshore AC transmission for 3 core cables typically lies from 6 kV – 220 kV ratings. Single cores can be supplied to higher ratings but 3 core systems are more useful for windfarms.

For static wind farms, the lower the voltage rating of the cable, the lower the costs of the cables. At the moment 33 and 66 kV cables are well established technology for 3 core ‘wet design’ cables which are used for the majority of wind offshore wind farm cabling. Higher voltages may be employed for export cables (larger cables which transmit the power from the offshore sub-station to land).

As windfarm cables are customised for each solution there was little data available publicly on cable properties which could be reviewed. Core sizes generally range from 75 mm^2 up to 800 mm^2 for up to 66kV cables. Triad export cables can contain larger conductors (e.g. 1200 mm^2) where needed. Single core subsea cables can be found with up to 2500 mm^2 conductors. Large export cable cores may have increased armouring or require additional protection for onshore approaches. All windfarm subsea array cables found contain at least one fibre optic cable. Weights and sizes vary drastically.

Indicative 33 kV static subsea cables have been publicly published by Nexans UK and ABB Ltd. Cables and gathered from JDR Cable Systems. As these values are indicative only, the cable supplied on windfarms will vary when they are customised to each project, however they are all reasonably aligned indicating comparable base cable design methodology within the industry. On this basis JDR will provide indicative 66 kV dynamic cable designs for the COREWIND project as it is assumed to be reasonably representative.

Indicative Cable properties for 33 kV (MV) Triad of Copper Conductor, XLPE insulated, Copper Screen Wire Cores, a Fibre Optic cable, Roved Single Armoured Static Subsea Cables								
Conductor Size (mm^2)	Cable Outer Diameter (mm)				Cable Weight (kg/m)			
	Nexans [49]	**ABB Ltd** [49]	**JDR**	**Average**	**Nexans** **[50]**	**ABB Ltd** [49]	**JDR**	**Average**
70		100.6	95	**98**		18.2	14.2	**16.2**
95	100	104	99	**101**	14.2	19.5	15.8	**16.5**
120	104	107	102	**104**	15.5	20.7	17.1	**17.8**
150	108	110.5	107	**109**	17.3	22.1	18.6	**19.3**
185	111	114	110	**112**	18.6	23.6	20.1	**20.8**
240	116	118.9	115	**117**	21	25.9	22.6	**23.2**
300	121	123.9	121	**122**	23.8	28.2	25.4	**25.8**
400	130	129.9	128	**129**	28.3	32	29.5	**29.9**
500	137	137.3	136	**137**	33.4	36	33.8	**34.4**
630	145	145.1	146	**145**	39.1	40.9	39.5	**39.8**
800	157	154.4	154	**155**	48.9	47.2	45.9	**47.3**

Table 3.1-4 – Comparison of industry indicative 33kV Static Windfarm Cable Designs

3.1.5 Cable Components

Windfarm cables typically contain a triad of electrical cores and at least one fibre optic cable.

Fibre optic cables form the communication network across the field which allows for feedback of data readings at each turbine and OSS governing intervention if needed. Quantity and type(s) of fibres in the optical cable vary significantly depending on communication requirements and redundancy considerations. For windfarm applications it is not unusual for a single cable to contain up to 96 fibres which are a collection of the graded index multi-mode type and single-mode type. Fibre bundles are contained within non-hydroscopic gel inside a steel tube. Due to its small size an additional layer of armour and sheathing may be applied for protective purposes before inclusion inside a wind farm cable. Overall optical cable size generally depends on fibre capacity relative to internal tube size and the sheathing layer Outer Diameter desired. Where possible, cable manufacturers tend to standardise the Fibre Optic Outer Diameter to streamline the subsea cable design process, optical cable transport and manufacture setup processes to reduce cost of labour and equipment and lower procurement costs for bulk orders.

Large power cores are included within the subsea cable to transmit power from the turbines. Stranded cores are used for any application which requires flexibility of the product. Conductors are longitudinally water blocked (semi-conducting sealant and swelling powder) to meet CIGRE 490. Insulation thickness is based on

Voltage rating. Screening and sheathing requirements depending on application factors. The cores are inherently stiff so are adequate for layup and protection by the outer cable layers.

For component design the function, size, stiffness, weight, minimum bend radius, strength, design life, fatigue resistance, length, cost and water penetration considerations are reviewed. If long lengths are required jointing of cable components is also an important factor and the number and quality of jointing can influence component performance. Component joints developed for the static cable windfarm application are designed only for low level fatigue and tension levels and are therefore never included within any sections which may be subjected to continual loading or areas under significant tension (e.g. in the section of cable from the seabed floor to the elevated termination point within the wind turbine structure during installation). As this is standard practice there will be no joints considered allowable within the dynamic sections of cables within the COREWIND project.

Installation and cost factors significantly influence cable design. The force required to bend a cable and the ability of the cable to withstand loading are critical.

Small wind farm cables generally have greater flexibility as indicated by small minimum bend radius characteristics. In general, relatively small cables have reduced costs associated with materials, transportation, and installation. Core size has the largest impact on cable outer diameter. Choice of material for conductors have a direct impact to core size. Conductors for windfarm applications are typically either copper or aluminium. High conductivity means copper conductors are small. Lower conductivity means aluminium conductors need to be larger than copper conductors to meet current carrying requirements to transmit the same level of power.

Since 2004, copper has become relatively more expensive than aluminium. Significant investment in primary aluminium production was prompted as substitution of aluminium for copper became increasingly popular in the automobile and aerospace industries, accompanied by China’s rapid growth demands, resulting in a surplus on the world markets. In comparison, supply has remained relatively stable while demand has increased for copper resulting is price growth.

Historically the cost drove the preference for aluminium cores however given the current market prices for both materials, there is little difference between the two materials from a cost per unit of power transmitted perspective given:

- the increased conductor size required for aluminum cores
- larger subsea cable size costs required to accommodate larger cores
- transport and installation considerations
- greater power loss over the operational life of the product

Copper cores have greater fatigue resistance being able to withstand larger vibration amplitudes over longer durations than aluminium without cracking or breaking. Copper displays low levels of creep in comparison to aluminium and is also less prone to failure due to the respective oxide properties; copper oxide is soft, conductive and breaks down easily whereas aluminium is strongly attached and electrically insulating [52], which can also make jointing more challenging. As a highly reactive metal, Aluminium cores are highly susceptible to corrosion by seawater so additional mitigation is often required with associated costs [51]. Copper cores are heavier so subsea cables are more likely to be stable on the seabed floor, whereas Aluminium cores are lighter so the cable is more likely to require burial or other expensive additional stability measures in sections where stability cannot be achieved by cable weight alone. Greater cable weight often results in greater loading during installation, so cable axial strength members are sized accordingly.

Copper	Aluminium
• High Conductivity • High Density (Heavier) • Higher Cost Material • Widely available • Easy to Process	• Lighter • Lower Conductivity (≈60% compared to copper) • Lower Tensile Strength • Fluctuation in price w.r.t. Copper • Highly reactive metal

Table 3.1-5 – Conductor Material Review

Recent world growth has led to increasing demand for both metals, particularly driven by the recent expansion in Asia. As demand increases are expected, with windfarm developments contributing directly, the likely result will be increased prices for both metals during the next decade. With resources scarcity a concern for the future, and increasing focus on reducing emissions which from both copper and aluminium production processes, there should be a greater policy shift towards recycling becoming the dominant source of supply [53] for metals in the near future.

Insulation thickens also impacts core size and is directly related to material and voltage rating. Land based cables often historically used oil impregnated paper as a standard insulation system however this proved unsuitable for dynamic application. This was replaced by use of Cross Linked Polyethylene and Ethylene propylene rubber which have been proven excellent cable insulating compounds for submarine power cables. For MV cables, insulation thickness requirements are prescribed in IEC60502-2 and are identical for both materials. For HV cable design, the insulation thickness is chosen by the cable manufacturer to match the calculated electrical stress at the insulation layer boundaries. Although EPR has greater insulation resistance (10^{17} Ω·cm) than XLPE (10^{14} Ω·cm), due to the dielectric loss characteristic of EPR (loss factor tanδ 0.002), XLPE (loss factor tanδ 0.0004) [54] is often preferred as insulation for HV applications to minimise insulation thickness given the resulting higher breakdown stress achieved by XLPE.

Reliability studies should be undertaken by the cable manufacturer to check the quality of extrusion material is controlled to ensure consistency. EPR has a lower level of expansion at elevated temperatures and thus is often used for very high temperatures may need to be managed [55] such as within large Export cables. Temperature limits for both EPR and XLPE may be up to 90degC and short circuit conditions as 250degC according to MV land cable standard IEC60502-2. Beyond these temperatures, such as caused by uncontrolled current overload of a circuit, can damage the cable and reduce its life. All XLPE insulated cables, even after having been degassed to the requirements found in international standards, must be expected to contain some residual gaseous by-products from the cross-linking reaction of XLPE. The terminations, connections and handling procedures used must consider their expected effusion.

Material		Use	Considerations
XLPE	Cross Linked Polyethylene	Modern Array Cables	Modern co-polymers allow XLPE systems to be used in all applications for standard radial field power transmission cables. Moderate bend stiffness. Significantly Lighter than ERP.
EPR	Ethylene propylene rubber	Some Array Cables	Significantly heavier than XLPE. Dielectric loss prohibits use for HV at reasonable stress. Low bending stiffness. Typically, more Expensive. Lower hot viscosity so has a greater tolerance to contamination. Easier to joint.
Oil/Paper	Impregnated Paper	Older Systems Land Cables	Lower operating temperature. Can be expensive to manufacture. Due to the oil impregnation process manufacturable length is restricted in comparison to XLPE and EPR. Termination requires sealing ends carefully and can be harder to achieve. With a lead layer they can be difficult to install and have poor fatigue resistance.

Table 3.1-6 – Insulation Material Review

During triple extrusion operation (to minimize contamination) the insulation layer is sandwiched between thin extruded semi-conducting sheathing layers specifically designed to prevent electrical stress damage to the insulation.

Additional layers such as water blocking barriers, metallic screening and sheathing can directly influence core size. In general cores are characterised based on their layers they include, however there is no standard within the industry which details all classifications. CIGRE 490 states "A wet design allows water to migrate into the cable insulation and the conductor", but it does not define quantities of water moisture. Types presented below are understood to be common terms for different core design types within the industry. Semi-dry or Wet Core designs have proven sufficient for submarine cables use and due to their lighter weight, smaller finished diameter, and greater flexibility they are easier to handle for transport and installation. Semi-dry sheathed solutions were most commonly found. The sheath adds a level of protection to the core during transport and layup.

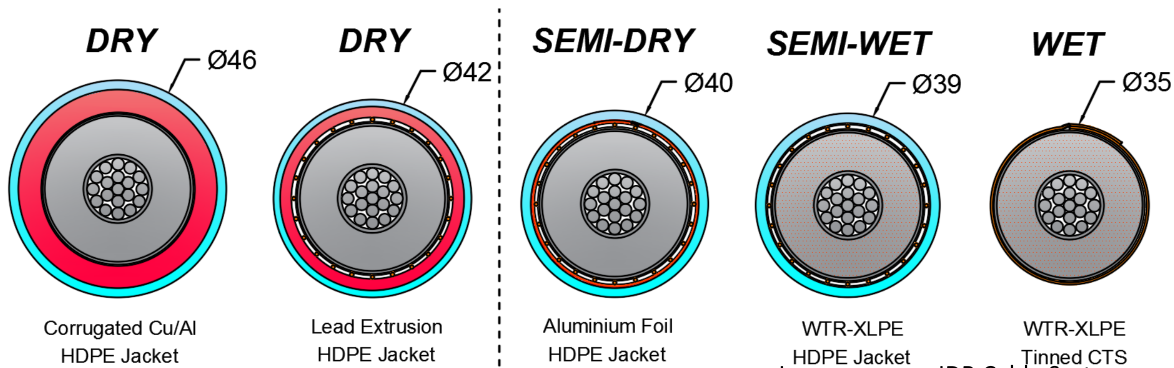


Image source: JDR Cable Systems

Figure 3.1-2 – Core design type examples

The metallic screen is designed to conduct charging current under normal operating conditions and short-circuit current under asymmetrical fault conditions. Where greater flexibility of the cable is required an open helix equalisation tape and water blocking are applied over a copper wire screen such that fault currents will be shared between the copper wires in the screen.

An armoured electro-optical composite cable is a complex structure which consists of many different materials having different values of Young’s modulus. Component strain checks should also be undertaken to identify the optimal component position, suitable bundle twist angle and cable armouring required. When tension is applied to the cable, the cable extends as one, and, at the lay angles used in cables of this type, the cable strain approximates to the strain in each helically laid component. The conservative approach is to analyse the armouring only, the dominant material due to its high strength and Young’s modulus, and to ensure that the cable strain does not exceed the yield strain of each component. In these cables the stainless steel optical fibre tube will typically yield at 0.3% strain. Hence the cable strain must not exceed this value.

3.1.6 Cable Fabrication

Cable components in the same layer are twisted together to achieve smaller minimum bend radius of the bundle and greater fatigue resistance. Additional component length to facilitate this twist equates to additional conductor length per meter of cable, which equates to greater resistance and therefore greater energy loss. Careful consideration of mechanical performance vs electrical performance must be made during cable design. Tapes may be used as processing aids during this lay-up operation. In similar applications tapes have been included for functional performance (e.g. to reduce friction between components) however this is not currently standard for subsea cable design. Layup machines vary but components of carriages revolve around a central closing die to twist into the bundle. Cable position, back twist and tension must be carefully controlled to ensure correct bundle construction. The bundle may also be packed with supporting material to fill the intestacies and keep components in position. The factory joints are included where the total required finished cable length exceeds the manufacturing limit for the individual components. Due to transportation weight and size restrictions, this most often affects the power core as opposed to the fibre optic which is much smaller and lighter. Any inclusion of factory joints due to limitations in the continuous manufacturable cable length must be managed carefully to ensure it is retained within a static section of the cable. Joints in nearby components should always adhere to a minimum staggered distance apart as determined appropriate by the cable manufacturer.

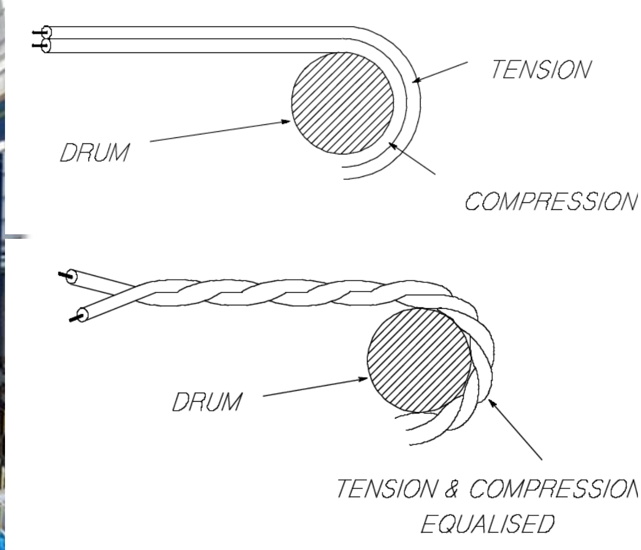


Figure 3.1-3 – Component layup operation and theory

Once the circular bundle is assembled, the cable layers are applied. This generally includes a bedding layer upon which the cable armouring will be applied, and a protective outer layer. The material most commonly selected for these layers within static windfarm cables are polypropylene rovings due to their light weight and the ability to apply them easily during the same pass as the layup or armouring applications. Where greater abrasion protection or cable bend stiffness is required, sheathing is often applied as polyurethane or polyethylene, or a combination of both. Polyethylene has typically greater bending stiffness.

The cable armouring is sized relative to the cable bundle size and the maximum loading the cable is expected to see during installation and operation as it acts as the principle strain member. The armouring provides external mechanical protection, impact protection, weight and strength. Careful consideration is given to the number of armour layers required regarding the level of torsional balance required for product transport, installation and operation. Even layers designed correctly can offer approaching zero inherent torsion.

Figure 3.1-4 – Application of Armour Wire Reinforcement and Roving Layers illustrated

To optimise cable manufacture efficiency in order to reduce costs, several short array cables of the same design may be manufactured in one continuous process length.

For dynamic applications, where the seabed section is relatively stable, the end sections of the cable lengths may be transitioned to be suited for dynamic application, however the cost savings from this process may be materials only as it often requires the full manufactured cable length to be run through the setup for each process.

3.2 Key differences between dynamic and existing static considerations

Cable design must take into account both electrical and mechanical performance requirements. In comparison to Static Renewable Energy Cable (REC), cables for dynamic applications are required to be of optimised bend stiffness and torsional balanced to prevent damage during installation where longer lengths are managed under elevated tensions, and able to withstand greater fatigue during operation. Cable manufacturing constraints mean dynamic cable layers require separate production processes, unlike static cables where multiple layers can be applied in one production run of the cable length. The additional layers and subsequent current manufacturing constraints mean the cost per metre of a dynamic cable design will always be more expensive than a static cable.

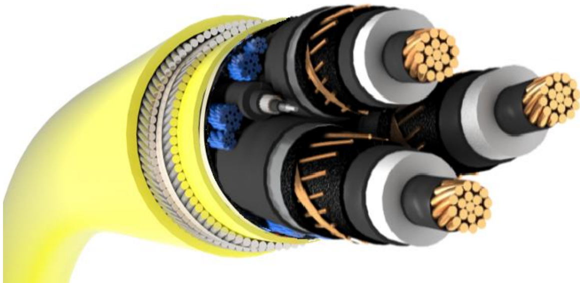
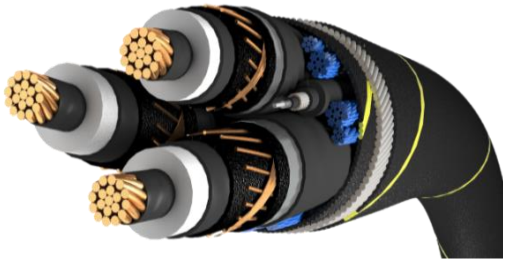
Dynamic Power Cable	Static Power Cable
Image source: JDR Cable Systems 	Image source: JDR Cable Systems 
Outer Protective Sheath	Light Protective Rovings
Even number of Contra-helical Armour Wire Strength Member Layers	Single Armour Wire Strength Member Layer
Inner Bedding Layer Sheath	Inner Bedding Layer Rovings
Twisted Triad Bundle of Fibre Optic Cable and Electrical Cores with Wire based Screen	Twisted Triad Bundle of Fibre Optic Cable and Electrical Cores with Screen
Good Torsional Balance Greater Axial Strength (Max Tension) Greater Fatigue Resistance Greater Bend Stiffness Greater Weight and Outer Diameter Greater Abrasion Protection and Impact Resistance	Coil-able for low cost basket vessels Sufficient Axial Strength for shallow installation Light Weight Greater Flexibility (Smaller Minimum Bend Radius)

Table 3.2-1 – Dynamic vs Static Power Cable Construction

The electrical core screen design must tolerate flexibility which means screen tape alone is no longer adequate and the screen must be formed by screen wires. Stranded copper may be advantageous for cores rather than stranded aluminium given the fatigue performance required and the additional weight it would offer with regards to seabed stability.

Torsional balance is introduced for dynamic cables as greater twist control is required during installation and operation. Greater terminated axial load carrying capability is also considered given the elevated loads in dynamic application induced by waves and currents as well as management of a longer heavier free-hanging length for installation and operation. Typical working load limits appear to be at least 5:1 for dynamic cables compared to 4:1 for static cables.

Increased bending stiffness supports ease of handling and offers some resistance to kinking. All these contribute to ensuring the installation window is as wide as possible. Greater cable weight increases chances of self-stability which minimizes expensive stability measures to retain the cable along the route.

Component joints should never sit within the dynamic regions of the cable. Where possible, delays or stops should be avoided during installation where it is close to a joint region in order to avoid excessive fatiguing of the joint. In the event that the installation must be stopped close to a joint region then measures must be taken to minimise cyclic fatiguing of the joint.

3.2.1 Optimised Electrical Cores

There will be few changes from an electrical design point of view between static and dynamic cables.

For each project upfront engineering studies are undertaken to ensure the product is suitable for in application conditions and to cost-optimise the design for the economically viable electrical performance.

The operating frequency of the field is also critical. When AC current flows in a conductor, the resultant magnetic field forces electrons towards the outside of the conductor, increasing AC resistance and inductance. This is known as the skin effect. As frequency increases, the skin effect increases. Combined with the proximity effect of 3 conductors in the triad formation, the associated current density through a reasonably sized conductor is shown below. Static windfarms typically operate at 50 or 60 Hz.

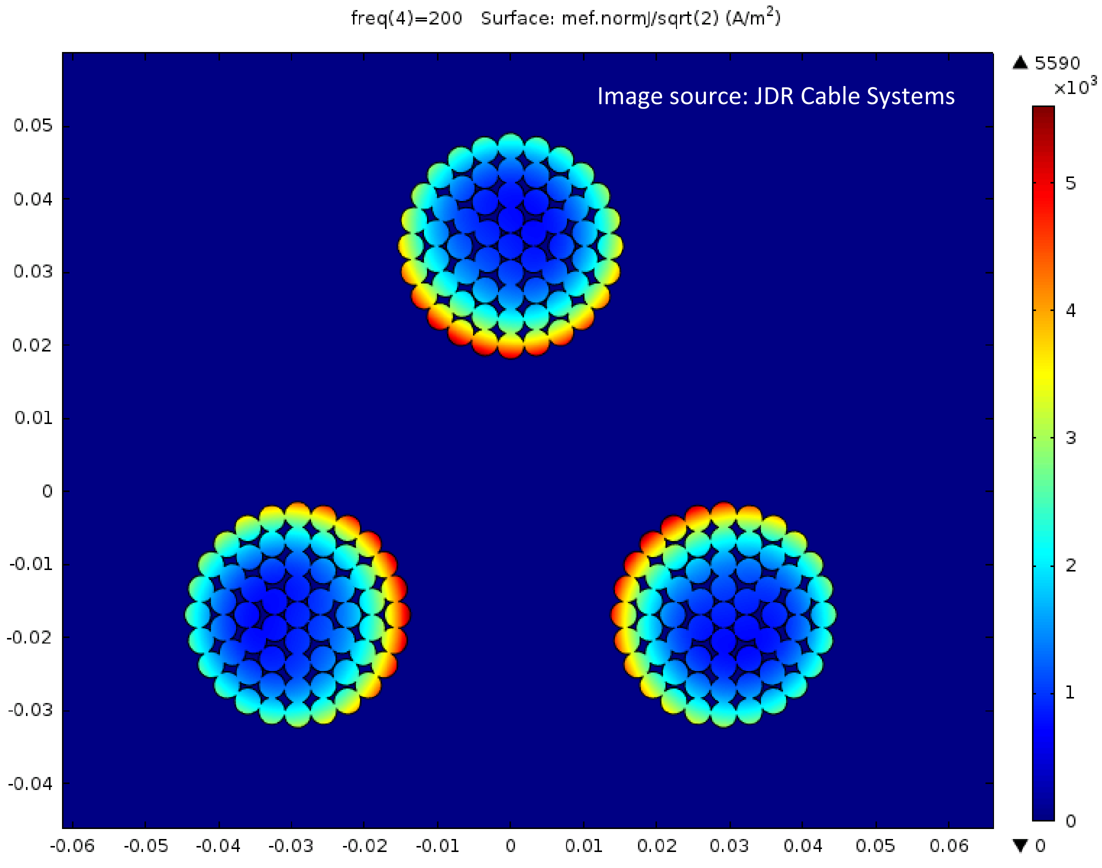


Figure 3.2-1 – ***AC Current Density plot at elevated frequency to demonstrate the skin effect in conductors within the subsea cable triad formation***

Steps to size conductors generally include:

1. Power Transmission Requirements / Efficiency
2. System Voltage
3. Environmental Restrictions (e.g. Thermal or Electromagnetic)
4. Confirm Conductor Material
5. Confirm Power Core and Cable Material Thermal Properties and Limits
6. Define Insulation from Electrical Stress evaluation if needed
7. Thermal Evaluation where Environmental conditions drive design
8. Allowable Continuous Current defined
9. Evaluate for Fault Current and amend if needed
10. Electromagnetic Field Evaluations if needed

At a basic level cables are then sized and rated to IEC 60287 based on top level wind farm details of required power transmission. To confirm current ratings for a design we need to identify the power losses before cable temperature exceeds maximum limits. Detailed electromagnetic and thermal analysis of cable design are undertaken to accurately assess heat losses due to induced currents arising from magnetic coupling within the build between the strength member wire and the conductors. The analysis must simulate the cable within the worst-case thermal bottleneck conditions identified along the cable route to confirm the thermal continuous current ratings along the cable.

In addition, the variable output of the wind turbine generators, as a result of variable wind speeds, allows the use of non-continuous power loading to be considered which may reduce CAPEX. The figure below compares the instantaneous loading against the exponential moving average.

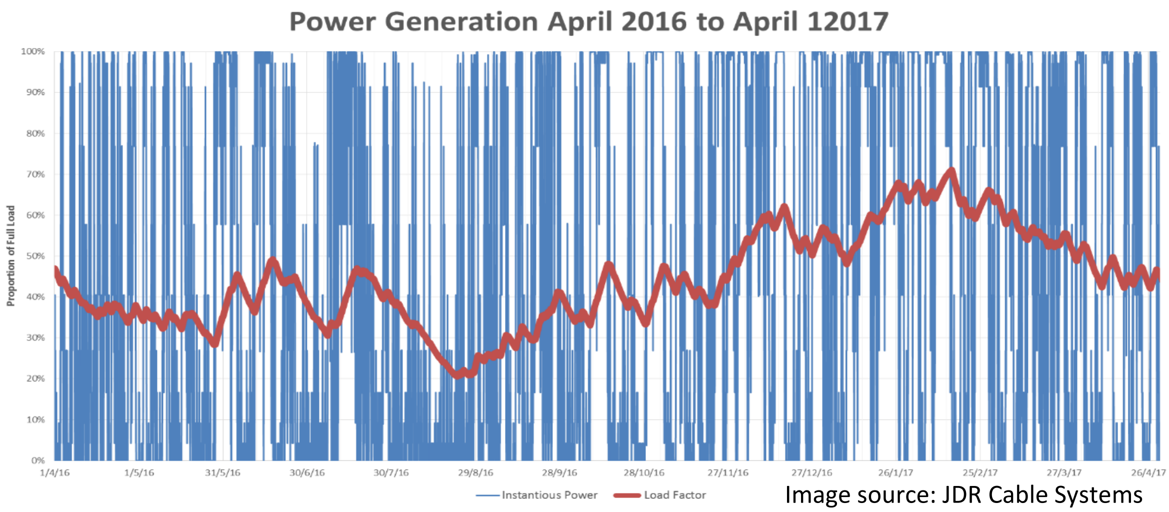


Image source: JDR Cable Systems

Figure 3.2-2 – Power load fluctuations across a windfarm and overall moving average

3.2.2 Cable Mechanical Optimisation

Subsea cables for windfarms are generally intended for an operational design life of between 5-25 years depending on the application conditions. Analysis is undertaken to identify the performance of the cable within the project application to identify optimal configurations, cable design validation and offer guidance on ancillary hardware requirements where needed.

- Seabed Stability studies over the life of the product in application to determine optimal Diameter to Weight ratios and any mitigation requirements to ensure stability.
- Dynamic analysis studies over the life of the product in application to:
    - determine heave compensating configuration required including minimum length required from entrance to platform down to touchdown point
    - determine fatigue damage over the life of the product in application
    - provide curvature plots which inform ancillary hardware designs such as bend stiffeners, etc.
- Local analysis Component stress checks for fatigue performance

Corewind will be focused on identifying the optimal configuration and evaluating cable fatigue performance as well as identifying relevant requirements of cable ancillary hardware design.

Critical cable parameters for this type of modelling are:

- Outer Diameter
- Weight
- Bend Stiffness
- Axial Stiffness
- Axial Safe Working Load

During detailed studies tension will be evaluated. Excessive negative tension / axial compression should be avoided under normal conditions wherever possible to minimise the risk of cable damage. Negative tension / axial compression is acceptable at the touch down point provided that the negative tension is less than 5-10 % of the recommended working load and the minimum bend radius is not compromised. Side wall pressure may also be reviewed and limited where needed by the cable manufacturer.

3.3 Corewind Cables

The main purpose of the Corewind project is to derive and evaluate cost effective dynamic cable solutions through analysis and optimisation of cable configuration and establishments for ancillary hardware.

As no details on the windfarm layouts or conditions are known at this time, and no inputs have been identified by cost base case to date, the electrical aspect of the cable design methodology for this project has been simplified to consider factors outlined below which are believed to be typical:

Attribute	Assumption	Value
Maximum Power Transmission Requirement from field (per circuit)	50 x 15 MW Turbines	750 MW*

Maximum Power Transmission Requirement per string (maximum number of turbines connected in String before connection to Substation (including redundancy backlinks))	10 x 15 MW Turbines	150 MW
Distance between Turbines	7 x 240m Rotor Diameter	1680 m
Maximum length of cables	1.1 x Distance between Turbines	1850 m
Maximum allowable Voltage Drop		4%
Operation Power Frequency		50 Hz
Load power Factor (-Lagging)		- 0.9

*Most large scale floating windfarms planned in the next few years do not exceed 750 MW according to COREWIND Matrix compiled.

Table 3.3-1 – Windfarm Assumptions for the Corewind Project

Sections 2.2 and 2.3 demonstrate cable designs are fully-cost optimised solutions only when tailored to suit project specific applications. As this is intended to be applicable across multiple sites and due to the level of complexity of this process, cable designs selected to be studied in the Corewind project have been chosen to represent indicative cable designs to ensure the model outputs are obtainable and useful.

It is not clear from the information provided to participants on the proposal base line if the cost estimated was based on 33 kV cables but this is likely based on the majority of the established fields, however there is little use in developing a 33 kV solution where core voltages look set to increase in line with turbine size expansion. As detailed in the proposal, the Corewind project cables are high voltage cables with 66 kV rating (36 / 66 (72.5) kV). This voltage is representative of the majority of the modern established wind farm static cabling based on wind farm details shown within the Corewind group literature review and falls in line with the floating windfarms being planned before 2030 detailed within Corewind Matrix compiled. Copper cores and XLPE insulation has been selected to minimise cable size of the cable and achieve a cost-optimised solution while retaining functional requirements.

Considering mechanical characteristics, and the lack of details regarding the base case models, the following two cable sizes have been selected for modelling. By modelling cables close to both ends of the scale is likely the output from the studies will be able to be applied to both demonstration and commercial scale floating wind farms. Modelling the 800 mm^2 core cable, it is expected the findings can also be more readily be applied to larger export cables (up to 220kV) in the future.

It is worth noting that although 100% torque balance could be designed within the cable using armour layers with different armour wire sizes and optimised angles within the armour package, to make the study more representative of possible cables supplied the same size armour wire for the armour package has been used which is not unusual within the industry.

Cable Property	Unit	CW001	CW002
Cable Voltage Rating	kV	36 / 66 (72.5)	36 / 66 (72.5)
Core Material	-	Copper	Copper
Core Size	mm^2	150	800
Nominal Outer Diameter	mm	146	192
Nominal Weight in air	kg/m	36.5	72.3
Nominal Weight in seawater	kg/m	22.4	45.4
Nominal Axial Stiffness	MN	439	830
Terminated Axial Working Load Limit (TWWL)	kN	125	155

Table 3.3-2 – Initial Indicative 66kV cable properties for COREWIND study

corewind

3.4 Dynamic cable configuration

This section introduces dynamic cables used for floating offshore wind turbines from a configuration point of view focusing on potential dynamic cable configurations, equipment associated. The main design drivers for configuration selection will be screened. At the end of this section examples of dynamic cable configuration sued on demonstration projects are presented.

3.4.1 Existing dynamic cable configurations

Typical dynamic cable configuration and main equipment is illustrated in Figure 3.4-1 and represents the cable from floater connection on the left towards transition to static cable.

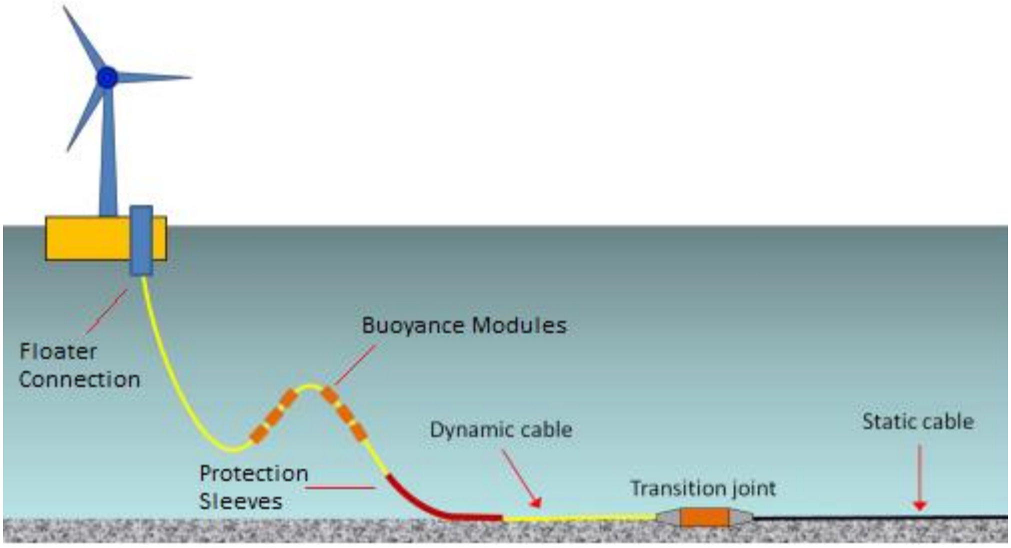


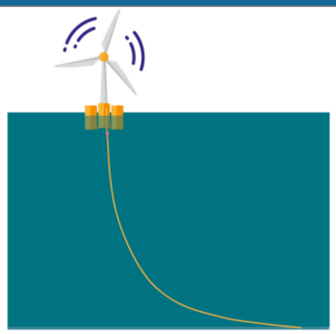
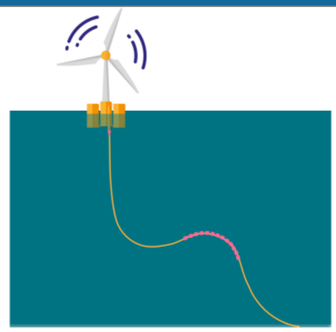
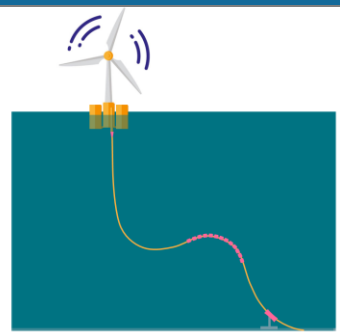
Figure 3.4-1 – Components of a Dynamic Cable System, Source: [1]

There are various configurations possible based on required functionalities and solicitations. Next section describes 6 main configurations which could be envisaged for floating wind projects. The list is not exhaustive, and some configurations might be required related to water depth or environmental conditions constraints.

In general, the cost increases with greater depths or greater movement of the floating platform which needs to be tolerated. This leads to greater quantity and required performance of ancillary items in the cable protection system and increased cable length required to be managed within the water column between the floating structure and the seabed.

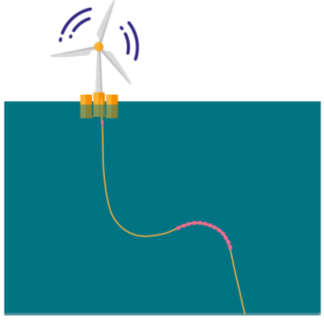
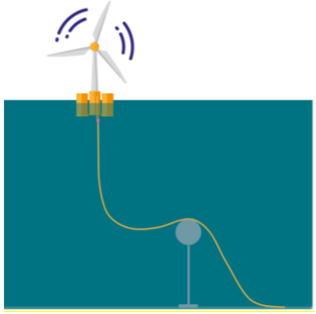
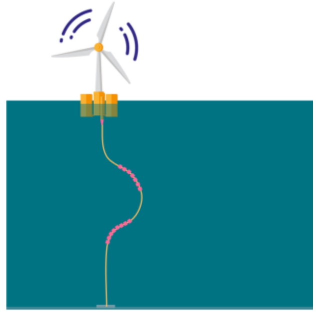
Advantages and Drawbacks

Configurations are recalled in reference [1], main advantages and drawbacks are listed for each configuration. Design drivers and selection criteria will be addressed in next section.

Name	Free Hanging (catenary)	Lazy wave	Tethered wave (Reverse pliant wave)
Description	 A line extends in a catenary shape from the floater to the seabed	 A lazy wave provides lift to at a midwater cable section by attached buoyancy modules.	 A tethered wave is similar to a lazy wave with the addition of a tether restraining the touchdown point.
Advantages	Simplest configuration	- Simple configuration - Buoyant section which decouples reasonable dynamic FOWT motions from fixed subsea end - Accommodates reasonable levels of marine growth relative to depth. For shallow waters it may be possible to accommodation higher levels of marine growth by adding buoyancy modules during the lifetime of the system. - Proven use for deep water application.	- Buoyant section which decouples FOWT motions from fixed subsea end - Tether reducing touchdown point migration under cross current - Accommodates reasonable levels of marine growth relative to depth. - For shallow waters you can accommodate higher levels of marine growth without the need for adding extra buoyancy modules during the lifetime of the system.
Disadvantages	- Vessel motions are not decoupled - No restriction of lateral motion - Likely to require a bend control at the floating structure entrance	- No restraint on lateral motion - Change in configuration shape with marine growth - Requirement for a bend control at the floating structure entrance - Requirement for Buoyancy modules	- Requirement for hold-down tether and clamp which will increase complexity and time of installation. - Requirement for a bend control at the floating structure entrance - Requirement for Buoyancy modules

Name	Free Hanging (catenary)	Lazy wave	Tethered wave (Reverse pliant wave)
Overall Comment	- Lowest Cost Cable Solution. Likely suitable for minimal dynamic motion. - Unsuitable for applications where reasonable or significant dynamic motion is expected.	- Low cost cable solution. Suitable for applications where reasonable dynamic motion is expected. - May be unsuitable for applications with significant dynamic motion and offsets. - - May be unsuitable where there is a significant field size constraint restricting distance between the floating structure and touchdown point. - Unsuitable where strong currents lead to touchdown point migration.	- Mid-range cost cable solution.

Table 3.4-1 – Dynamic Configurations advantages and drawbacks table

Name	Steep wave	Lazy S	Chinese lantern
Description	 A steep wave is like a lazy wave, but a subsea base and subsea bend stiffener are added to connect the cable vertically to the top face of a seabed junction.	 A lazy S is similar to a lazy wave but a subsea buoy (fixed or buoyant, called mid-water arch) is used instead of buoyancy modules.	 U-shaped cable slack keeping the tether vertically aligned with the cable entry in the floating platform
Advantages	- Buoyant section which decouples FOWT motions from fixed subsea end but subsea base and bend stiffener limiting vessel motions - Limited changes in configuration shape with reasonable levels of marine growth - Subsea base reducing excursions under cross current - Reduced distance between floating structure and seabed termination point required.	- Buoyant section which decouples FOWT motions from fixed subsea end, no restriction to large vessel motions - Limited changes in configuration shape with marine growth - Subsea buoy reducing excursions under cross current - Accommodates reasonable levels of marine growth relative to depth. - Sag bend location is carefully controlled	- Buoyant section which decouples FOWT motions from fixed subsea end but subsea base and bend stiffener limiting vessel motions - -Subsea base reducing excursions under cross current - Prevents migration of the cable over the touchdown point. - May accommodate reasonable levels of marine growth.
Disadvantages	- Requirement for a bend control at the floating structure entrance and subsea base connection point. - Requirement for Buoyancy modules	- Requirement for a bend control at the floating structure entrance - Requirement for a buoyant mid-water arch upon which the cable is clamped - Requirement for hold-down tether and clamp - Sag bend location is fixed	- Requirement for a bend control at the floating structure entrance and subsea base connection point. - Requirement for Buoyancy modules - Configuration limited regarding water depth accommodation - Feasibility ~~strongly~~ linked to

Name	Steep wave	Lazy S	Chinese lantern
			product bending stiffness and expected offsets
Overall Comment	- High cost cable solution given the requirement for additional termination units and permanent subsea equipment.	- High cost cable solution. Not typically economical for single cable. - Good for dynamic applications where the offset distance requires further control or where multiple cables are approaching a hub (e.g. offshore sub-station). Minimum separation distances between cables can be controlled to prevent clashing and significant current rating reductions.	- Low cost cable solution. - Significant heave can be accommodated, depending upon the depth. - Unsuitable for applications with significant dynamic motion and offsets.

Table 3.4-2 – Dynamic Configurations advantages and drawbacks table

The choice of functional solution considers the combined cost of procurement and installation. For the COREWIND project the Lazy Wave is the Initial Configuration selected for analysis as it will be the most likely suitable cost-effective solution.

Overall configuration references are shown in the figure below. Section a (the blue line) represents the free hanging length from the floating structure connection down to form a catenary, commonly referred to as the sag bend. Section b (the yellow line) represents the section elevated by buoyancy models. Section c (the green line) is the remaining free hanging length down to the touchdown point at horizontal distance d from the cable connection to the floating structure.

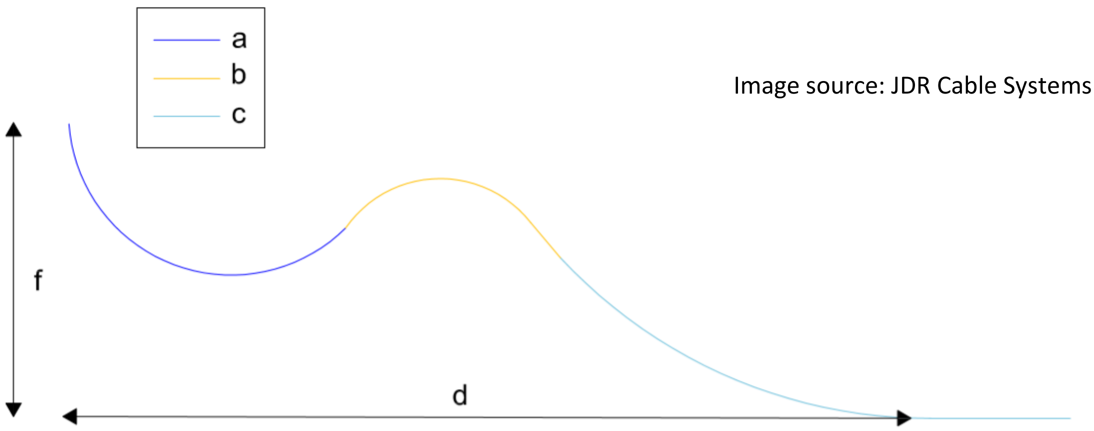


Figure 3.4-2 – Lazy Wave Configuration Section Designations

For floating windfarm applications, the cable can usually be manufactured with a dynamic section at each end and a static section (of different cable layers) in the middle. Alternatively, as illustrated in Figure 3.4-1, the static and dynamic sections can be made separately and a permanent subsea transition joint can be installed during installation to connect them. This is adequate for floating turbines and cablings system which are permanently installed throughout the life of the product. These joints are constructed using established permanent subsea joint technology, however greater testing may need to be performed to verify suitability at greater depths.

In future turbines may need to be disconnected within the operational life of the cabling system network (e.g. for structure maintenance, replacement or repositioning), or in excessively high fatigue areas where the dynamic section of cables may need to be replaced during wind farm life. The number of detachments and associated costs of both the operation and hardware will vary and must be considered for each project to mitigate high LCOE.

Hardware of the cable at the connection to the floater would need to be developed in conjunction with methods of detachment for the project to ensure a reliable solution without cable or hardware damage and facilitate ease of reclaiming the cable end for re-connection. Alternatively, a temporarily mate-able joint between a dynamic cable and a static cable may be implemented. Currently there are no standard commercially available wet mate solution known for this application.

The Corewind project assumes the floating structures are permanently installed. Any future developments outside the Corewind project in either the hardware connection or the subsea wet mate connection technologies should be able to be fairly easily incorporated into cost models as the topology to be modelled for the cable system will start from the exit to the floater and end after the touch-down point. In this way the Corewind project models are expected to remain relevant and easily adaptable.

3.5 Configuration design

The configuration must be designed to consider cable motions induced by water particles and imparted by the moored floating platform.

Main configuration design drivers are:

- Floater motions and horizontal excursions
- Environmental conditions
- Marine Growth
- Cost of Cable system including Ancillaries with respect to the Mooring system cost

3.5.1 Floater motions and horizontal excursions

Floater response is a key element for the dynamic cable design and should be determined from global performance studies accounting for environmental conditions (Wind, waves and current particularly). Critical cases in terms of excursion and vertical motions and dynamic cable hang-off for the cable must be identified and applied to verify cable structural integrity.

Excursion directly impacts the configuration selection and line length to accommodate horizontal motions. The condition is called far as it is offset furthest from the cable touch down point. As the WTG moves from its nominal position to its far point the cable system is pulled. The configuration must contain sufficient pliability to account for both near and far offsets while retaining its function of decoupling the heave motion section from the static seabed cable section.

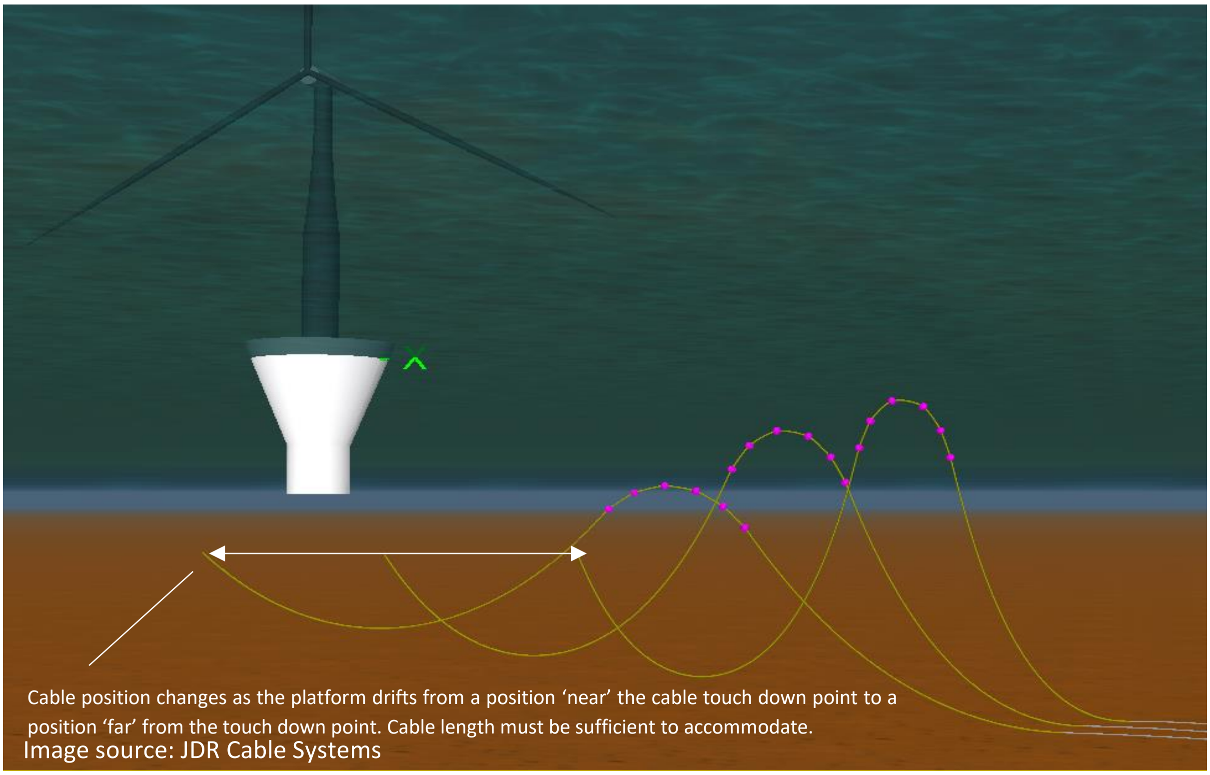


Figure 3.5-1 – 'NEAR' and 'FAR' positions relative to moored-structure offsets

Allowable excursions are usually mainly driven by dynamic cable or the windfarm layout and will become the design driver for mooring design. The lowest cost cable solution would be minimal cable length and hardware, which would require stringent tight moored-floating solution. Whilst placing stringent limitations on the maximum permitted excursion of the floating structure will reduce the cost of the cable system required to accommodate these motions, this would not produce the lowest cost of the total cost of moored and cable topology. The purpose of this COREWIND study is to attempt to identify the conditions which create a minimum total cost of the combined systems.

Detailed analysis must be undertaken to evaluate the system for cable system design relative to offsets provided as this is difficult to judge at preliminary stages.

To minimize fatigue levels the buoyant section must remain clear of the splash zone (region near the sea surface where water particle movement is extremely volatile). The sag bend must remain clear of the seabed surface to avoid repetitive impact loading which could damage the cable and disturb seabed marine life.

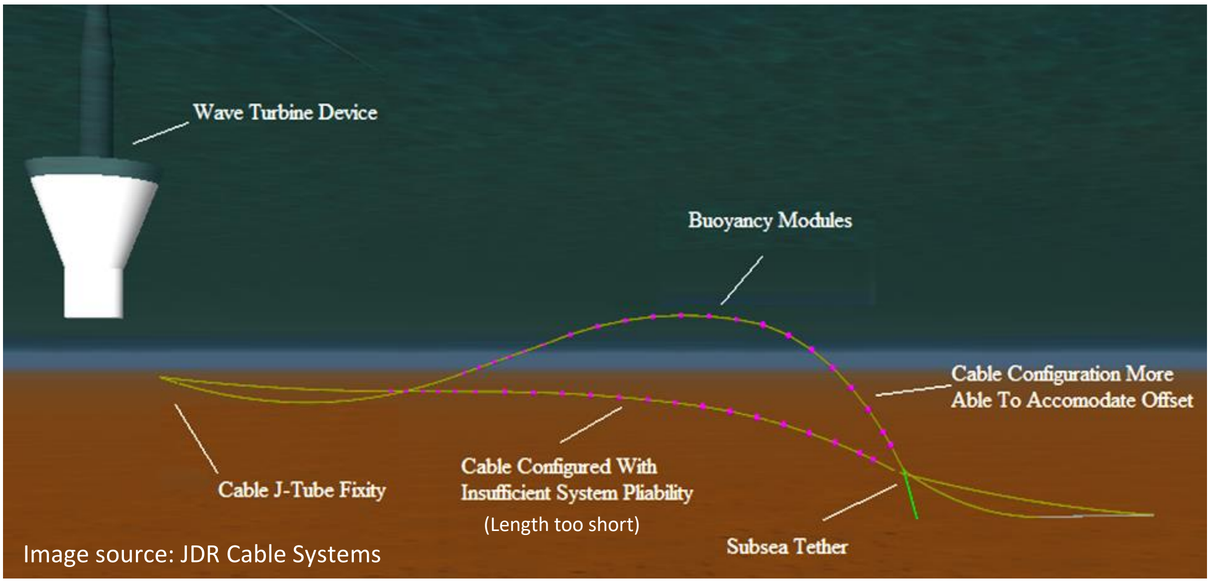


Figure 3.5-2 – 'FAR' position considerations

The maximum excursions limits of the platform are the subject of several tasks within the COREWIND project. The following are indicative limits for excursions limits defined in WP1 D1.2 design basis. The maximum allowed excursion during idling conditions is 30 m in each direction. Before that, an alarm is generated when 15 m are reached, which is the limit for operation conditions. If reaching 30 m, the turbine is stopped by the mooring solution.

EXCURSION RESTRICTIONS	
DoF / Limit typology	**Limit**
Horizontal offset (alarm limit) (mean during operation)	15 m
Horizontal offset (WTG shutdown). Maximum during parked conditions	30 m

Table 3.5-1 – Excursions Limits

In the event the floater is not halted, e.g. in the extremely unlikely a mooring line fails, the cable system must detach from the floating structure to avoid damage to the floating structure. As the floating structure is of significantly greater cost than the cable system, generally the cable is considered sacrificial and would be replaced after such an event.

Evaluations of the configuration will be undertaken in WP3.2 when input RAO data from WP1 and WP2 are made available.

3.5.2 Environmental conditions

As well as the impact of environmental conditions on floater motions, water partial movement induced by current and wave effects will have a significant impact on cable configuration. Wave motions tend to have a dominant impact in shallow water applications while current velocity is typically dominant in deeper water applications. Requirements to anchor the configuration (Pliant wave for example) are identified from cable motion response to the environmental loading during analysis.

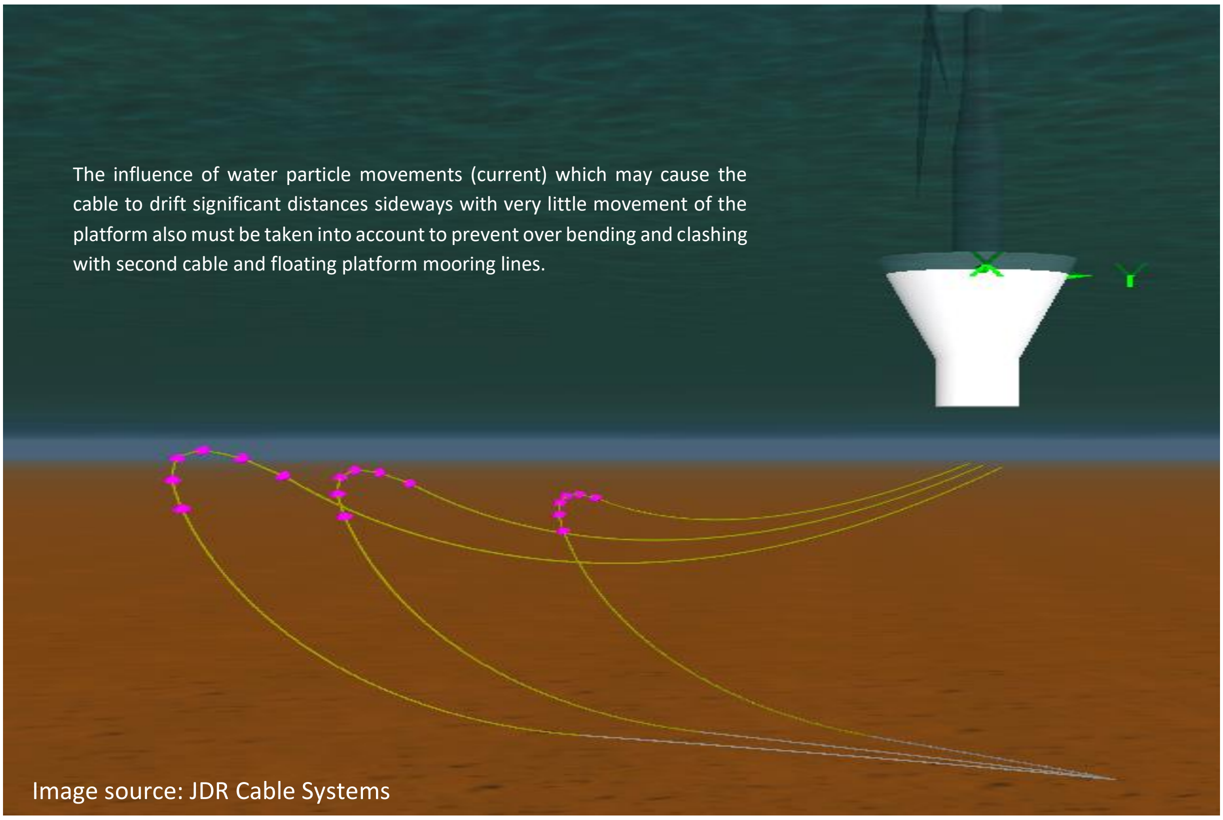


Figure 3.5-3 – 'SIDE VIEW' considerations

3.5.3 Marine Growth

After prolonged duration in water, marine growth will start to form around the cable system, including buoyancy modules. Marine growth is critical for the dynamic configuration and is highly dependent of selected geographical zone. The added weight onto cable product and increased diameter impacts the configuration behaviour when fully developed.

Reference [36] notes that marine growth can have a material impact on the cable configuration adding mass that alters the buoyancy of cables and shifts the distribution of fatigue loads. The extent of marine growth must therefore be carefully considered and factored into configuration evaluation. For configuration analysis, the marine growth should be modelled as an end of life condition which will be the most onerous based on increased drag area with product diameter increase. A subsea tether may be added to the configuration if needed.

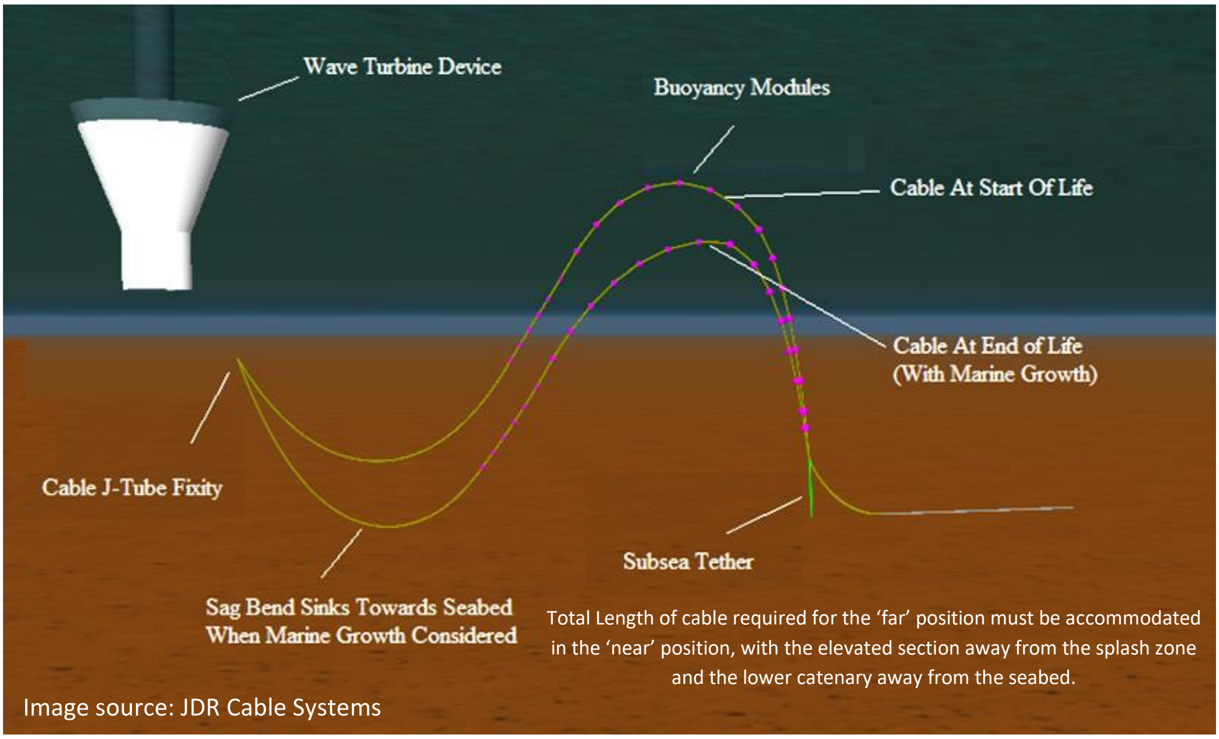


Figure 3.5-4 – 'NEAR' position considerations – Marine Growth impact

Marine growth profile against water depth should be defined to properly account for the fact that marine is expected to be more prevalent near the surface of the ocean, where the water is oxygenated and warmer. Marine growth considerations will be taken into account as detailed in D1.2.

It should be emphasized that marine growth is site specific and project development should account for marine growth survey if not covered by actual specifications.

DNVGL-ST-0437 section 2.4.11 (Reference [37]) provides guidance regarding following geographical zones:

- Central and Northern North Sea (56° to 59° N)
- Norwegian Sea (59° to 72° N)
- Baltic Sea
- Gulf of Mexico
- Offshore West Africa

For other areas specific survey should be performed as this is a critical engineering input for dynamic cable configuration.

3.5.4 Other Factors:

Main configuration design parameters have been highlighted above however multiple criteria should be considered. The following list is a guidance for criteria definition:

- Product and ancillaries' cost
- Frequency of use / track record
- Minimal subsea infrastructure / footprint
- Simple and reliable installation, retrieval
- Configuration Robustness / sensible versus design parameters modification
- Adequate access for inspection, maintenance and repair
- Avoidance of snatch loading
- Avoidance of compression
- Avoidance of wire 'birdcaging' within the cable armour package
- Can accommodate large vessel offsets
- Avoidance of lateral excursions and interferences
- Minimization of dynamic responses
- VIV response
- Minimization of the effect of corrosion, erosion and wear
- Limiting dynamic loads at the subsea connection unit
- Weight variation (Marine growth uncertainty for example)

3.5.5 Dynamic Cable Ancillaries and equipment

Bend stiffeners

Bend stiffeners can be used to limit the curvature of the cable by adding a local stiffness to the cable at the point of connection in order to limit bending stresses and curvature to acceptable levels.

Bend stiffeners available on the market of offshore components are made of moulded polyurethane elastomers. Polyurethane elastomer is chosen because of its low modulus and high elongation at break. In addition, this material is light and does not require any corrosion protection system.

Each bend stiffener is designed individually to protect the umbilical minimum bending radius under a defined tension and angle combinations, meeting the load cases (tension vs angle) of each application. For this application, the bend stiffeners should be sufficiently long in order to avoid the line to exceed its radius of curvature at the end of the bending stiffeners. However, the length should be kept reasonable for installation purposes (for example required length on deck and handling on installation vessel).

The design of a bend stiffener considers:

- Power diameter
- Operational environment (water)
- Interface requirements with load bearing steelwork/end termination
- Fatigue loads and cycles. (for dynamic bend stiffener design)
- Tension and angle combination. (for dynamic bend stiffener design)

Several types of bend stiffeners exist:

- Static: mainly used for protection during installation
- Dynamic: used for protection during the service life
- Some manufacturers also propose split bend stiffeners: used for facilitating installation

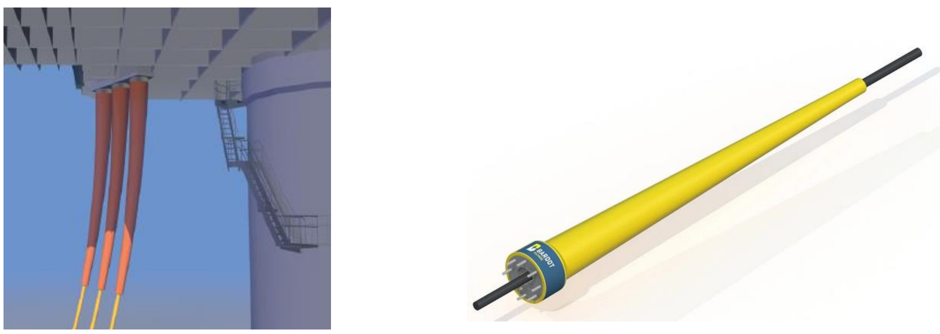


Figure 3.5-5 – Example of shape and locations of bend stiffeners; a) Bend stiffeners used in parallel; example from BMP (see reference in next table); b) Bend stiffener design example (Source)

Provider	description	External line diameter [mm]	Length [m]	Weight per limiter [kg]	External diameter [mm]	source
EXSTO	Dynamic and static	30-400	1.2-8	15-3500	300-2000	http://www.exsto.com/DYNAMIC-OR-STATIC-BEND-STIFFENERS,106
Trelleborg	Static and dynamic	Project specific	Project specific	Project specific	Project specific	http://www.trelleborg.com/en/offshore/products/bend--control--solutions/subsea--bend--stiffeners
Bardot	Static, dynamic and split	Project specific	Project specific	Project specific	Project specific	http://www.bardotgroup.com/fr/solutions-surf/controle-des-rayons-de-courbure/bend-stiffener http://www.bardotgroup.com/fr/solutions-surf/controle-des-rayons-de-courbure/bend-stiffener
BMP	Static, dynamic and split	no data	no data	no data	no data	http://www.bmpworldwide.com/pdf/Offshore_Energy_Products.pdf
Balmoral	Dynamic, and static; split	Project specific	up to 14 m	Project specific	Project specific	http://www.balmoral-group.com/balmoral-offshore/index.php/products/surf-products/bend-stiffeners
Plastiprene	Static and dynamic	Project specific	up to 12 m	Project specific	Project specific	http://www.plastipreneoffshore.com.br/pdf/cat_bend.pdf

Table 3.5-2 – Examples of some providers and characteristics of bend stiffeners

Dynamic bend restrictors

Dynamic bend restrictors are manufactured from a number of interlocking elements. They are also called Vertebrae Bend Restrictors (VBRs). They can be made of polyurethane or steel, or a combination of both materials, depending on loading conditions.

Next Table summarises some potential bend restrictor providers and the main characteristics of bend restrictors they can provide.

(a) **(b)** **(C)**

Figure 3.5-6 – Dynamic bend restrictors; a) Polyurethane VBR, b) steel VBR; c) hybrid VBR From ABCO subsea [39]

Provider	description	External line diameter [mm]	MBR (m)	Weight per half limiter [kg]	source
EXSTO	polyurethane or steel VBR	30 to 400	0.5 to 15	0.5 to 100	http://www.exsto.com/BEND-RESTRICTORS?var_ajax_redir=1
ABCO subsea	steel VBR	100 to 400	no data	no data	http://www.abcosubsea.com/wp-content/uploads/2014/06/steel-vbrs.pdf
Trelleborg	subsea and renewable VBR	no data	no data	no data	http://www.trelleborg.com/en/offshore/products/bend--control--solutions

Table 3.5-3 – Examples of some providers and characteristics of dynamic bend restrictors

Bell mouth

Bell mouths consist of multiple cones of various diameters.

Bell mouths may be used to eliminate the need of bend stiffeners or bend restrictors. However, they are less suitable for congested locations. In addition, they are less appropriate for a dynamic use, and the clash of the power cable line on the wall of the bell mouth may damage the power cable. In addition, the bell mouth should be sufficiently long to avoid bending of the power cable line at the exit of the bell mouth.

Figure 3.5-7 – Example of bell mouth

Bend Stiffener Latching mechanism

The bend stiffener latching mechanism aim is to lock rigidly bend stiffener to floater. The bending shear and bending moments load obtained from dynamic cable motions are transferred to floater at this location. Several technologies are available depending of the attachment interface to the floater platform (See **Figure 3.5-8**) and installation method (using divers, automatic, semi-automatic with ROV use).

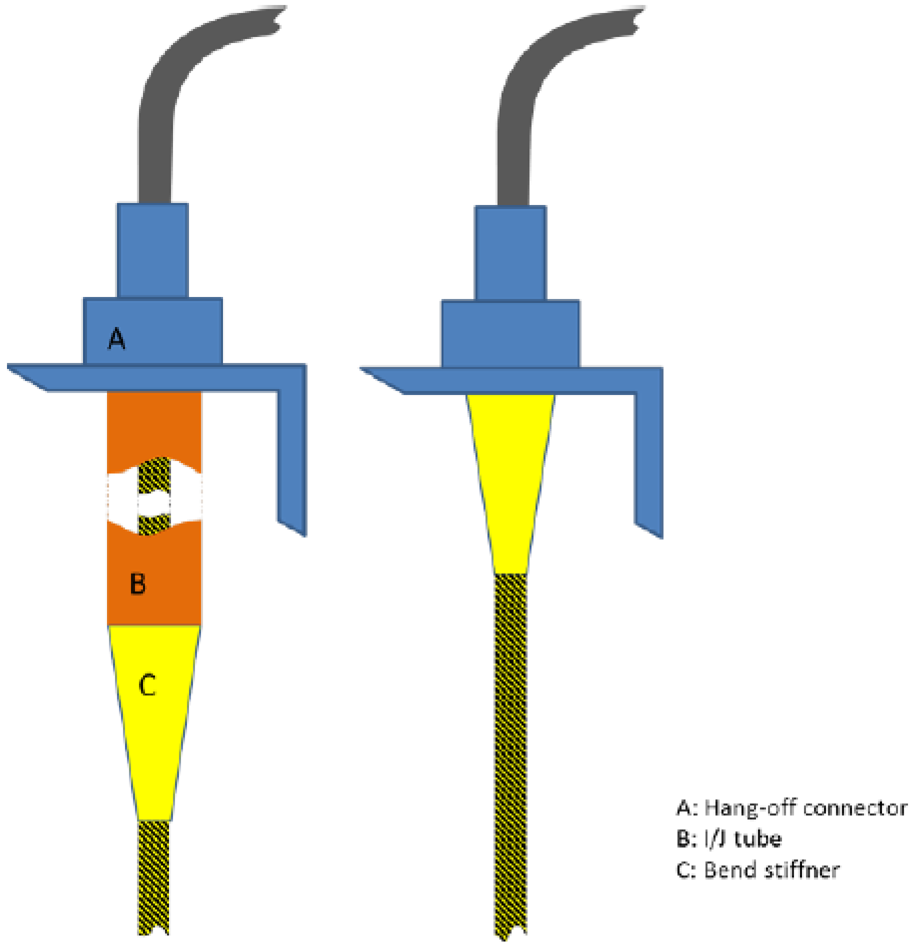


Figure 3.5-8 – Cable with Hang-off and stiffener with flange mounted on the I-Tube or directly to the support structure , Source : [1]

This equipment is critical as it will transfer the bending moment and shear force loads to the floater and will thus also be submitted to fatigue loadings. Used technology should thus be qualified versus extreme and fatigue loadings.

Next figure presents an example of diverless latching mechanism:

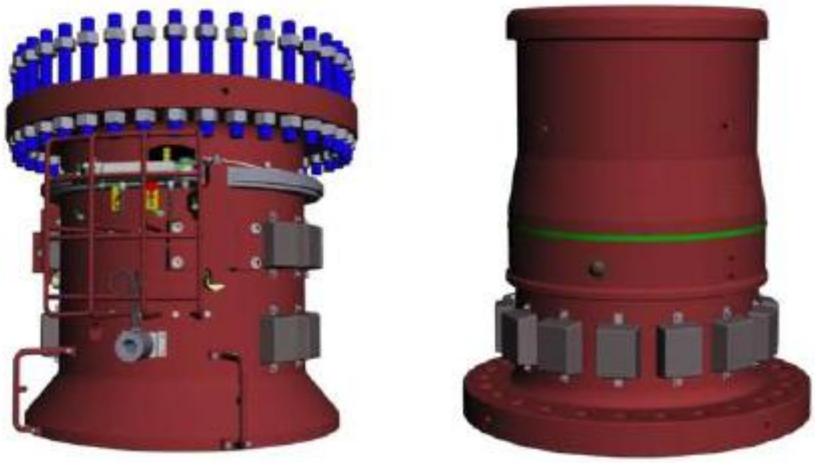


Figure 3.5-9 – Example of diverless latching mechanism. On the left is presented female part connected to I-Tube for example. On the right Male part connected to the bend stiffener, Source : [41]

Hang-Off

As described in reference [1] dynamic cable is anchored at the top of the I-Tube or directly to the support structure on the floating platform by a hang-off. The hang-off device shall be designed to cope with the mechanical dynamic loads expected without compromising the integrity of the dynamic cable.

The hang-off will mainly be submitted to tension loadings. Hang-off can for example consist of two steel half shelves installed around cable head to transfer the tension loads to platform.

Buoyancy Modules

Buoyancy modules attached to the dynamic cable can be used to create an upward force. Such a layout is especially attractive for deep water applications (See Lazy Wave configuration for example). As detailed in reference [1], buoyancy modules usually consist of two main components:

- Buoyancy element, with two halves shelves held together by two corrosion resistant securing straps or bolts.
- An internal clamp designed to the minimum outer diameter of the dynamic cable is attached directly to the dynamic cable.

The application of the internal clamp should not be harmful to the outer serving of the dynamic cable. The reduction of the minimum outer diameter of the cable should be carefully assessed taking into account the maximum axial tensile loads and long-term creep. The effect of seawater absorption and hydrostatic compression should also be carefully addressed as it impacts the equipment buoyancy for the long-term configuration behavior.

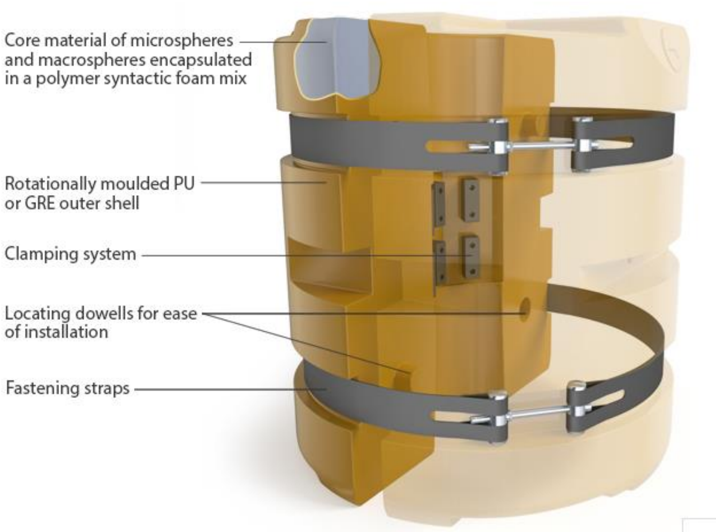


Figure 3.5-10 – Example of buoyancy modules, Source: [40]

Other Equipment:

- DMA / Anchors: Dead Man anchors to typically anchor the dynamic cable for Pliant wave configurations for example.
- Protective sleeves for the touchdown point: Mainly to counteract cable potential abrasion issues at cable touch down point submitted to dynamic motions.
- Helical strakes: Mainly to reduce or remove the Vortex Induced Motions risks

3.5.6 Industry Examples

Fukushima Demonstrator Project

For the Fukushima Demonstrator Project off the east coast of Japan, a floating substation approximately 25km off the coast was connected to a switching station onshore in the years 2014 and 2015. Additionally, dynamic cables were laid from the substation to a 2MW FOWT. The status after installation can be seen in figure below. In the following, the main cable characteristics and configuration is described.

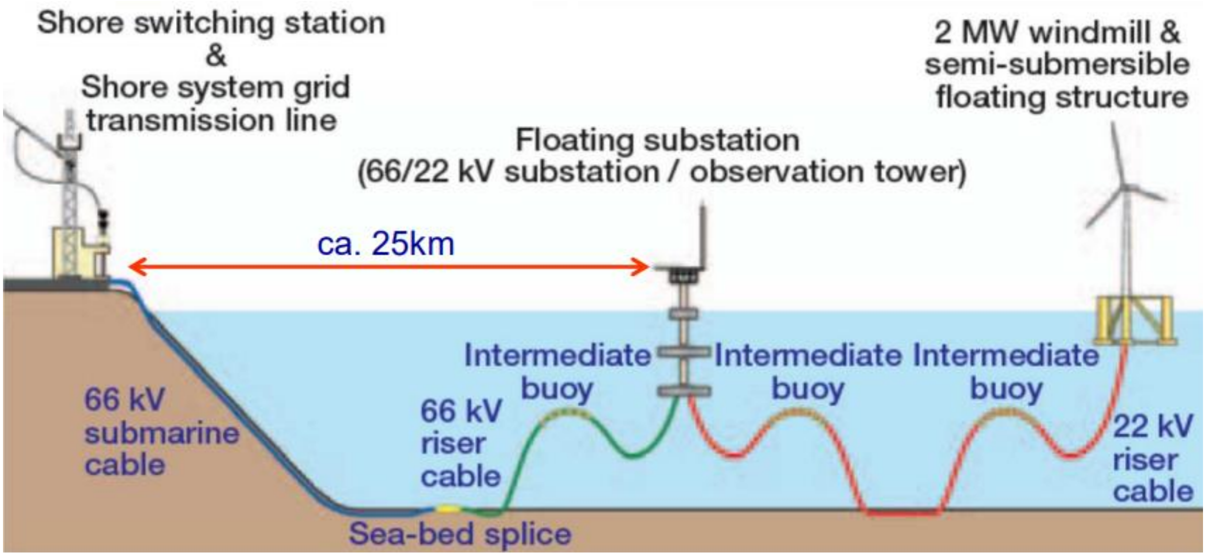


Figure 3.5-11 –Illustration of aspired status after installation; Source: [15]

Static analyses, dynamic extreme analyses and fatigue analyses have been performed to validate the dynamic cable configuration design in this application. Lazy wave configuration has been adopted as show in next figure.

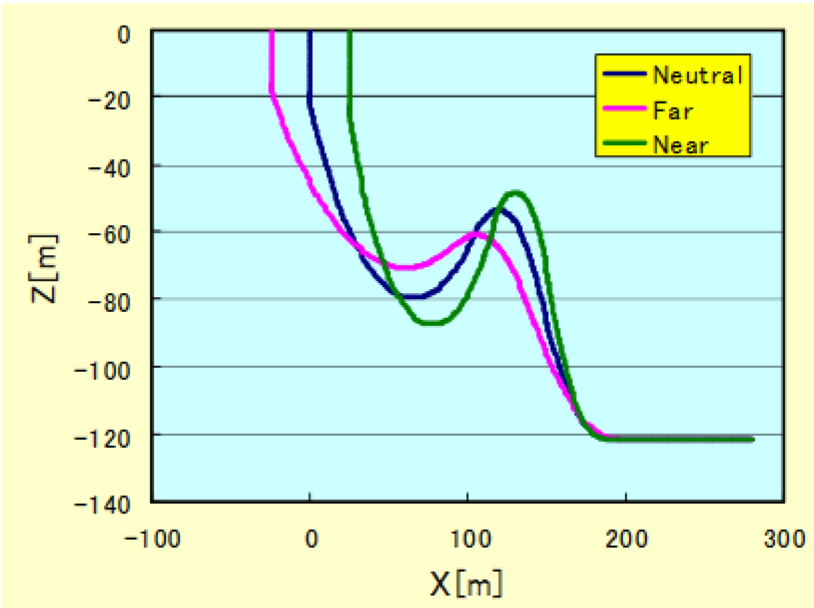


Figure 3.5-12 –Obtained Cable profile in water at Sub-station, Source [15]

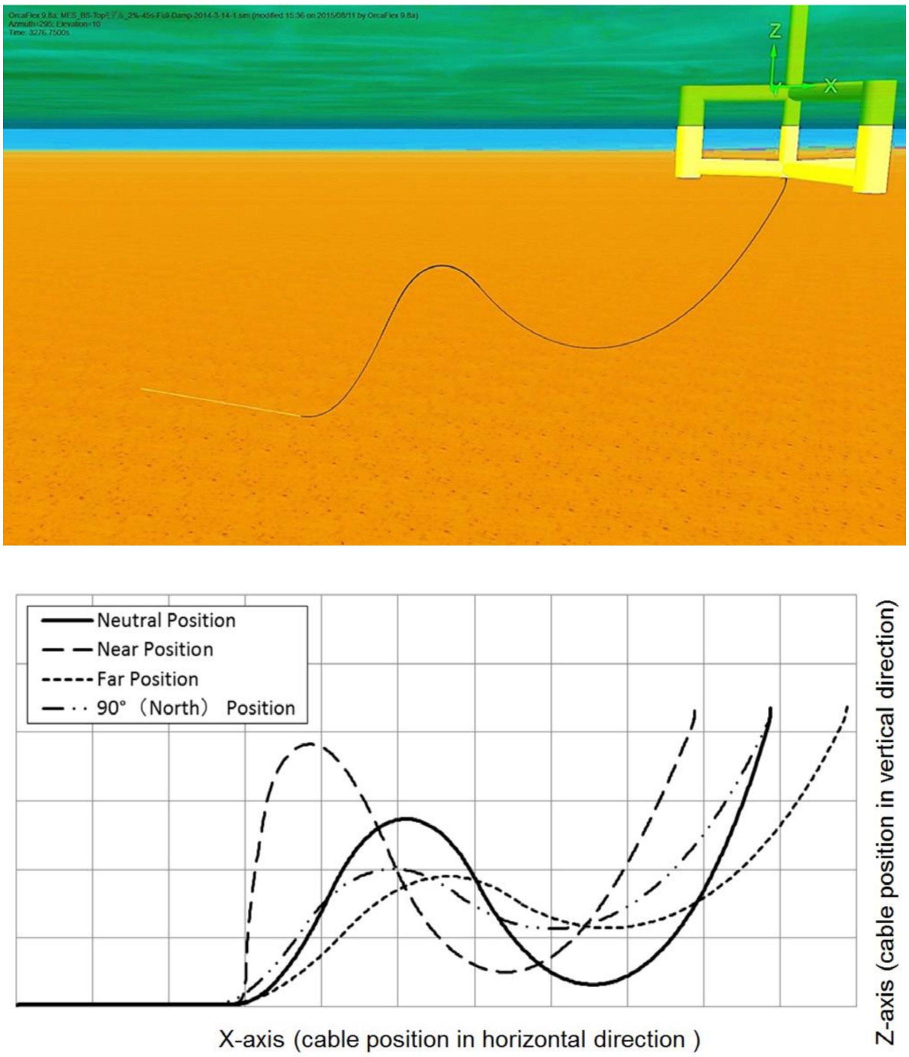


Figure 3.5-13 –Obtained Cable profile in water at Turbine floater, Source [42]

Hywind demo

A Tethered Wave has been used as shown in next figure for the design of the Hywind pilot FOWT plant in Scotland. The lengths of the different sections of the cable are summarised. The Hywind Scotland pilot park presents depths between 95 m and 120 m. The seabed is made of silty sand and gravel, overlain with scattered boulders.

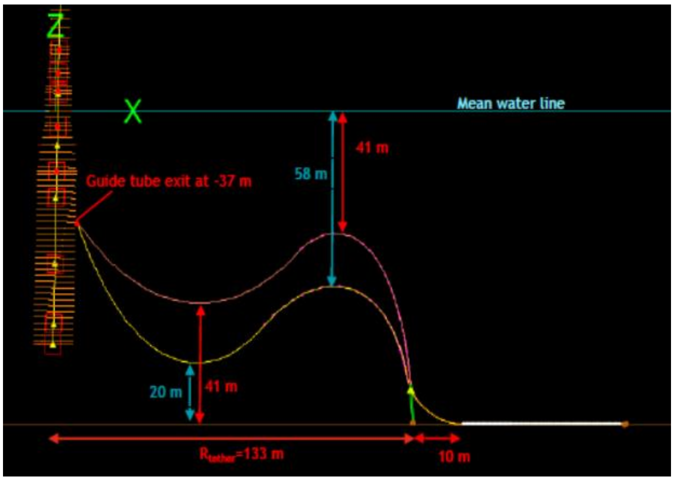
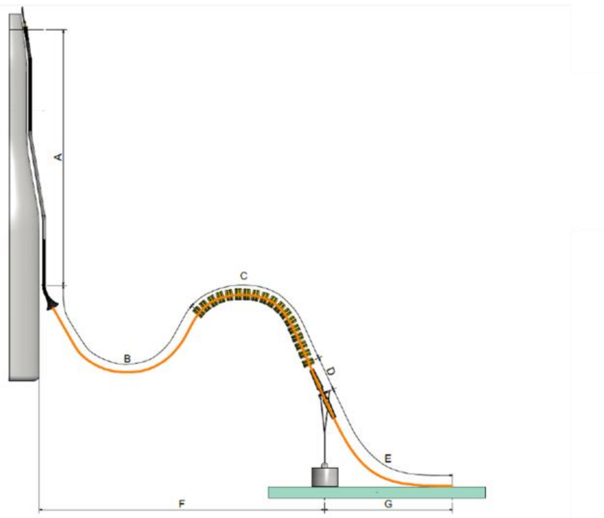


Figure 3.5-14 – Hywind Scotland dynamic cable configuration, Source [43]



Section	Description	Unit	HS1	HS2	HS3	HS4	HS5
A	Guide tube section	[m]	47,5	47,5	47,5	47,5	47,5
B	Upper catenary	[m]	122,3	116,3	111,3	118	112,7
C	Buoyancy section	[m]	60,3	60,3	60,3	60,3	60,3
D	Center lower bouyancy to center clamp	[m]	3,0	3,0	3,0	3,0	3,0
E	Lower catenary below center hold-down clamp	[m]	56,0	56,0	56,0	56,0	56,0
F	Distance from guide tube center to hold down anchor	[m]	125	125	125	125	125
G	Distance from hold down anchor to hold-back	[m]	50	50	50	50	50
	Total dynamic section length (from platform to hold-back)	[m]	289,1	283,1	278,1	284,8	279,5

Figure 3.5-15 – Hywind Scotland dynamic cable configuration, Source [44]

4 MARKET WATCH OF DYNAMIC CABLES

A market watch has been performed within the consortium with main aim being to identify current floating wind projects in operation and associated technological choices in particular:

- Dynamic Cable configuration (including tether detail if needed)
- Export Cable Construction Notes
- Export Cable Construction Notes
- Array Cable Construction Notes
- Required cable Power rating (i.e. cable rating, line current details, etc)
- Specific Equipment (ancillaries & hardware)
- Distance from Shore
- Cable Installation Vessels
- Installation Methodology

The research has been extended to projects currently in construction phase and future planned projects. Main highlights below mainly focus on projects in operation.

The following projects in operation have been mainly screened:

Status	Project	Ownership - Developper	Location	Total capacity (MW)	Development status	Region details	Installation
Construction	WindFloat Atlantic	WindPlus (EDP, Engie, Repsol, Principle Power) Floater designed by Principle Power	Portugal	25	wind farm (first turbine producing since 31-12-19)	Viana do Castelo	2020
	Kincardine	KOWL (Majority by Cobra Group)	UK	50	wind farm (in construction)		2021
Operation	Hibiki (is this also called Kitakyushu NEDO Next Generation Demo?)	IDEOL / NEDO	Japan	3	full-scale demonstrator	Kitakyushu	2018
	Floatgen (SEM-REV testing site at Le Croisic) 4C Offshore	FLOATGEN (includes IDEOL / Uni of Stuttgart / ECN / RSK Environment Ltd) 4C Offshore	France	2	full-scale demonstrator	off St-Nazaire port	2018
	Kincardine Pilot	Pilot Offshore Renewables Limited	UK	2	first turbine	North Sea (Forth/Cromarty). 4C Offshore	2018
	Fukushima Mirai	Mitsui Sozen (Fukushima FORWARD)	Japan	2	full-scale demonstrator	Fukushima	2013
	Fukushima Shimpuu	Mitsubishi (Fukushima FORWARD)	Japan	7	full-scale demonstrator	Fukushima	2016

Status	Project	Ownership - Developper	Location	Total capacity (MW)	Development status	Region details	Installation
	Hywind Demo	UNITECH Offshore A/S - Equinor ASA (previously Statoil ASA),Siemens Wind Power A/S	Norway	2.3	2,3MW demonstrator	Karmøy	2009
	Fukushima Kizuna (Advanced Spar)	Japan Marine United (Fukushima FORWARD)	Japan	NA	full-scale demonstrator	Fukushima	2013
	Fukushima Hamakaze	Japan Marine United (Fukushima FORWARD)	Japan	5	full-scale demonstrator	Fukushima	2016
	Hywind Scotland Pilot Park	Equinor (75%) / Masdar (25%) - Hywind (Scotland) Limited	UK	30	Floating Pilot Park	Scotland, Grampian	2017
	Sea Twirl S1	Sea Twirl	Sweden	0.3	30kW demonstrator	Lysekil test site	2015
	Floatmast	Streamlined Naval Architects LTD, ETME, ERGOMARE S.A., and Enalios Diving Center	Greece	NA	full-scale demonstrator	Aegean Sea	2019
Planned	Sea Twirl S2	SeaTwirl AB,Colruyt,NorSea Group	Norway	1	full-scale demonstrator	Rogaland	2020
	TetraSpar Demo	Innogy SE,Shell New Energies,Stiesdal Offshore Technologies	Norway	3.6	full-scale demonstration	Rogaland	2020

Status	Project	Ownership - Developper	Location	Total capacity (MW)	Development status	Region details	Installation
	Pivot Buoy - PLOCAN (CHEF PROJECT)	X1 Wind (and financed by the European Union through Horizon 2020)	Spain		scale demonstrator	Islas Canarias	2020
	Groix & Belle-Ille	EOLFI -CGN	France	28.5	pilot farm		2021
	EolMed	Quadran - IDEOL	France	28.5	pilot farm		2021
	Provence Grand Large	EDF Renouvelable	France	24	pilot farm	Faraman zone	2021
	Golfe du Lion	ENGIE - EDPR	France	30	pilot farm		2022
	FLOTANT		Spain		scale demonstrator		2022
	Reedwood Coast	RCEA	USA	150	wind farm		2024
	Saipem Hexafloat Windpark	Plambeck Emirates LLC	Saudi-Arabia	500	wave tank tests / full-scale prototype is planned off Ireland		2030

Status	Project	Ownership - Developper	Location	Total capacity (MW)	Development status	Region details	Installation
	DemoSATH	Saitec Offshore Technologies S.L.U.	Spain	2	full-scale demonstrator	País Vasco	2021
	Hywind Tampen (supporting 2 o&g platforms)	Equinor (and partners at Gullfaks and Snorre) i.e. Petoro AS,OMV (Norge) AS,Equinor ASA (previously Statoil ASA),ExxonMobil Exploration and Production Norway AS,Idemitsu Petroleum Norge AS,DEA Norge AS,Point Resources AS	Norway	88	wind farm	Sogn og Fjordane (Norwegian Continental Shelf (NCS))	2022
	Dyfed Floating Energy Park	Floating Power Plant A/S,DP Energy Ireland Ltd	UK		full-scale demonstrator	Wales	

Table 3.5-1 – Market Watch – Projects in Construction, operating and planned regarding Floating Wind

4.1 Main configurations used currently in the industry

Currently two configurations seem to be selected with the ones described in section 3.4.1. These present the main advantage of having limited ancillaries or relatively standard and good decoupling capability between floater motions and soil connection. These two configurations are respectively the Lazy Wave configuration and Tethered Lazy wave configuration as described below.

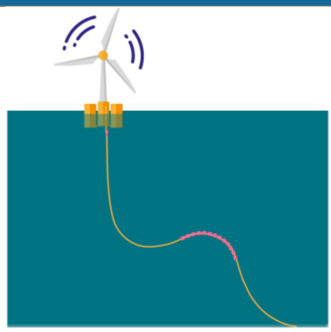
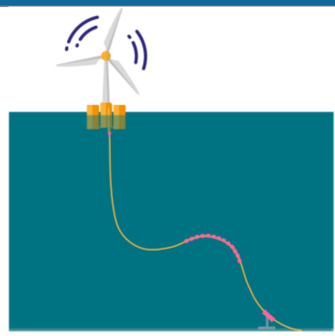
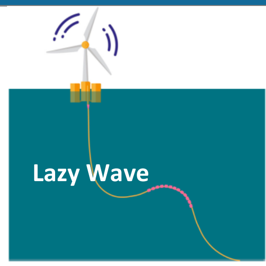
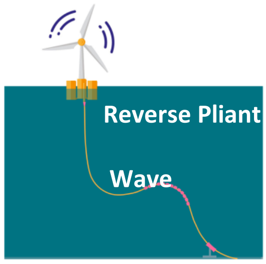
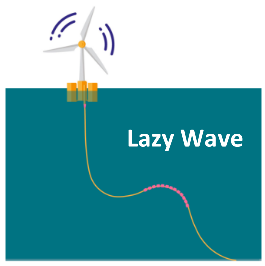
Name	Lazy wave	Tethered wave (Reverse pliant wave)
Description	 A lazy wave is like catenary, but support is provided about midwater by buoyancy modules.	 A tethered wave is like a lazy wave with the addition of a tether restraining the touchdown point.

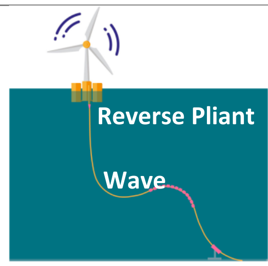
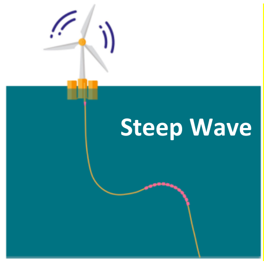
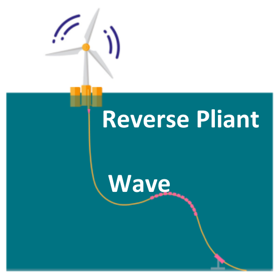
Table 4.1-1 – Main configurations used in Floating Wind industry

4.2 Configuration versus Floater type and water depth

Selected configurations will be driven by environmental conditions, floater excursion and floater dynamics. The following table provides guidance of floater type versus potential dynamic cable configuration:

Name	Environmental conditions (Current and Wave conditions) & Marine Growth	Comments	Possible / Foreseen configurations
Semisub **(Image / Source [48])**	Calm to moderate Wind, current and wave conditions Cable weight Variation due to Marine growth limited	Implies Catenary or Semi taut mooring, considering Calm to moderate conditions excursions will be limited. Marine growth Weight / Cable Weight < 20% (Indicative). Limited impact of marine growth on configuration equilibrium in water column.	

Name	Environmental conditions (Current and Wave conditions) & Marine Growth	Comments	Possible / Foreseen configurations
			
	Severe environmental conditions Severe weight variation due to Marine growth	Implies Catenary or Semi taut mooring for which high excursion can be obtained considering severe environmental conditions. Marine growth Weight / Cable Weight > 20% (Indicative). Significant impact of marine growth on configuration equilibrium in water column. Line anchoring required to enable position variation due to marine growth.	
Spar-Buoy **(Image / Source [48])** 	Calm to moderate Wind, current and wave conditions Cable weight Variation due to Marine growth limited	Implies Catenary or Semi taut mooring, considering Calm to moderate conditions excursions will be limited. Marine growth Weight / Cable Weight < 20% (Indicative). Limited impact of marine growth on configuration equilibrium in water column.	 

Name	Environmental conditions (Current and Wave conditions) & Marine Growth	Comments	Possible / Foreseen configurations
	Severe environmental conditions Severe weight variation due to Marine growth	Implies Catenary or Semi taut mooring for which high excursion can be obtained considering severe environmental conditions. Marine growth Weight / Cable Weight > 20% (Indicative). Significant impact of marine growth on configuration equilibrium in water column. Line anchoring required to enable position variation due to marine growth.	 
Tension Leg Platform **(Image / Source [48])**	Calm to moderate Wind, current and wave conditions Cable weight Variation due to Marine growth limited	Implies Taut mooring, considering Calm to moderate conditions excursions will be very limited. Marine growth Weight / Cable Weight < 20% (Indicative). Limited impact of marine growth on configuration equilibrium in water column.	
	Severe environmental conditions Severe weight variation due to Marine growth	Implies Taut mooring, considering Calm to moderate conditions excursions will be limited. Marine growth Weight / Cable Weight > 20% (Indicative). Significant impact of marine growth on configuration equilibrium in water column.	

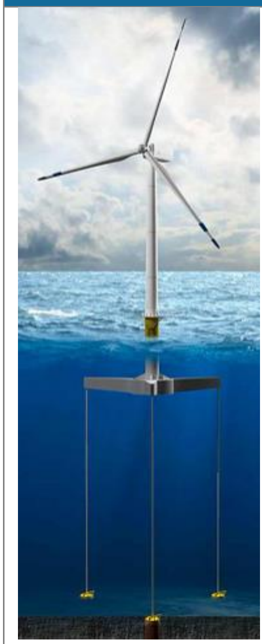
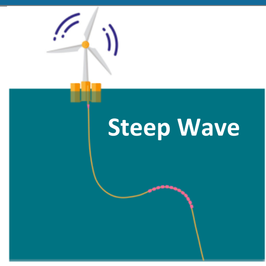
Name	Environmental conditions (Current and Wave conditions) & Marine Growth	Comments	Possible / Foreseen configurations
		Line anchoring required to enable position variation due to marine growth.	

Table 4.2-1 – Configuration versus floater type

4.3 Excursion range

Little information has been extracted from the literature review about floater excursions used as input for dynamic cable configuration design. Current position on COREWIND is to take a varying value with respect to water depth function of selected sites:

- For 100 m case, 30% of water depth is defined based on on-going projects feedback.
- For Deepwater case (870 m), and based on O&G standard, excursion limitation is function of water depth and ranges between 5% to 12% typically (for Intact and damaged cases respectively) which would give an upper bound of 104 m approx.
- For the intermediate case (250 m), an intermediate value 60 m (2 x 30 m) is proposed (24% Approximately of water depth.

This is a starting point and target for mooring design and dynamic cable design but will be determined precisely within further WP2 and WP3 tasks.

5 INSTALLATION AND MAINTENANCE TECHNIQUES

5.1 Installation

This section introduces how dynamic cables are installed on floating offshore wind turbines and how this procedure is integrated into the entire installation process. Before the engineering and installation phases of a project, geotechnical and geophysical surveys for the field are normally undertaken. They provide information on the project specific boundary conditions. Going into the installation phase, special vessels are hired to do the job. At the end of this section examples of floating platform installation from the offshore wind but also from the oil and gas sector are presented.

5.1.1 Preparation

5.1.1.1 Site Investigations

Site surveys are normally executed before the engineering and installation phase in order to inform a project risk assessment. They provide information about the subsea terrain, topography, soil properties and include hazard identification, hazard and operability studies and/or failure mode and effect analysis (FMEA) to outline the project specific conditions at the site [5], [6]. Generally, two kinds of surveys are undertaken:

Geophysical Survey

The geophysical survey is a non-penetrating survey. A vessel traverses the project site emitting pulses via magnetometer. Through this approach, nearby boulders, shallow faults and debris flows can be identified. Additionally, seismic tests are undertaken. By sending seismic pulses via powerful air guns, different layers of the seabed can be identified to a certain depth. In Figure 5.1-1 an illustration of a geophysical survey can be seen. In addition to the survey vessel, an ocean bottom hydrophone is also illustrated on the left of Figure 5.1-1. It is used to detect seismic energy in form of pressure changes under water during the seismic survey.

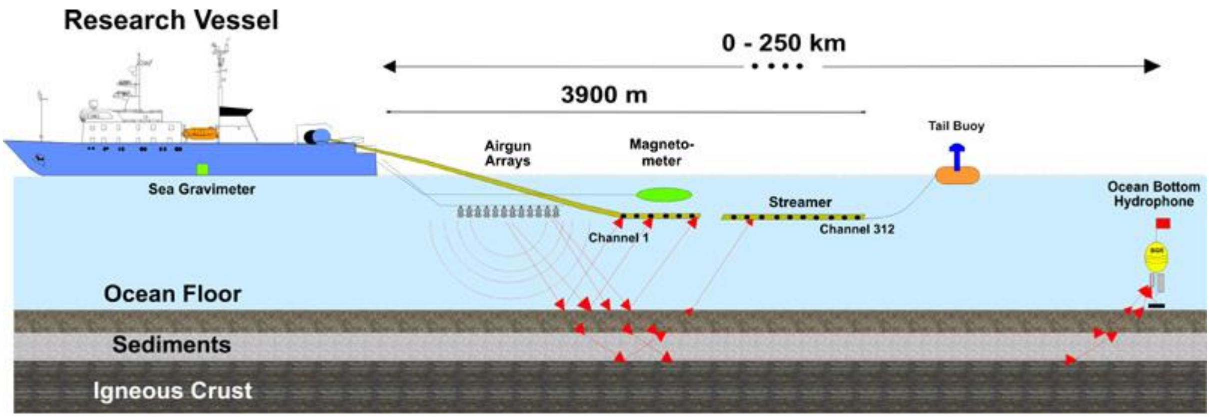


Figure 5.1-1 – Illustration of a Geophysical Survey; Source: [7]

Geotechnical Survey

Within the scope of geotechnical surveys soil sampling and soil investigations are being conducted. By drilling, 6m soil samples can be collected which are analyzed in the lab in order to determine soil properties. In addition, cone penetration tests are being used to test the resistance of the seabed towards penetration of a test cone object.

Specially for engineering the mooring system, and to develop a potential static cable route, site investigation is a standard procedure [5]. For engineering the dynamic cable, it can be assumed that no extra surveys are conducted but that relevant information (mostly related to the geophysical survey) is provided to the dynamic cable supplier.

5.1.1.2 Logistical Processes before Installation

This sub- section briefly explains the logistical processes related to the dynamic cable before the actual installation process. Figure 5.1-2 describes how information and cables flow in the logistical process prior to the installation.

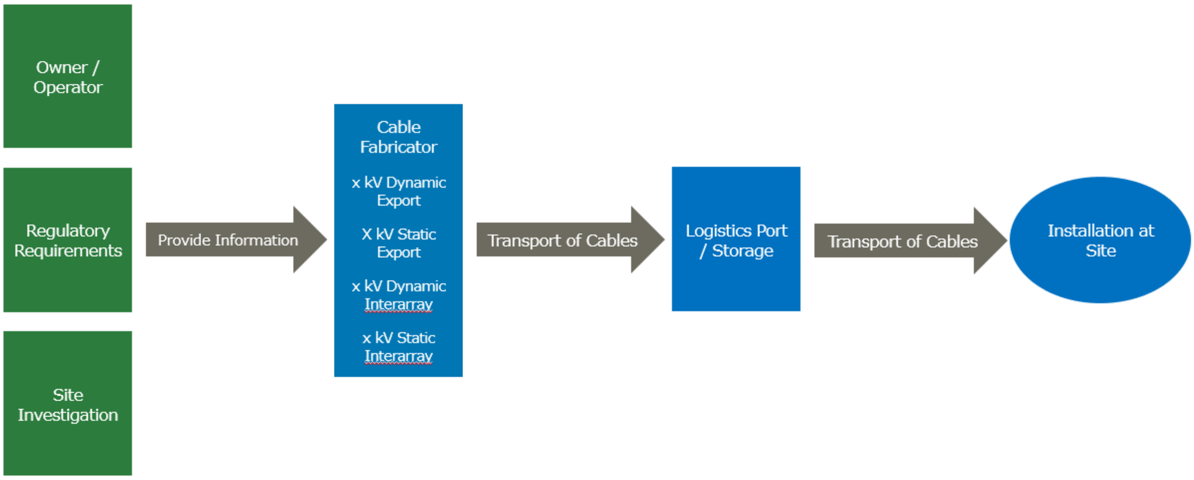


Figure 5.1-2 – Logistical process related to dynamic cables prior to installation

Fabricator

After the cable fabricator was contacted, information regarding the conditions of his scope of work are provided. Owner and/or operator of the windfarm, regulatory requirements as well as relevant conditions found by the site investigation are communicated to the fabricator. It must be considered that submarine dynamic power cables are mainly specialized products and usually not available as off-the-shelf components. Important parameters for choosing the fabricator are its fabrication rate as well as the fabrication costs and quality that differ from fabricator to fabricator.

Transport to Logistics Port for Storage

Transport of the electrical components is a major cost factor in the whole logistics process. Due to the large dimensions of the cable components transport via ship is the most common option. Loading times at the departure point and the port of destination must be considered when calculating the total vessel cost. In addition, weather related restrictions need to be taken into consideration when determining time estimates for the transportation process.

Storage at the Logistics Port

At the logistics port, storage underlies certain restrictions that are often times dictated by the fabricator, the logistics port itself or the project owner/operator. They should be followed in order not to damage the cable in any way and to keep it in an operational condition. Storage costs are the main cost drivers. To minimize them and to prevent possible unexpected damage to the cable during storage, storage time should be reduced to a minimum. Therefore, close communications with the dynamic cable fabricator should be established during the project ramp-up.

Transport and Installation at the Project Site

The transport to the installation site underlies the same parameters and conditions as the transport to the logistics port. In the following section 5.1.1.3 the overall installation is presented. A detailed view into the installation procedure of dynamic power cables is given in 5.1.2.

5.1.1.3 Installation Timeline

In this section the installation procedure will be described, which was also partly addressed in LIFES50+ D5.5 report [8]. The starting point is defined after the fabrication of the substructure is completed. The procedure is representative for a semi-submersible floater. For other designs, for example TLPs the procedure may vary, but most steps are generally applicable. Generally, the installation consists of six steps, which can be seen in next figure.

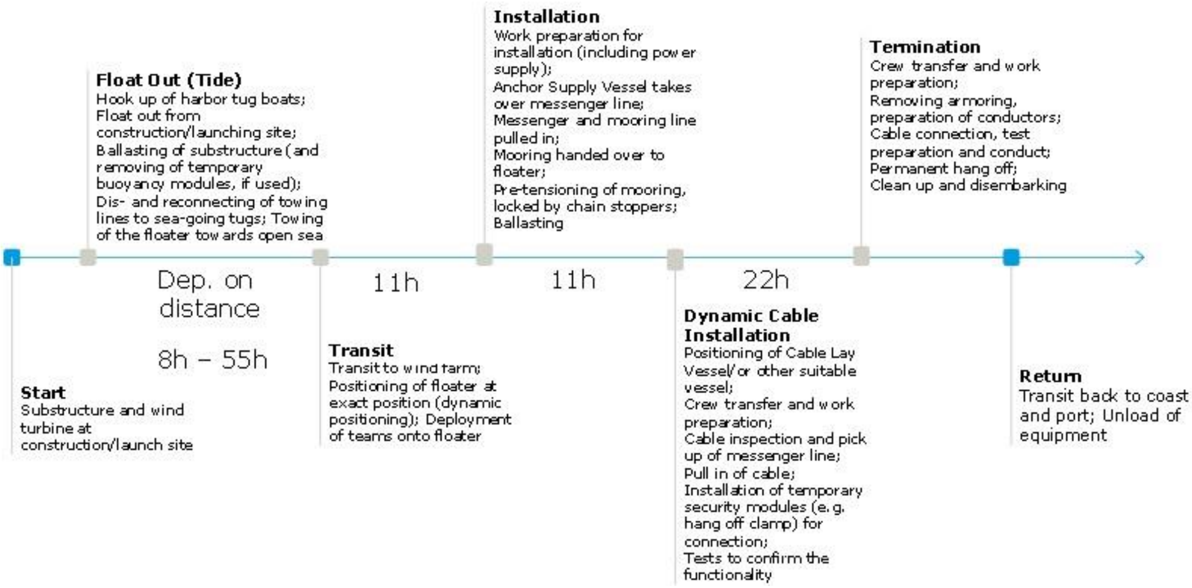


Figure 5.1-3 – Overview of Floating Offshore Wind Turbine and Dynamic Cable Installation Procedure; Source: [8]

The steps float out, transit and installation will be explained in detail below. The installation of dynamic cables as well as the termination will be addressed extensively in 5.1.2 and 5.1.3.

Float Out

The float out is the transfer a structure from a dry construction site to a self-floating condition. It consists of the actual float out from either the quayside assembly location, or the dry dock or construction barge into the harbor basin and the preparation for transit to the wind farm. Depending on the port choice and assembly procedure, the float out may either take place after the wind turbine is mounted on the substructure (in case of dry docks), or before the float out (if the structure is assembled quayside). In the latter case, the substructure (without WT) is first launched into the water, e.g. on soft ramps using airbags or using specialized skidding systems or cranes (if the mass is sufficiently low), floated to the quay location where the crane for WT assembly is located, and then ballasted to rest on a prepared seabed section within the harbor basin. Once the WT and floater are mated, the float out procedure is initiated by de-ballasting the substructure. For substructures produced quayside, the float out process may also include load out (transfer a structure from land onto a vessel) and float on/off (transfer a floating structure onto a vessel and vice versa) operations. In case the construction shipyard and installation port are not identical, the load out and float out may occur at different ports. For dry-docks, the float-out action is typically performed by tug boats, which enter the dock and hook the floater up. They connect the towing lines to the floater and ensure that the floater is not damaged due to an uncontrolled contact with the dock walls. This operation might be affected by weather conditions. In general, the float out is the first time that the FOWT (substructure and WT) is free floating and therefore wind and waves must be considered. In addition, the tides may influence the float out schedule. Especially in smaller ports, where the depth of the basin does not exceed the floaters draft significantly, this is important. During the launching and the actual float out, the floater is likely to use the minimum ballast with the smallest draft possible to safely perform the operations within the port, where typically the draft is limited. If the floater's draft still exceeds the depth of the construction port or dry-dock, additional buoyancy modules will have to be installed. After the floater has entered deeper water, the buoyancy modules are removed, and it is ballasted for transit. Equipment for these actions may include, amongst others tug boats, winches, rigging and slings, pumps, slides, skidding systems, and possibly cranes. The towing vessels for the transit then connect to the floater. This includes the dis- and reconnection of different towing lines, so that the tow out can be executed. The last step is to exit the sheltered harbor area, possibly crossing shipping routes, and then head towards the open sea.

Transit

After the tow out, the floater is brought from the construction site to the wind farm. It must be ensured, that the tug vessels can transport the floater safely, regardless of possible weather changes. For this operation environmental restrictions regarding primarily wave height and wind speed must be considered. Since the floater is not fully ballasted and also unanchored, the stability of the floater is likely considerably different than after the installation, which must be considered. Due to the fact, that at this point the wind turbine has already been installed, the wind speed should not exceed a certain level. Additionally, a maximum wave height for this operation should also be defined and not exceeded as well. Even though, the limits are less restrictive compared to the actual installation, weather related limitations need to be adhered to, especially for increasing distance between port and wind farm. Large distances between port and wind farm cause higher possibilities for a change in the weather during the transit and installation process. Reasonable assumptions for weather limits during the tow-out are part of transport analysis. The required weather window, however, highly depends on the distance to the wind farm from the logistics port, meaning that this value cannot be applied to any other project. The distance between port and wind farm influences the required time for the tow-out as well. Due to the typically low towing speed, the time for the transit increases significantly if the distance is higher. It will be shown later, that the overall installation time in many cases mainly depends on the tow-out and transit time. Therefore, the aim should be to reduce the towing distance. After arrival of the floater at the project site, the exact installation position is to be determined. Therefore at least one tug-boat must be equipped with a dynamic positioning system. The last step of the transit is the deployment of teams and tools onto floater or other vessels in order to prepare the installation process. A Fast Rescue Boat might be required. During this step the floater must be held in place. This step may be executed before the final positioning of the floater.

Installation of the floater

The actual installation process is initiated with the installation preparation. These preparations depend on the chosen techniques and vessels and cannot be generally described without further information about the intended methods. After the preparation, the mooring lines are extracted from the water and hooked-up by Anchor Handling Tug Supply Vessels (AHTSV). This can be a rather complicated procedure that is not further discussed here as it is out of scope. The installation procedure has weather restriction and it must be taken into account that high wind speeds and waves can influence the installation process. However, restrictions due to wind are often times much less significant than for bottom-fixed offshore wind systems, where the wind influences the offshore assembly of the wind turbines.

5.1.1.4 Cable Vessels

In order to assure a smooth installation of the dynamic cables after hook-up the choice of the installation vessel is crucial. It is dependent on the cable design, cable length, water depth, the deployment area as well as the prevailing environmental conditions and its costs [1]. It should be considered that it is more difficult to effectively install cables in deeper waters than in near-shore operations [9]. For handling the grid connection via dynamic cables simple tugboats are unfeasible. Therefore, larger and more specialized vessels are required [8]. Vessels typically used for dynamic cable installations are cable barges and cable laying ships. The latter vessel type is typically more expensive than cable barges due to its specialization on cable handling. The following items should be considered when selecting cable installation vessels [1]:

- Adequate storage for the cable lengths and weight in drums, coils or turntables
- Maneuverability to determine accuracy of laid cable on the selected route
- Tension control equipment, tension measuring instrumentation and cable deployment system
- Deck facilities for cable installation and recovery for repair
- Workshop facilities for equipment repair and cable jointing
- Control rooms for all equipment and data logging system
- Global positioning system for accurate positioning of the cable on the ocean floor
- Navigation and propulsion system to hold the vessel on station

Cable Barges

A barge is a flat bottom vessel which normally is not self-propelled and therefore relies on tug boats, anchors and winches to move and position it. The tug boats are used to move individual anchors one at a time while the barge adjusts its position using the fixed anchors [1]. This technique has to be applied carefully, if there are any electrical or mooring components on the seabed nearby. Using a barge is the cheapest installation method but comes with several limitations and typically further additions are necessary. Barges normally underlie limitations on the cable length and weight so that long cable lengths can be an issue. Additionally, barges do not come with integrated turntables to easily store and unwind the cable during its installation. But they can be fitted with equipment such as tensioning caterpillars and storage drums. Adding an autonomous or remotely operated vessel (ROV) to the installation equipment can be a helpful step to reduce risk during installation [1]. ROVs can do a lot of the necessary underwater work without exposing divers to the risk of the ocean environment [9]. In direct comparison to cable ships barges are relatively slow moving and regarding the prevailing weather and water conditions it has to be predetermined whether a barge is suitable. Barges can be equipped with a differential global positioning system to identify its exact position during installation but are typically not equipped with thrusters for station keeping. Due to the limitations in length and weight cable barges may be more useful for windfarm array cable installation where the distances are shorter and the cables smaller than the export cable [1].

Cable Ships

In contrast to cable barges the specialized cable ships are self-propelled and often come with dynamic positioning systems and thrusters to maintain position on-station. Data logging while positioning the cable can provide an important data to be used in later project stages. Cable laying vessels are typically equipped with capstans, caterpillars or multiple wheel linear type machines that provide control over cable tensions and installation speed. Turntables prevent cable twisting, while sonar, depth sounding, and fault location equipment facilitate the installation process. Most of the vessels come with an integrated ROV and large workshop areas allow jointing and storage of equipment in addition to regular crew accommodations. To give an example Van Oord´s cable ship 'Nexus' can accommodate 90 workers and up to 5,000 tons of cable on the carousel. It can be seen in the following Figure 5.1-4.

Figure 5.1-4 – Van Oord`s Cable Laying Vessel 'Nexus'; Source: [10]

5.1.2 Dynamic Cable Installation

The connection of the floating wind turbine to the grid is the next step during the installation. The choice of the electrical cable is usually determined by the mooring system and the design offset of the floater [8]. Due to the offset of the floater from the initial position caused by environmental forces during operation, the cable must be designed to accommodate for the motion of the floating platform within the watch circle (typically by being installed in a lazy wave configuration). The cable laying must be planned with respect to the anchor and mooring line position.[8]

To understand how the installation of dynamic cables takes place it is helpful to review the target state after installation, illustrated in next figure.

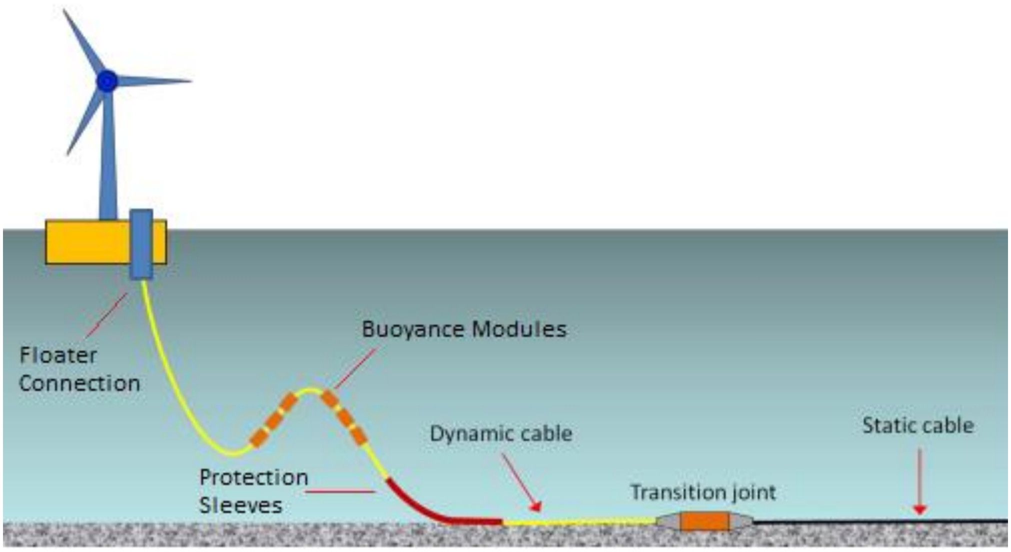


Figure 5.1-5 – Components of a Dynamic Cable System; Source: [1]

To install the dynamic cable on the site there are currently two procedures that differ depending on how the floater is being deployed to its final location (1st: floater is already hooked-up and dynamic cable is not yet deployed; 2nd: dynamic cable is already pre-laid and floater installation is following). In both cases the static cable is already in place on the seabed.

Dry-storage

In the first case presented, the floater is being positioned at the installation site, prior to deploying the dynamic cable. This is called “dry-storage”, because the dynamic cable is still on a turntable, drum or on a coil before its actual connection [1].

As the floater has been hooked up with the mooring lines, the cable laying vessel with the dynamic cable onboard can start its work. As a first step it is recommended to undertake a so-called ”first-end pull in”, where the dynamic cable gets attached to the floater while the rest of the cable is still on the installation vessel. This comes with the advantage, that the rest of the cable is still on the vessel and other interarray cables around the floater are in smaller risk to be damaged during installation. To manage this pull-in operation, a project specific procedure should be developed, based on an analysis considering friction between cable and platform, effects of vessel motion, minimum allowable cable bending radius, maximum side wall pressure and maximum tensile load. During the pull-in operation these parameters shall be monitored [6]. To pull the cable into the platform, the floater should be fitted with so called “Messenger Wires” while the cable end is wrapped with so-called “Chinese Fingers”. Before installation of the dynamic cable, the messenger wire is normally hanging out of the floaters entrance point (J- or I-Tube) to connect with the approaching dynamic cable via the chinese fingers. For a better understanding of this procedure, an exemplary cable end with Chinese fingers wrapped around it, can be seen in next figure below.

Figure 5.1-6 – Chinese Fingers on cable end; Source: [35]

After successful connection with the chinese fingers, the messenger wire pulls the dynamic cable through the J-tube into the floater [11],[1]. Running the dynamic cable through the floater can be challenging. If the length from hang-off point to the switchgear (GIS) inside the structure is too long, the cable becomes unmanageable inside the structure. As the cable reaches its destination at the GIS it is secured at a temporary hang-off point but not yet connected to prevent damage during further installation steps.

Now, that the cable is secured on the platform the cable laying vessel moves the rest of the cable away towards its next location. During the placement of the cable, inspections shall be performed. A ROV can be used to determine the completeness and adequacy of the ongoing installation [6]. Another option to assure the cables condition is monitoring during the cable laying process (see 5.2.4.2). During unrolling the cable naturally wants to return to the shape it took while being stored on the carousel. Without monitoring and keeping the appropriate tension during installation, lopping can occur [9].

Like mentioned above, the static cable has already been laid in advance, sealed and stored on the seabed. As the cable lying vessel reaches the jointing point a detailed planning of the jointing process is required. It should include a qualified and well-trained crew as well as a suitable vessel and equipment. The vessel should be stable enough to handle two cable ends including the transition joint. Equipment like cranes or ROVs should be able to reach a certain depth for cable laydown [6]. At this point, there are two possible techniques to facilitate the jointing process which depend on the kind of transition joint installed. In the case presented above, the transition joint is mate-able (it can be dissembled and re-connected without harm). The non-mateable joint will be explained in more detail in the next case. Mate-able joints can be wet-mate or dry-mate connectors. While wet-mate connectors can be mated and de-mated underwater by a ROV (using ROV normally comes with a cost reduction), dry-mate connectors must to be assembled outside the water on the vessel. Therefore, the static cable end has to be pulled up and after connecting the two cables, the transition joint must be lowered carefully to its planned resting place.[1]

Wet-storage

In the second case, the first-end pull-in operation is not possible. Therefore, it may be necessary to store the dynamic cable offshore and do the pull-in at a later time. This is called "wet-storage". It is useful, when the float out operation of the substructure is delayed or certain logistical parameters allow a pre-lay-up of the whole electrical system in one process including static and dynamic cable. [1]

In this case, both, a permanent or a mate-able transition joint can be used. After assembly, permanent connectors can only be separated by cutting the cables. When a mate-able connector is used, an onshore pre-lay-up assembly (if possible) is recommended in order to reduce offshore installation time.

The wet-storage procedure requires a waterproofed sealing at the free end of the cable. Additionally, it should be fitted with appropriate rigging and ground rope to enable a safe recovery for later attachment to the floater. The position of the cable within the surveyed route corridor needs to be recorded and all parties involved in nearby offshore operations must be informed about the location of the cable. For identification and to facilitate the pick-up for later attachment the cable can be outfitted with buoyancy modules. Those prevent sinking and the buoy visualizes the cable's position.

After the cable is laid-up and the substructure has arrived at the site for its installation, the pull-in operation can take place like described above. With the only difference being, that the cable vessel is approaching to the floater with the dynamic cable already attached to the seabed.

5.1.3 Conclusion of Installation process

After the installation of both FOWT and cable, the process is concluded with the power connection. Before the power connection is initiated, the floater is ballasted, and the final tensioning of the moorings is done by winches. The power connection requires electrical operations and varies depending on the chosen WT and other external factors. Because this step takes place on the FOWT only, no specialized vessel is required but specialized equipment is needed and transferred onto the FOWT. After the removal of temporary attachments and parts such as the cable armoring, the conductors are prepared and connected to the cable system from the switchgear. Before the connection is possible, the armored wires of the dynamic cable need to be removed. For the dismantling process, the required electrical equipment should be in an accessible position with sufficient space. Additionally, the screens of the phases and the sheath of the optical fiber cable need to be earthed[6],[12]. For the electrical connection "dry-connectors" for each phase at the cable termination are used. For floating offshore wind turbines (FOWT) this connection is required to be pluggable [13]. This allows mating and de-mating without loss of quality in case the floater needs to be towed-in for major repair work (see 5.2.6.3). Additionally, the possibility of separating these parts of the electrical system shortens the offshore installation time and allows individual testing of these items (see 5.2.4.2) [14]. While dry-connectors were able to handle up to 132kV in 2014 it can be expected that state-of-the-art dry-connectors are now able to handle up to 170kV [1],[14]. Optical fibers contained within the power cable should be terminated in suitable boxes / cabinets which provide adequate space for splicing and are designed for offshore use. All connections for current-carrying parts and earthing connections should be fixed to prevent loosening due to floater movement. As for bottom-fixed offshore wind systems, additional safety requirements need to be fulfilled. This implies additional power wires to be used in case of emergency. After the electrical connection is done, a set of tests are conducted to ensure the functionality of the unit. Wave heights should stay in a moderate range during testing.

Figure 5.1-7 – Animation of a dry connection between sea and tower cable inside tower, Source: [14]

5.1.4 Examples

Fukushima Demonstrator Project

For the Fukushima Demonstrator Project off the east coast of Japan, a floating substation approximately 25km off the coast was connected to a switching station onshore in the years 2014 and 2015. Additionally, dynamic cables were laid from the substation to a 2MW FOWT. The status after installation can be seen in next figure below. In the following, the steps for cable installation regarding connection from shore to substation are explained. For the installation procedure, the dry-storage method (section 5.1.2) was used including a dry-connecting transition joint.

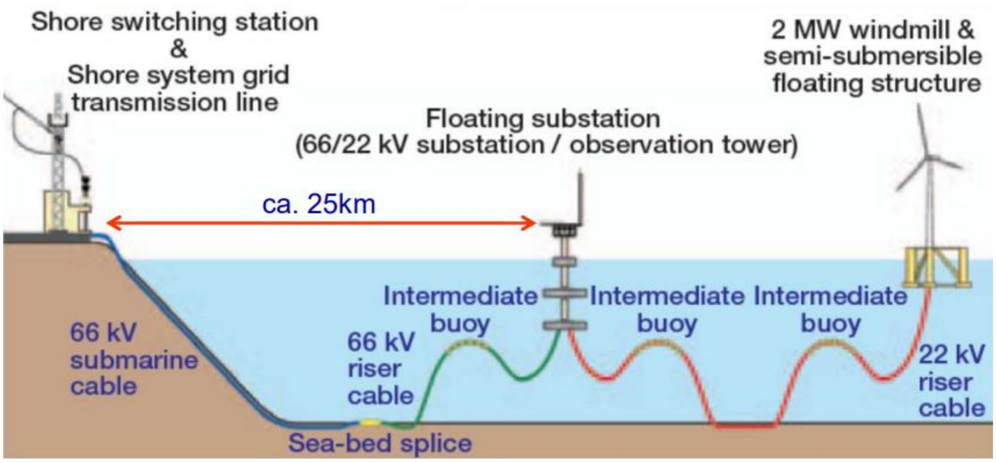


Figure 5.1-8 – Illustration of aspired status after installation; Source: [15]

As a first step, the static export cable was laid and stored on the seabed prior to being connected to the dynamic cable. The laying procedure was conducted by a specialized CLV, such as presented in 5.1.1.4. After the static cable was secured on the seabed, the dynamic cable was ready to be attached to the floating substation. While moving towards the termination of the submerged static cable and away from the substation, the CLV lowers the dynamic cable with attached buoyance elements until it reaches the jointing-point. To connect the static with the dynamic cable, the submerged static cable had to be pulled up while holding the termination of the dynamic cable. It is not clear if a ROV has been used or if the cable was pulled on the attached buoyance modules. After successful recovery, the CLV connects the two cables via the onboard-stored transition joint including static bend stiffeners which protect the entries to the transition joint. Subsequently, both cables are lowered to the seabed. In the following figure the described procedure is illustrated.

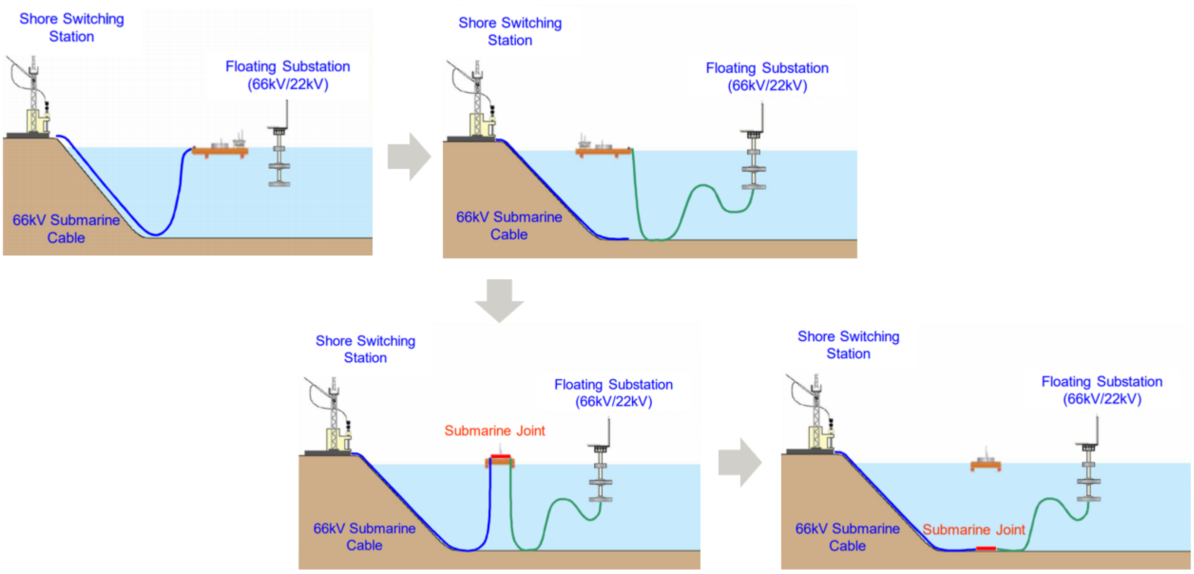


Figure 5.1-9 – Illustration of the Cable Installation from substation to shore; Based on: [15]

Figure 5.1-10 – Pictures from the Installation Procedure of Fukushima Demonstrator Project; Source: [15]

Figure above shows selected pictures of the installation procedure:

Top left: Transition joint on the CLV with bend stiffeners (yellow) at each side

Top right: Dynamic Cable with bend stiffeners (yellow) on CLV shortly before being attached to substation

Bottom left: Dynamic Cable laying at wind turbine

Bottom right: Dynamic Cable attached below turbine (bend stiffeners give conical shape at entry point)

Oil and Gas Platform at Gjøa

Another example for dynamic cable installation is the floating oil and gas platform in the Gjøa oilfield in the Norwegian section of the North Sea. The cable was transported and installed using a CLV with a loading capacity of 5,800t. To verify the methods for installation during the 98km route, a sea trial was performed previously. The trial included verification of the handling of equipment and cable accessories and to verify relevant conditions for cable-laying in deep water. The trial was also seen as a training opportunity for the cable laying crew. In contrary to the described installation at Fukushima, the entire cable system (including static and dynamic cable) was laid in one length with a flexible transition joint connecting the cables. The cable system consisted of a three-phase, 115kV static cable with 240mm² conductors and three-phase 115kV dynamic cable with 300mm² conductors. Both with an integrated optical-fiber cable, which is used for later monitoring (see 5.2.5). The cable-laying work came with several challenges, including:

- The shore landing of the cable
- Laying the cable down a steep underwater cliff including VIV suppression strakes
- Routing of cable through an exposed area of sea
- Laying cable at a water depth up to 540 m
- Continuous touchdown monitoring during cable laying using underwater ROV
- Safe handling and unloading of bending stiffener, pre-installed pull-in and hang-off body
- Installation of 73 permanent buoyancy modules for the “lazy wave”

During cable-lying, a continuous OTDR-Measurement was performed to monitor the cables condition. The OTDR-Measurement is explained in detail in section 5.2.4.2. Immediately, after positioning the flexible transition joint and installing the buoyance modules an electrical test was performed to verify the cable was still in an operational condition.

After laying the dynamic cable end (including the buoyancy modules), the bending stiffener and the pull-in head and hang-off body were temporarily placed on the seabed for approximately three months before the pull-in operation.

Before the pull-in operation, the wet-stored cable needed to be raised from the seabed. Its pull-in head was secured to the platforms messenger wire and the pre-installed hang-off body was then raised to the hang-off table on the platform. To finish the installation, the armored wires on the dynamic cable were removed and the three phase cables and the optical cable were connected. [16]

Figure 5.1-11 – Left: Cable drum on CLV at cable landing location; Right: Cable being pulled with messenger wire onto platform (yellow = bend stiffeners); Source: [16]

For a more detailed presentation of the whole installation procedure please see [16].

5.2 Inspection and Monitoring

After the successful installation, the cable owner and/or operator shall establish and maintain an asset management system in order to ensure smooth operation as far as possible [6]. Analysis of insurance pay-outs have shown that 70-80% of all pay-outs on offshore wind projects are spent on cable damages [17],[9]. This chapter is intended to cover methods of inspections as well as monitoring techniques of dynamic power cables which help to maintain these components economically.

5.2.1 Regulatory Requirements

In general, the overall structure shall be operated in accordance with the design and operating premises and the efficient operation must be assured regarding health and safety, environmental influences and the required system availability. Therefore, certain aspects shall be considered [6]:

- Philosophy for maintaining the integrity of the cable system
- Design and function of cable system
- Operational conditions of cable system
- Probability and consequence of failures
- Monitoring, testing and inspection methods
- Spare part considerations (policy, inventory)

To assure an unproblematic operational and maintenance procedure in-service activities should be established prior to the start-up operation. With these planned maintenance activities an inspection schedule should be developed.

5.2.2 Inspection Schedule

The inspection schedule should consist of two types of inspection. Firstly, starting with the first status assessment, especially important regarding an economical maintenance program is the decision on which basis long-term inspections are premised. The premises and requirements of the inspection schedule need to be updated during service life time. For each survey an extra detailed external inspection plan must be prepared including the specifications for the concerned survey which requirements are based on previous inspections [6].

5.2.2.1 As-laid inspections

To verify that the completed installation work meets the specific requirements and to identify the first cable conditions an as-built survey should be performed [6]. Due to the previous installation, space at the test location may be limited what may lead to reduced safe working distances. Additionally, it can be a challenge to get the test equipment offshore. Therefore, testing may have to be applied through adjacent components, e.g. testing all consecutive cables or all cables in a branch with one test or performing tests that require smaller equipment such as partial discharge measurements (see 5.2.4.2) [1]. Besides electrical tests, visual inspections can be performed (mostly by video-capable ROVs). Those recordings should be saved with comments made by the inspector. In general, every damage and any discrepancy between the actual as-built-status and the nominal planned state should be addressed with enough detail and documented in a report in order to facilitate future inspections. Additionally, a detailed list of all components can be attached including manufacturer, serial number and/or other identification [5]. To evaluate the need for an as-built survey its benefit must be compared with the costs and risks of testing [1], but analysis of cable failures due to mechanical damage had shown that damage that occurred during installation is often the direct cause of failure in service [18].

5.2.2.2 Long-term Inspections

After the installation procedure and the following as-built survey has been accomplished and the dynamic cables are in operation, the planned maintenance and inspection activities should be executed. General subjects of those planned activities include [1]:

- Route inspections/surveys
- Survey of subsea crossings with other cables or equipment
- Inspection of the cable
- Inspection of connection points (platform and transition joint)
- Removing of marine growth

The frequency of undertaking those planned inspections considers several aspects, as for example, the requirements of the authority and the cable operator, the probability and consequences of failure (which can be immense, e.g. downtime of the entire windfarm in case a major cable branch or the export cable is affected), and the results of previous inspections as well as changes in the operational conditions. Hence, critical sections of the cable system that are prone to damage or that undergo major changes in their service lifes should be at least inspected at adequate periods of time [6].

Maintenance can be distinguished into three different types which each differ from the trigger of the maintenance work. In following figure the different types and their classification are illustrated while their effects on the condition of the object to be inspected can be seen.

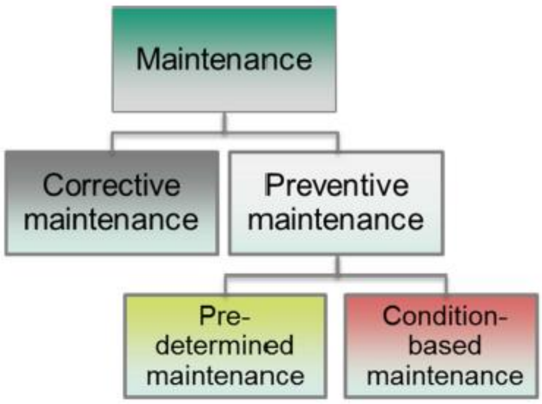


Figure 5.2-1 – Classification and types of Maintenance; Source: [19]

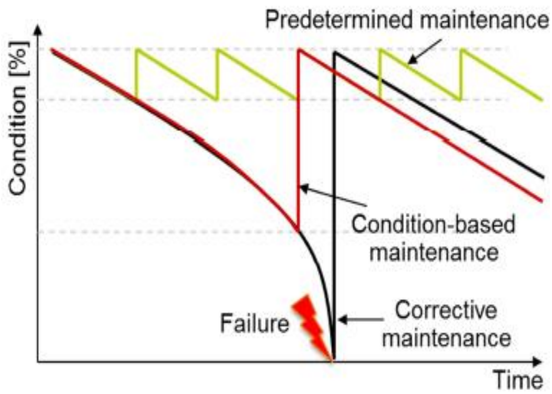


Figure 5.2-2 – ffects of maintenance types on inspected object`s condition, Source: [19]

Corrective Maintenance

Corrective Maintenance is a non-planned repair or replacement work after failure has already occurred. This kind of maintenance is especially expensive because locating the fault, organizing the external survey, getting access to the required equipment and personal and undertaking the actual repair work must take place as soon as possible and on a spontaneous basis [1], [17]. Related downtimes depend strongly on the prevailing weather conditions. How to handle major repairs is covered in 5.2.6.

Predetermined Maintenance

Also known as "Time Based Maintenance" (TBM), predetermined maintenance performs preventive maintenance based on a specified time schedule. This kind of maintenance is often the basis and is carried out as offshore surveys. As the observed condition is steady and no significant changes over several inspections can be seen the period between inspections can be increased. In the case of condition worsening the TBM may result in the next maintenance type [1].

Condition Based Maintenancea

The Condition Based Maintenance (CBM) is performed upon the condition of the cable and not with a fixed time interval. This allows pre-emptive repairs to minimize lost generations and allows the inspector to take advantage of predictable future surveys. Due to the larger distances from shore which floating offshore wind farms (FOWF) make accessible since they are easier to install in deep waters, travel time will increase significantly. Hence, a high-quality Operations & Maintenance plan and a decreasing number of visits is important in order to work economically [20]. The challenge here is to predict the remaining life time of the cable concerned. Good starting points are the observations at TBM activities and also are provided by monitoring the cable's electrical, thermal and mechanical characteristics [6]. These tests are not fail or pass measurements like at the as-laid inspections but their purpose is to follow the evolution of the cable system and to plan appropriate maintenance activities [1].

5.2.3 Failure Mechanisms of Dynamic Cable Components

Dynamic cables on floating offshore wind platforms experience great levels of mechanical stress due to their dynamic environment [21]. The cables are continuously subject to external forces like bending and twisting caused by floater movement and tidal current which can be seen in the following figure. Tensile forces normally do not apply on dynamic cables, since the mooring lines limit the floaters horizontal drift before the dynamic cable can reach its maximum stretch.

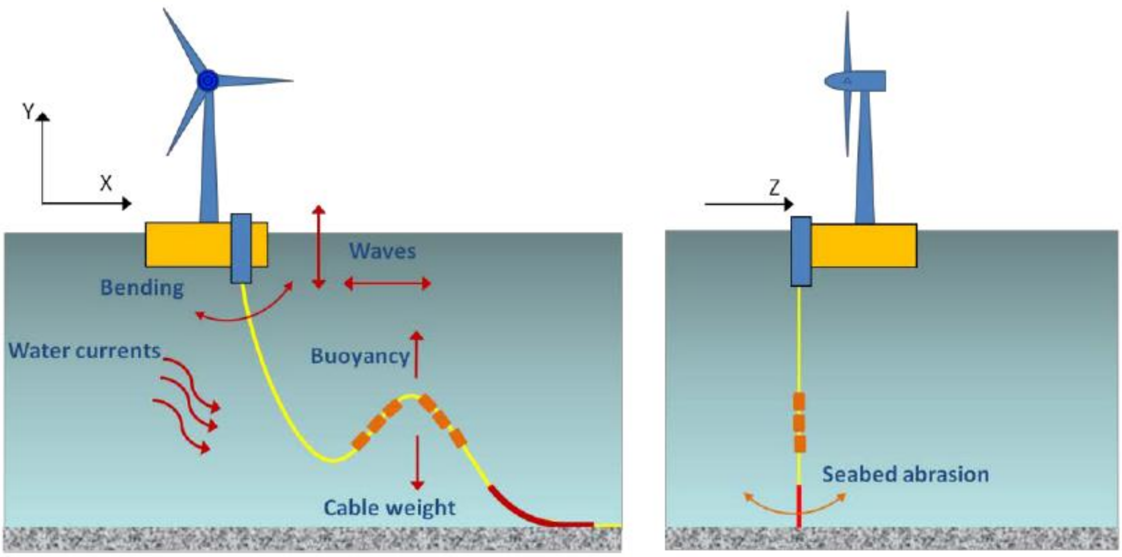


Figure 5.2-3 – External Forces on Dynamic Cables; Source: [1]

Hence, dynamic cables are likely to suffer damage in various sections during their operational time [22] but not only natural damages may occur as Table 5.2-1 illustrates.

Table 5.2-1 – Overview of submarine power cable damages applied to dynamic power cable; Source: [20];

Damage category:	Kind of damage:	Applicable:
Installation	Loss of Dynamic Positioning	yes
	Anchoring damages	yes
	Kink	less likely
	Loading / re-loading	less likely
	Trenching	no
	Small bending radius	yes
	Emergency cut	less likely
Human Activities	Fishing equipment	less likely
	Anchors	no
	Jack up	less likely
Operational	Free span	yes
	Joint failure	yes
	Geo-hazards	yes
	Internal defects	yes

Among damages that happen during the operational lifetime, damages in the installation and/ or maintenance process are also possible. As already pointed out in section 5.2.2.1, damages that occur during installation are often the direct cause of failure in service since the damage exacerbates due the natural forces described in previous figure. Damages caused by human activities, on the contrary, are less likely to happen due to a 500m-2000m safety zone recommendation for FOWF. This cannot be applied on static cables, especially export cables, which may cross existing shipping routes and are exposed to human activities.

After pointing out possible damage sources and explaining natural external forces acting on the cable this chapter will treat typical damages that should be considered while inspecting the different cable components. It can be said that areas that are subject to constant movement like the top end at the floater interface and the touchdown point at the seabed deserve special attention during an inspection.

5.2.3.1 Cable

Due to the dynamic environment the integrity of cable protection is in danger and mechanical damage like cut and abrasion can occur. This damage is often caused during installation when the cable is in contact with sharp edges during deployment and retrieval but can also be caused by falling objects. In the case of wet-storage the dragging on a hard seafloor can cause abrasion marks [5]. Once the insulation is damaged and show tiny pores soil and water can invade. Those pores do not have to be visible to the naked eye. Consequently, water trees in the cable insulation occur and weaken its integrity and enable electrical failure to occur. Water trees (can be seen in next figure below) take time to grow and propagate but are responsible for unexpected failures after an otherwise healthy cable´s lifetime [21].

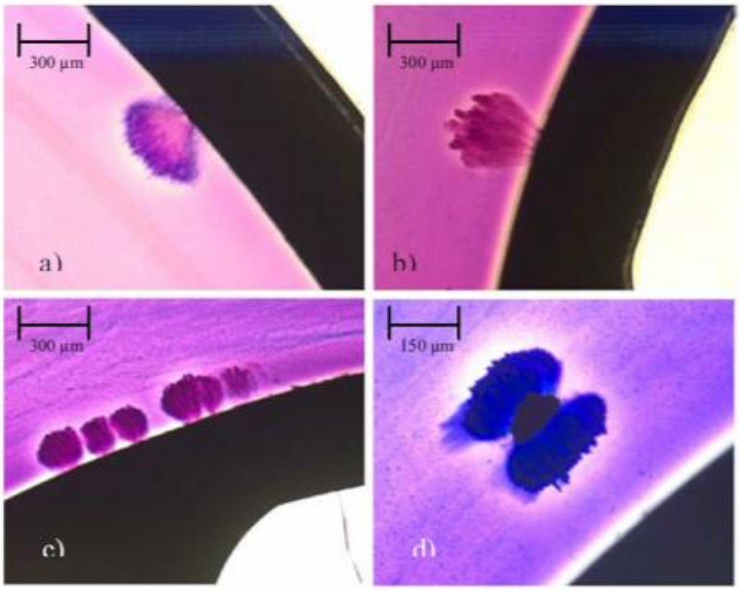


Figure 5.2-4 – Differing types of water trees within cable insulation layers; Source: [21]

Once the protection is no longer in-tact the mechanical forces accelerate mechanical fatigue as one form of damage may lead to another [18].

During operational time it can be expected that the buoyancy modules that keep the lower part of the dynamic cable from dragging on the seafloor are losing 10% of their buoyancy [20]. While inspecting it should be verified that the modules did not lose more buoyancy than expected and that the lower cable part is not rubbing on the seafloor. To reduce the weight of the cable and to protect the insulation from growing marine life the marine growth should be removed periodically.

5.2.3.2 Protection Sleeves

As mentioned above, the touchdown point of the dynamic cable represents a critical area that should be inspected closely. The interaction between the dynamic cable and the seabed should be carefully assessed. Driven by the cable movement abrasion will trigger premature damage of the outer protection layer which can be followed by water penetration, corrosion and mass loss. Therefore, the specially designed protection sleeves around the cable's touchdown point need to be checked on a continuous basis, while considering the surface quality of the prevailing ocean floor [1]. Considering the depth, a visual inspection by using a ROV is most likely.

5.2.3.3 Transition Joint

The transition from the static to the dynamic cable often contains extra equipment such as metallic screen disconnections or connection knots of fiber optic cables so that it makes sense to check it on a regular basis. Due to the deep location of the transition joint visual inspections can be made by using ROVs. To ensure the transition joint does not suffer thermal anomalies infra-red cameras can be used to detect local hotspots. Although the transition joint is placed on the seabed it is not exempted from movement. Moving sand dunes underwater or seismic activities can dislocate and bury the transition joint. Especially after seismic activities a re-survey should be undertaken [1]. In case of major debris on or around the cable joint the disturbance should be removed to prevent future damages that may occur [6]. Due to the transition from a dynamic to a static behavior the cable is subject to high degradation so that abrasion and wear marks can present themselves.

5.2.3.4 Substructure Connection

The top part of the dynamic cable which is attached directly to the floater experiences the most movement due to nearby floater motions. Nevertheless, in many cases it is the accessory attached to support the link between cable and floater that initiates the failure and not the cable. By movements or a simply poorly installed interface the accessory gets damaged which eventually will damage the cable [18]. Typical failure location at the platform are the hang-off point, the fixing clamps of the cable on the platform, the bending restrictors as well as damages to the coating which may lead to corrosion e.g. at the J-tube. Due to these damages the cable itself could get damaged and therefore needs to be inspected too (see 5.2.3.1). Those external damages are not the only potential failure occurrences. As well, the termination of the dynamic cable inside the floater needs to be inspected on a regular basis if not equipped with monitoring techniques [1].

5.2.3.5 Spare Parts

Dynamic subsea cables are mainly specialized products that are mostly tailor made for their purposes. This indicates that the delivery time in the case of cable failure might be long and that the concerned wind turbine is incapable of transport electricity. To make sure the spare parts remain in a good and operational condition they should be inspected on a regular basis. A visual survey is mostly enough to locate possible damages. Some products in the accessory kits have an expiring date and need to be replaced before. If possible, the management of the spare parts including undertaking inspections may can be outsourced to the cable supplier [1].

5.2.4 Inspection methods

In this section different inspection methods of dynamic cables are introduced. To differentiate “inspection” from the later used term “monitoring” (see 5.2.5) following definition is used:

Inspection is when human action (offshore or onshore) is required and executed to obtain condition data from site. The frequency of data collection is not the indicator for differentiation. However, monitoring data is usually measured continuously or in short-term steps (minutes, seconds), whereas inspections can be performed after longer time periods (weeks, months, years) or unscheduled on demand. based on [23], p.9.

Visual inspections have the purpose to determine whether a cable is, for the most part, in a good condition or if the environmental influences are causing the cable problems. The visual inspections are mainly kept general here as a common method of inspection in a dynamic environment (e.g. mooring equipment). The offline measurements are highly cable specific and are used to determine whether the cable has non-visible damages.

5.2.4.1 Visual Inspection

General visual inspection is the most common method that is carried out by a continuous slow ROV flight or diver swim past the item being inspected. The quality of this inspection depends highly on the knowledge of the inspector and on the prevailing water clarity and the access to the item. Therefore, it should be free of marine growth. To film and stream the item being inspected (whether by a ROV or diver) an adequate camera resolution is required. To allow a complete real-time record of the inspection process it is of advantage if the device used is capable of videotaping which allows to rewind when in doubt. Throughout the discovery of external damage possible internal damages can be deduced. [5]

To determine whether a ROV or a diver is best fitted to undertake this survey the item inspected must be considered. In shallow waters, diving could be successful but with a considerable safety risk to personnel even though all precautionary measures are taken. Especially when it comes to a close-up visual inspection where a particular component is the subject, diver inspections are not the favored option simply due to the required close proximity. Due to the highly dynamic environment constant movement and unexpected motion (from the floater and/or the dynamic cable) are a great risk for divers nearby. Although not all ROVs can fly sufficiently close to a component, it is considered more safely. Additionally, by using ROVs the depth limitations are far greater. [5]

5.2.4.2 Offline Measurements as an Inspection Method

In addition to the above-mentioned maintenance activities offline measurements can also be performed in order to examine the cables internal condition and to find damages that may cannot be seen by visual inspections [1]. Unlike online measurements where the subject tested is powered by the grid during the tests, offline measurements are performed while an external voltage source is attached [24]. Those measurements are performed manually and therefore rely upon the skill of the inspecting personnel.

Time-Domain Reflectometry

Main concepts of offline measurements are based on reflectometry. One measurement method is the Time-Domain Reflectometry (TDR). It is used to locate low resistive faults and cable interruptions. Also, the exact location of joints along the cable and the total cable length can be analyzed. A low voltage pulse is sent into the cable and at any impedance change within the cable a reflection will be seen. The time between release and return of the pulse from any reflection is measured and with the propagation velocity of the pulse, the distance to the reflection can be calculated. This can help to identify the type of impedance change and/or detect possible failure that could be present in the cable [25].

Optical Time-Domain Reflectometry

The Optical Time-Domain Reflectometry (OTDR) is only applicable if there is an additional optical fiber cable in the interstices of the dynamic cable. This can be considered standard nowadays (See next figure). The method works similar to the above-mentioned TDR but sends light pulses through the optical fiber. The scattered or

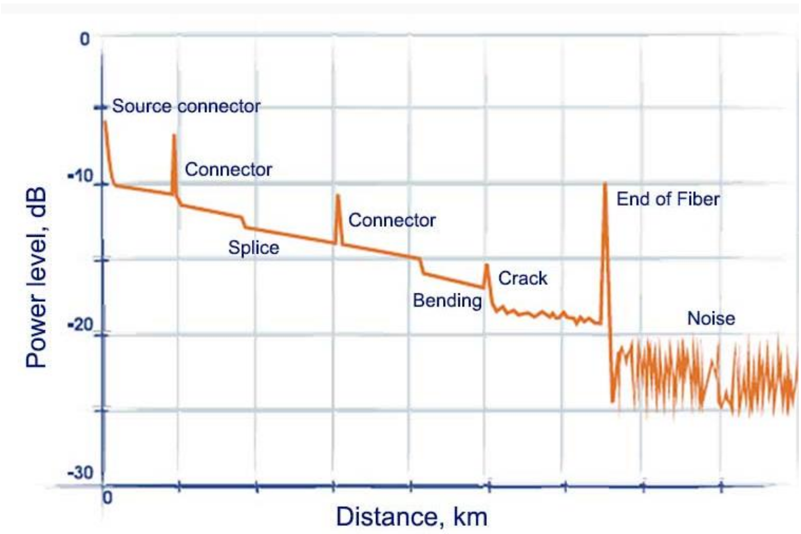


Figure 5.2-5 – Typical OTDR trace and its interpretation; Source: [26]

reflected light pulse is used to characterize the optical fiber in order to find possible anomalies in the cable or its surface. The strength of the returning pulse is measured and integrated as a function of time and plotted as a function of fiber length [26]. The most typical OTDR trace can be seen in the following illustration:

This technique of monitoring the cables condition is currently used during lay-up, load-out and as a post installation test to monitor strains on the fiber which may indicate damages on the rest of the cable [16].

Partial Discharge Measurements

Partial Discharge (PD) is a failure of part of the insulation system to withstand the electrical field applied to it. PD can be a result of poor design, poor workmanship, defective materials, contamination or aging which results in a high frequency discharge along with a current that flows through and on the insulation. The discharge sparks erode the insulation from the inside through heat and ionization till the discharge occurs on the cables surface. The most likely consequence then is the development of water trees (seen 5.2.3.1). To measure PD the cable should be disconnected from external equipment and connected to a high-quality voltage source. The test equipment itself should be free of discharge due to danger of results invalidation [27]. There are currently two methods of measuring PD which differ in the strength of the test voltage. When measuring PD with the normal supply voltage, warning signals (if any) are very small. If discharge is of such significance to be observed damage may be too big and it may be too late to guarantee a remaining life time. To see even minor defects on the cable before failure in service can occur the test voltage has to be increased. In this case an appropriate maintenance can be planned [18]. In the following illustration a typical installation of PD measuring can be seen:

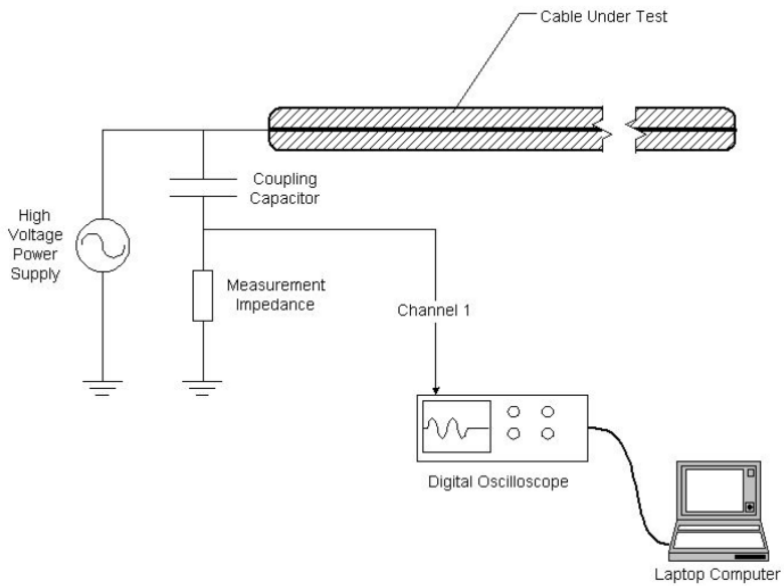


Figure 5.2-6 – Typical installation of an offline PD testing; Source: [34]

5.2.5 Online Monitoring

Offshore interventions are very expensive and therefore need to be planned very well [1]. With improving technology, it is possible to monitor an entire subsea cable grit while providing alerts as soon any faults crop up [17]. To prevent confusion between inspection and monitoring following definition of the terms “monitoring” and “online monitoring” is given:

Monitoring is defined as an automated inspection being a subset of inspection. A monitoring system collects and stores data automatically and continuously in a predefined time-step (usually short-term) or if a predefined threshold value is reached. It continuously measures conditions without the need of offshore human operation. Usually, the monitored data is transferred directly to onshore servers for storage and further usage, therefore we speak about online measurements. based on [23], p.9

This can give useful input for the upcoming maintenance activities. The objectives for continuous online monitoring can be summarized in [6]:

- Record status of cable system
- Verify and detect changes in operating conditions
- Provide input for the assessment of cable integrity
- To take mitigation actions

To accomplish those goals three general steps are necessary [19]:

- Collection of raw data from sensors installed on the cable
- Data processing and diagnosis to detect where defect or damage takes place and/or starts developing
- Prediction of remaining life time of component

As an important part of the asset integrity management online monitoring should be enforced as a viable means to address the condition of the dynamic cable system in conjunction with inspection programs so that the collected data can be fed into the maintenance plan [5], [20]. The more data collected the more comprehensive is the picture of the condition of the cable. Therefore, it is recommended to integrate different monitoring techniques and to synchronize the different information to get an overall view [1].

5.2.5.1 Distributed Temperature Measurement System and RTTR

The transportation of electricity over cables creates heat. Even tough submarine dynamic cable pass through relatively cold water, wear can occur which might end in other unanticipated problems [17]. To radar a cable's temperature during operation and therefore its thermal condition the cable needs to be equipped with an optical fiber in the interstices [16]. The Distributed Temperature Measurement System (DTS) is a well-established technology which uses the change in behavior of optical signal to determine the temperature of the fiber optic. A laser pulse is travelling down the optical fiber in the cable and the reflected signals are measured. The position of each measurement point is determined by its travel time from laser sending while the back-scatter intensity is depending on the fiber optics temperature. To detect the very small changes in the optical signal, complex electro-optical devices are needed [18]. For a more detailed view on this procedure please refer to [18]. From the temperature of the optical fiber the temperature of the nearby conductors can be calculated. This monitoring method is especially useful where the cable is not rated for the full output on a continuous basis but instead a dynamic rating. The DTS allows sampling every two meters in a total fiber length of up to 30km and due to their immunity against EMC interferences the sensors used for DTS have a significant advantage and can be used in hazardous areas [18]. In following figure a result of a DTS-Measurement can be seen. It is a function of calculated temperature over the cable length.

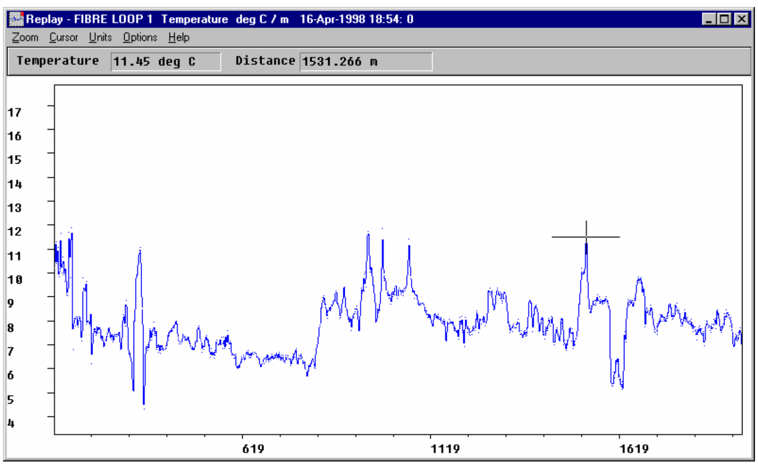


Figure 5.2-7 – Resulting temperature profile over cable length; Source: [18]

Additionally, the DTS can be equipped with a Real Time Thermal Rating (RTTR). By taking the current load, historic loads, thermal conditions and other factors into account, the RTTR continuously calculates the conductor´s temperature and at the same time predicts the maximum permissible load considering the current condition and emergency situations [28].

5.2.5.2 Distributed Acoustic Sensing

The Distributed Acoustic Sensing (DAS) works like the above mentioned DTS method. An optical fiber conducts a laser pulse while the inside scattering sites cause the fiber to act as a distributed interferometer. It detects the acoustic signals that may be caused by a fault or disturbances nearby the cable. If any acoustic disturbances occur, the oscillations cause microscopic elongations and compressions (like micro-strains) on the fiber. This leads to a change in the phase relation and/or amplitude of the laser pulse. Vibrations caused by cable failures are typically located in the low-frequency range and therefore can be identified [29]. The DAS is currently used at the fixed button wind farm Horn Rev. 3 in Denmark. The system used is configured to monitor the power cables in real time, visualize the acoustic energy over time and distance and store the measured data for later analysis. Additionally, it is equipped with alarms in the case of fault events [30].

5.2.6 Repair Methods and Procedures

5.2.6.1 Preparation

During the operational life time of dynamic cables certain damages discussed in the section above can occur. Some may result in a damaged but usable accessory, others will cause a total loss of the submarine dynamic cable. After a failure has been noted it has to be considered whether the damage is too significant to postpone the inspection and repair work or if the projected remaining life time is in an acceptable range. Anyway, to plan and actually undertake the offshore inspection the type and location of the failure must be found. Then, after the requirements are clear, the mobilisation of the repair vessel can start, and the cable repair crew can be contacted [1]. It should be noted, that especially for the handling the grid connection via dynamic cable, large and specialized vessels are required [8]. When the crew and vessel are ready to operate and the detailed procedures are established based on the previous analyses, the location has to be free of obstructions. Additionally, the level of uncertainty in the weather forecast must be taken into account [6].

5.2.6.2 Repair

When the reparation work finally takes place, which can take weeks or even month, critical parameters should be monitored continuously and the repairs should be inspected and electrically tested, comparable to an As-laid Inspection discussed in 5.2.2.1. It should be noted, that if a dynamic cable is seriously damaged and the remaining life time is no longer acceptable, it is most likely to replace it in its entirety to prevent subsequent faults [16]. This is done, because the dynamic cable is relatively short and to cut and replace the damaged part would not be worthwhile. The repair work should be documented to capture the current status of the structure and to simplify future surveys [6]. It is generally valid that the better prepared the procedures for repair work, the shorter is the repair time expected to be and therefore the disconnection time from the grid [1].

5.2.6.3 Disconnection for Tow-In Operations

The disconnection procedure for either the decommissioning or major repair works, which are planned to be done inshore, is in many terms similar to the installation procedure. This applies especially for the towing procedure. For the disconnection step of both dynamic cable and mooring system from the floater, all explained installation steps are conducted in opposite order. After all operating systems are shut down, the operational ballast system is emptied in order to reduce the draft. Hereinafter, first the cable system and then the mooring system are disconnected. The following towing process terminates the disconnection process, [8]. During the absence of the floating substructure at the site, wet-storage of the dynamic cable is most likely. To prevent the cost intensive procedure of picking up the cable from the seabed, additional buoyancy modules can be attached, and the cable can be easily recommissioned at a later time.

6 MODELS FOR OPTIMIZATION

DNVGL-ST-0119 [11] is the top level design code for this project. Analysis is performed using recommended practices detailed in this code.

Modelling will include Static Configuration Checks, Extreme Event (ULS) Analysis, Fatigue Analysis and Interference checks if needed. These will be undertaken as detailed in D1.2 report.

6.1 Softwares

6.1.1 OrcaFlex Analysis Software

OrcaFlex, published by Orcina, is the 3D, non-linear, time domain finite element analysis program which will be used to simulate realistic mooring lines and cables in the Corewind project. Wave structure interaction can be modelled using different schemes, from simple imposed motions to second order potential flow analysis with multi-body interactions. It is commercially available software which has been successfully applied to both dynamic deep water Oil and Gas applications and shallow relatively static renewable cable applications.

OrcaFlex can model a wide range of objects including:

- Lines (Fully coupled bending, torsion and axial stiffness, Bend Stiffener / Tapered Stress Joint model generation, etc.)
- Vessels;
- Subsea structures;
- Winches;
- Turbines.

6.1.2 FAST

FAST is NREL's open source tool for simulating the coupled dynamic response of wind turbines. FAST joins aerodynamics models, hydrodynamics models for offshore structures, control and electrical system (servo) dynamics models, and structural (elastic) dynamics models to enable coupled time-domain nonlinear aero-hydro-servo-elastic simulation.

FAST is based on different modules responsible for different parts of the simulations:

- **AeroDyn** is an aerodynamics software library (module) for use by designers of horizontal-axis wind turbines. It is designed to be interfaced with FAST for aero-elastic analysis of wind turbine models. The aerodynamics model in AeroDyn is a detailed analysis that includes Blade Element Momentum (BEM) theory (with modifications to improve accuracy in yawed flow).
- **InflowWind** is a FAST module that allows to process wind-inflow, either steady wind model internally calculated or using various types of input files (uniform, binary TurbSim full-field, binary bladed-style FF, binary HAWC wind files).
- **Elastodyn** is a structural-dynamic model for horizontal-axis wind turbines based on modal superposition theory. It includes structural models of the rotor, drivetrain, nacelle, tower and platform.
- **HydroDyn** is a time-domain hydrodynamics module that has been coupled with FAST to enable aero-hydro-servo-elastic simulation of offshore wind turbines. HydroDyn allows for multiple approaches for calculating the hydrodynamic loads on a structure: a linear potential-flow theory solution, a strip-theory solution, or a combination of both. Hydrodyn requires importing the hydrodynamic database in frequency domain obtained by a potential flow solver (e.g. NEMOH).
- **ServoDyn** is a control and electrical-drive model for wind turbines. It includes control and electrical-drive models for blade pitch, generator torque, nacelle yaw, high-speed shaft brake and blade-tip brakes. ServoDyn can use an external controller defined by a DLL, so-called “Bladed-style” because it

uses the same communication scheme as DNV GL's Bladed.

- The **Mooring Analysis Program (MAP++)** is a library designed to model the steady-state forces on a Multi-Segmented, Quasi-Static mooring line. This model is developed based on an extension of conventional single-line static solutions. Conceptually, MAP++ solves the algebraic equations for all the mooring elements simultaneously with the condition that the total force at connection points sum to zero. Seabed contact, seabed friction, and externally applied forces can be modelled with this tool. This allows multi-element mooring lines with arbitrary connection configurations to be analysed. This library will not be used in case FAST is coupled to Orcaflex.
- The **TurbSim** stochastic inflow turbulence tool has been developed by NREL to enable the numerical simulation of a full-field flow that contains coherent turbulence structures. The purpose of TurbSim is to provide the wind turbine designer with the ability to drive FAST simulations of advanced turbine designs with simulated inflow turbulence environments that incorporate many of the important fluid dynamic features known to adversely affect turbine aero-elastic response and loading. TurbSim is used in pre-processing, before FAST simulations.
- **BModes** is a finite-element code that provides dynamically coupled modes for a beam. The beam can be a rotor blade, rotating or non-rotating, or a tower. Both the blades and tower can have a tip attachment. The tip attachment is assumed to be a rigid body with mass, six moments of inertia, and a mass centroid that may be offset from the blade or tower axis. In addition to the tip inertia, the tower can also have tension-wire supports. Both the tip inertias and tension-wire support can substantially influence the coupled modes mentioned earlier, especially for a tower. BModes is used in pre-processing, before FAST simulations.

FAST will not be used directly for the Dynamic cable simulations but for the floater global performance essentially and part of the software package to evaluate the floater excursions.

6.2 Global model to local models

In order to evaluate the fatigue property of the cable for each application, local analysis must be evaluated against the results from the global model as shown in the figure below.

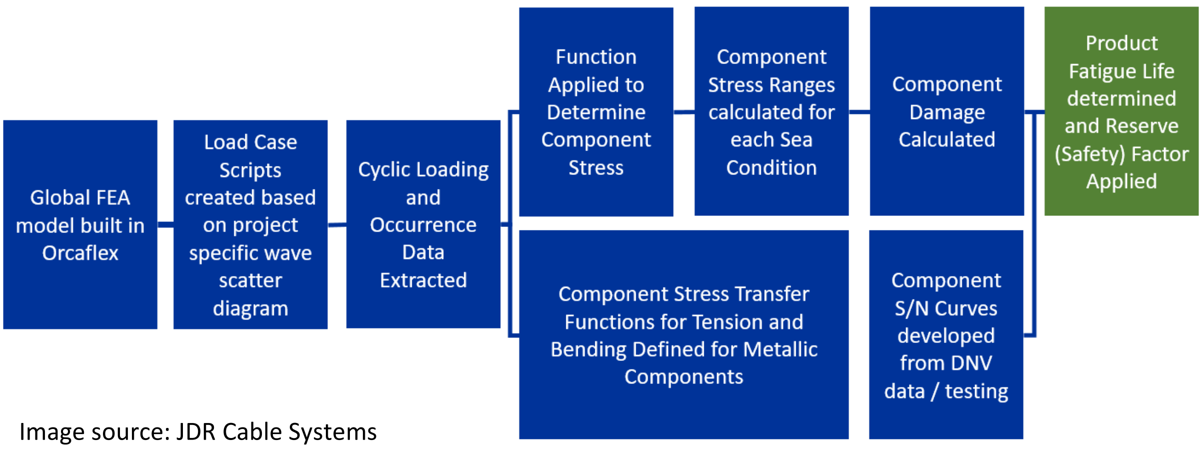


Image source: JDR Cable Systems

Figure 6.2-1 – Assessment of Cable Fatigue Performance

Tension and bending stress factors are extracted from an analytical stress calculation tool. A range of tensions and bend radii are considered to provide results across the range of performance of the cable. The results are converted into appropriate stress factors for use in the fatigue analysis.

The stress factors are then applied to the global loads extracted from the OrcaFlex assessment to determine the component level fatigue damage over product lifetime. Details on S-N data to be used is contained within the D1.2 report.

6.3 Interface between the Mooring and Cable Models

The floating turbine will be contained within the FAST model. Mooring system will be analysed within the FAST/Orcaflex model. The cable system will be analysed within ORCAFLEX model. For the coupled mooring and cable system review in WP3.3, an interface will need to be developed with inputs and outputs. Preliminary discussions within the participant group have established an excel interface sheet would be the best way to link the models. This will be regularly re-evaluated as needed throughout WP2.2 and WP3.2 task model development to ensure they are designed with the interface development capability required for WP3.3.

6.4 Simplified Model Development for cost and Optimization Tool integration

This section describes specific toll planned to be developed within the project frame.

6.4.1 Objective

The cable layout optimization for floating offshore wind farms is a complex task due to the number of elements involved and their nature. Some existing softwares allow dynamic calculations and simulations to assess in detail specific configurations of the cables, but none has the ability to couple the dynamic models to the layout of the farm. The main objective of the simplified cable model is providing a realistic view of the dynamic cable tensions and curvature in extreme conditions, allowing its integration into a layout optimization algorithm.

6.4.2 Specifications

A lumped mass model and the finite element method are used to find the static position and mechanical stresses of the cables, keeping a balance between computational time and the quality of the results. At this stage, only cables with buoyant modules are modelled, but bend stiffeners and clamps are expected in subsequent releases. Consequently, the currently allowed cable configurations are the double free hanging catenary, the double hanging catenary with buoyancy, the single free hanging catenary and the lazy wave.

The model shows the effect of both marine growth and currents on the cable shape, and properties such as axial and bending stiffness are considered.

6.4.3 Model outputs

An example of the computed values during the simulation of a riser is displayed in the next table.

Step	Min T [kN]	Max T [kN]	Max curvature [m^{-1}]	Laid length [m]	Suspended length [m]
1	22.4	176.1	0.014	40	890
2	22.1	175.6	0.015	23	907
3	22.5	185.7	0.014	26	904
4	22.5	185.7	0.014	26	904
5	23.4	186.6	0.014	23	907
6	**23.3**	**186.6**	**0.014**	**26**	**904**

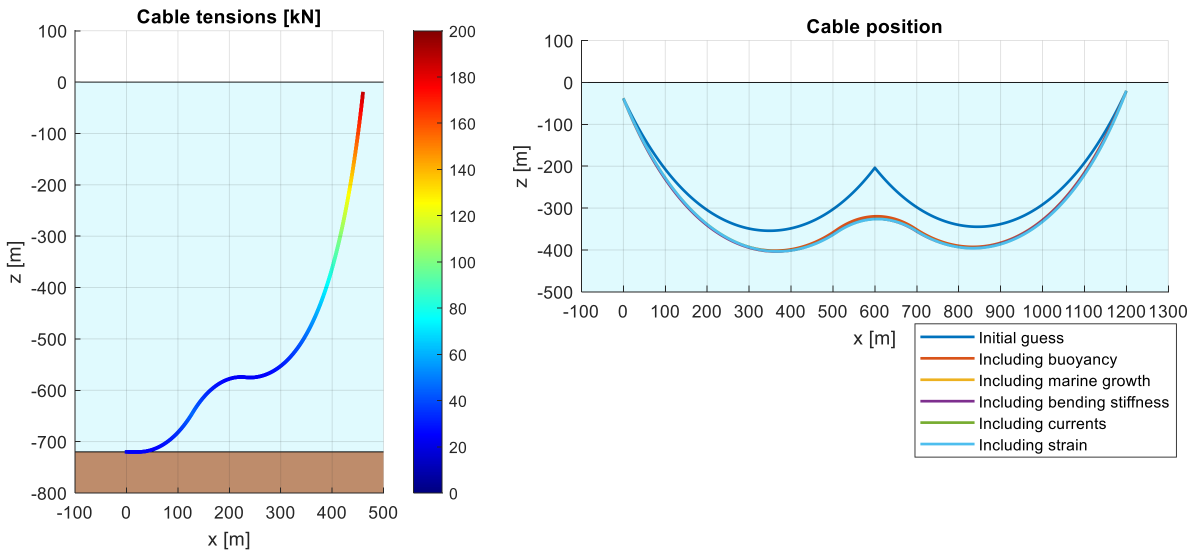


Figure 6.4-1 – Cable tensions and position for two different configurations

7 DYNAMIC CABLE INTERFACE CONSTRAINTS

While submarine cable is laid on seabed and protected, dynamic portion of the submarine cable for floating wind application needs to interact and cope with floater motions and environmental conditions (Wave and current predominantly). The cables are continuously subjected to bending and twisting forces, etc., caused by the tidal current and floater behavior; therefore, they are likely to suffer mechanical damage in various sections as detailed in reference [45]. Next figures extracted from reference [45] highlights the main constraints and interfaces i.e.:

- Interface with floater
- Interface with seabed
- Potential interface with mooring system

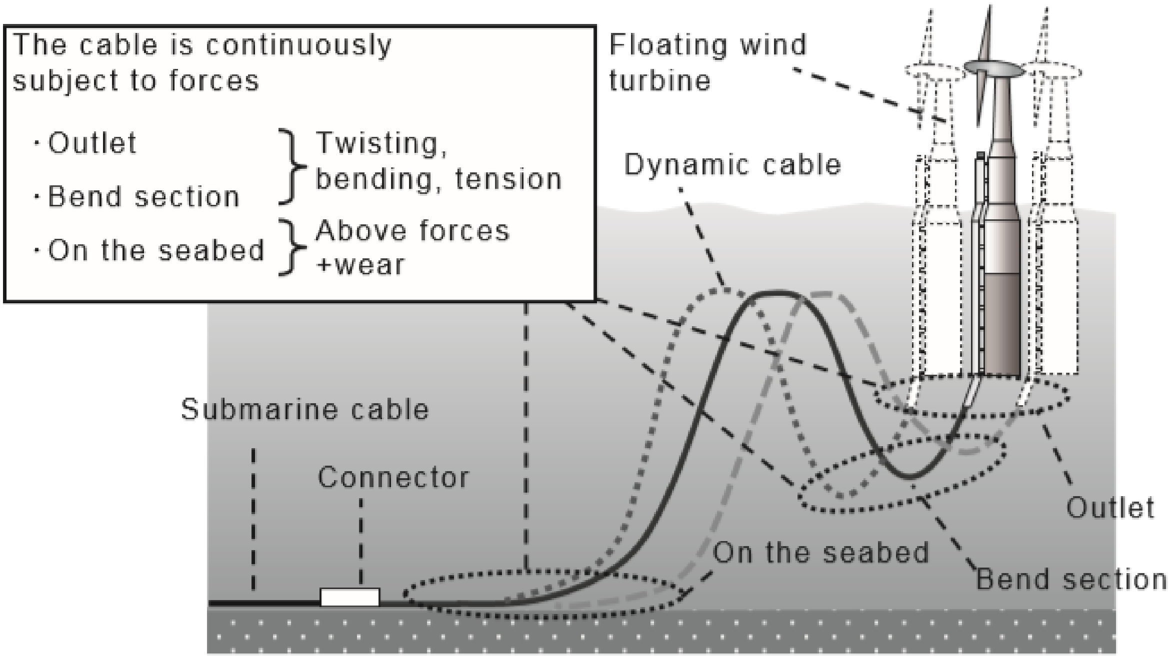


Figure 6.4-1 – Dynamic Cable configuration and main interfaces, Reference [45]

7.1 Cable interface with the floater

Dynamic Cable will be connected to floater to export power production. Mechanical link will be performed through a set of equipment which each having its own function. Some of them are defined in next figure extracted from reference [1] :

- Hang-off: Hang-off purpose is to transfer axial tension loads towards the floater structure. In case of I-Tube, Hang-off will be located at the top level.

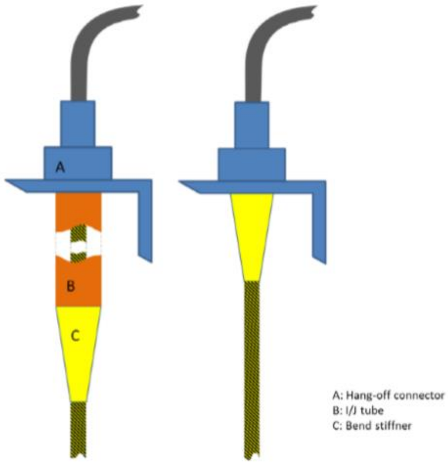


Figure 7.1-1 – Cable with Hang-off and stiffener with flange mounted on the I-Tube or directly to the support structure [1]

- Bend stiffener: Ensures dynamic cable is protected at floater connection point and ensures a stiffness transition from Cable (low bending stiffness) to floater (highly rigid). Model in Orcaflex will start from the bend stiffener base.
- Bend Stiffener latching mechanism: Purpose is to transfer imposed shear and bending moment loads imposed by dynamic cable motions to floater. This is a critical element as it needs to cope with extreme loads and fatigue.
- Disconnection mechanism: In case of severe damage to station keeping system and foreseen offsets out of Dynamic Cable design envelop it could be envisaged to incorporate a disconnection system with main aim to protect floater versus higher damage and abandon the dynamic cable. This is a complex system which should be further qualified.

7.2 Cable interface with the seabed

Cable will interface with the sea ground at the cable touch down point (TDP) in particular. Sensitivity to soil stiffness will be strongly linked to dynamic configuration selected and ability to decouple floater motions from soil contact area. For example, a simple catenary configuration will strongly interact with soil given the cable connection point heave motions.

The second soil interaction to be accounted for is related to the transition towards static cable and possibly use of transition joint. One main goal in this case will be to define the dynamic cable zero motion point and the residual tension at dynamic cable end. Regarding submarine cable routing, turn after dynamic cable section can be performed only after zero motion point and preferably without residual axial tension imposed by floater motions. One alternative can be to anchor the dynamic cable after the zero-motion point to counteract the residual tension. Based on cable route and soil axial friction factor the tension along cable laid on seabed can be assessed.

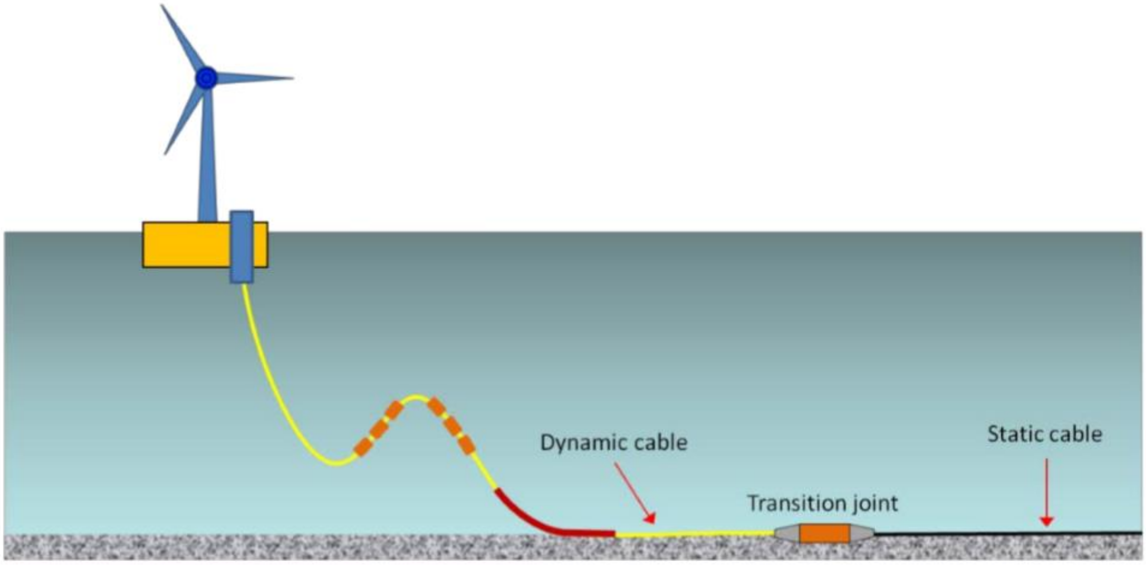


Figure 7.2-1 – Cable transition point from Dynamic Cable to Static Cable, Reference [1]

Regarding Cable global analysis and performance assessment, the seabed reaction force is the sum of a penetration resistance force in the seabed normal direction and a friction force in the direction tangential to the seabed plane and towards the friction target position as defined in [46]. The penetration resistance force depends on the choice of seabed model used. OrcaFlex software for example provides a simple friction model that can give an approximate representation of contact friction. This is commonly used to model seabed friction. Soil-Structure horizontal load law is illustrated in this case in next figure with D_{crit} evaluated with the following formulae:

$$D_{crit} = \frac{\mu R}{k_s a}$$

with:

- μ the friction coefficient;
- R the contact normal reaction force;
- k_s the shear stiffness;
- a the contact area.

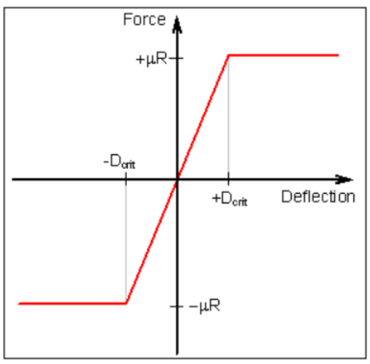


Figure 7.2-2 – Soil-Structure interaction horizontal loading law, Reference [46]

7.3 Interface versus mooring design

Dynamic Cable configuration is as described in design drivers strongly linked to floater station keeping performance. The excursion obtained under environmental loadings applied on floater will indeed drive the dynamic cable configuration. The excursion target has thus to be defined accounting for station keeping and dynamic cable constraints.

The second main interface versus mooring is the potential risk of interference / clashing. Such event is not acceptable for dynamic cable structures and this must be avoided as defined in reference [47], i.e. no collision is allowed. Dynamic Cable configuration should thus be verified versus mooring layout to avoid any critical interface.

In order to minimize the requirement for interference checks, the mooring system model from WP2 will provide the window the cable will need to operate within in order to ensure no clashes occur with the mooring lines.

8 REVISION OF COST EVALUATION

Different power cables are used in the Floating Offshore Wind Power Plant (FOWPP) such as dynamic and static inter-array cables as well as export cables. Different cable sections are used according to the power to be transmitted. Thus, in general, the total cable cost includes the sum of each cable cost [57].

Total cable cost: $TC_{Cable} = \sum_{i=1}^{n} Cpc * lpc * Npc$

Where C_{PC} is the cost of a single cable in (€/m), l_{PC} the length in (m) and N_{PC} the number of this cable used.

It is worth indicating that there are few publications on such topic; and since the dynamic cables are made case by case and not large amount of project data are available it is hard to estimate. In this some functions for the cables are given depending on the type: Static or Dynamic.

As indicated above the cable costs are considered as unit cost per unit distance. Such cable cost is estimated as an exponential function as defined in [58], which has been validated in [56].

Cpc = c1 + c2*exp(c3*S)

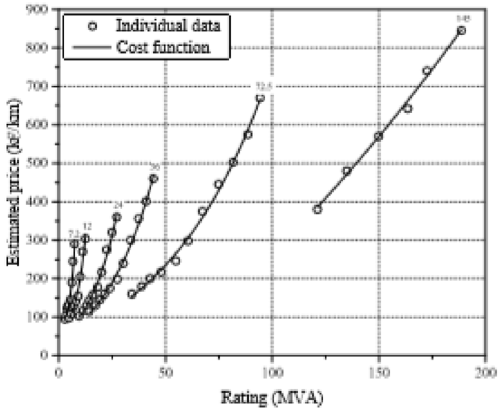
Where S is the cable rated power in MVA, c1-3 are cost coefficients and Cpc is the same as defined previously.

8.1 Static Cable Cost Function

Table 8.1-1 – Static Cable cost coefficients [56]

Voltage (kV)		Cost Coefficient			Range	Units	Year
Rated	Max	c1	c2	c3	(MVA)		
6.6	7.2	67.63	8.24	0.44	[2.9, 7.5]	k€/km	-
11	12	49.37	16.32	0.22	[4.8, 12.5]	k€/km	-
22	24	−1.27	50.66	0.07	[9.5, 27.2]	k€/km	-
33	36	−35.29	80.17	0.04	[17.0, 44.0]	k€/km	-
66	72.5	−57.35	105.20	0.02	[34.3, 94.3]	k€/km	-
132	145	−1337.00	1125.00	3.5×10^{-3}	[121.1, 188.6]	k€/km	-
MV	ns	0.5–2.0	0	0	ns	k£/m	2015
22	ns	0.284×10^6	0.583×10^6	6.15×10^{-2}	[10, 45]	SEK/km	2003
33	ns	0.411×10^6	0.596×10^6	4.1×10^{-2}	[15, 67.5]	SEK/km	2003
66	ns	0.688×10^6	0.625×10^6	2.05×10^{-2}	[35, 135]	SEK/km	2003
132	ns	1.971×10^6	0.209×10^6	1.66×10^{-2}	[100, 230]	SEK/km	2003
220	ns	3.181×10^6	0.11×10^6	1.16×10^{-2}	[290, 385]	SEK/km	2003
MV	ns	300–800	0	0	ns	€/m	ns
HV	ns	1000–2000	0	0	ns	€/m	ns
132	ns	7.471	39.28	1.40×10^{-2}	[150, 189] *	£/m	2008
220	ns	−1044	963.4	1.91×10^{-3}	[250, 315] *	£/m	2008
33	ns	100–200	0	0	ns	€/m	2012
132	ns	200–600	0	0	ns	€/m	2012

In the following figure, the exponential function previously presented with such coefficients.



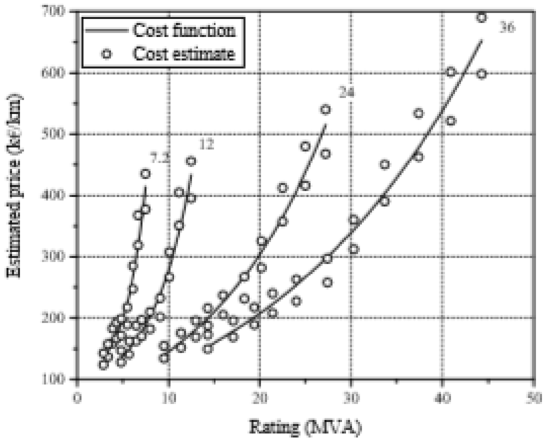
8.2 Dynamic Cable Cost Function

According to [56], the cost of dynamic cables will be more expensive than the equivalent power rated static cables. Those are about 30-50% more expensive for cables up to 33kV and ranging 60-90% for cases up to 66kV.

Table 8.2-1 –. Dynamic cable cost coefficients [56]

Voltage (kV)		Cost Coefficient			Range	Units	Year
Rated	Max	c1	c2	c3	(MVA)		
6.6	7.2	94.69	11.54	0.44	[2.9, 7.5]	k€/km	-
11	12	69.12	22.85	0.22	[4.8, 12.5]	k€/km	-
22	24	−1.78	70.92	0.07	[9.5, 27.2]	k€/km	-
33	36	−49.42	112.20	0.041	[17.0, 44.0]	k€/km	-
MV	ns	300–800	0	0	ns	€/m	2013

In the following figure, the exponential function previously presented with such coefficients.



In addition, as proposed in [59] the dynamic cable length used for WT interconnection can be approximated by:

Lac = 2*Dw*2,6 + Dwt

Where Dw represents the water depth and Dwt the distance between two Floating Offshore Wind Turbine (FOWT).

9 CONCLUSION

9.1 Cross section

Initial designs have been proposed within section 2.4. These have been determined as reasonable for the COREWIND based on participant experience given the little data available publically for review at the time this report has been compiled. Designs may be revised during the subsequent WP3.2 configuration modelling based on evaluations of minimum cable characteristics such as bend stiffness.

Largest opportunity for cost saving is to extrapolate minimum attributes required for ancillaries so that they are tailored to the applications outlined in D1.2 which have been deemed representative of floating windfarm sites by WP1. Standardisation of this hardware across the commercial-scale field should lead to significant cost savings.

Priority for Corewind models is to develop cost-optimised 66kV cable configuration solution and ancillaries for cost benchmark and reduction purposes. Where this is balanced with the mooring line cost optimal solution, it is important to note that as cost associated with the cable are typically less significant than the mooring line, a relaxed mooring line system may in fact lead to greater overall cost savings while absorbing marginally greater cable system costs.

9.2 Dynamic Cable configuration

Dynamic Cable configuration is strongly linked to actual voltage and associated cable cross section, floater excursion / dynamic motions and environmental conditions (particularly marine growth). A set of configurations is defined each having its own advantages and disadvantages thus projects specific constraints will drive the selection.

Currently dynamic cable design is performed independently from station keeping system, further investigation is proposed combined mooring/dynamic cable configuration assessment with goal being to go up to determine the maximum dynamic cable capabilities / cable design requirements to relax mooring design / benefits of relaxed mooring design against less costly cable design / configuration. This task is planned within COREWIND project.

9.3 Installation & Inspection

Installation of Dynamic Power Cables

The installation of dynamic power cables can be separated into two parts which occur one before the other but not in a specific order. Recommended for offshore units with many interarray cables nearby is a "first-end pull-in"-operation. The pull-in operation itself is known from fixed-bottom turbines and consists of the pull-in and the running of the cable towards its destination point, the switchgear. While the rest of the cable is still stored on the CLV (dry-storage) its first end is pulled in and attached on temporary hang-offs on the floater. The CLV lays the cable towards the pre-laid static cable and connects them depending on the kind of transition joint used, on the ship after pull-up or underwater by using a ROV. As the cables are connected the electrical connection takes place on the FOWT by using pluggable dry-connectors for each phase. Depending on logistical and/or technical parameters, the cable may be laid in one piece including the transition joint. The pre-laid cable is wet-stored on the seafloor or attached with buoyance modules to guarantee an easy pick-up process at a later date for the pull-in operation into the floating structure.

Generally, the procedure of the pull-in operation is relatively time intensive and requires valuable space inside the structure. To enable a faster and more efficient connection new technologies are being developed, like the Hybrid Wet Mate Connector [31] which can be seen in Figure 1.3-1.

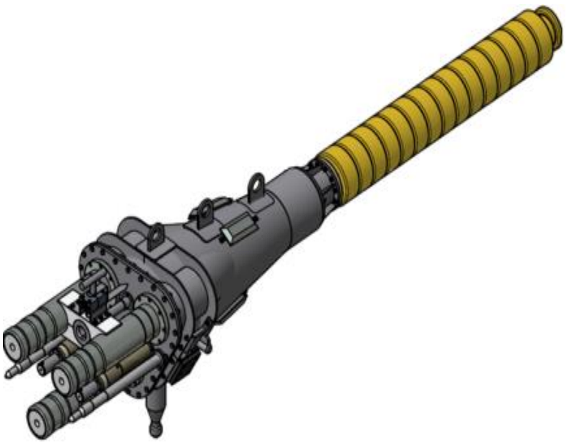


Figure 9.3-1 – MacArtneys 11kV Hybrid Wet Mate Connector Solution, Right: Male Connector, Left: Female and Male connector; Source: [31]

Since its maximum voltage of 11kV is too low, more research has to be done in the field, also to lower the high costs. Generally, this connection type enables an easy connection process. It eliminates the need to pull the dynamic cable into the floater and to run it through the structure. For this pluggable connection a ROV can be used. This shortens the time needed for connection and hereby making it possible to operate in waters with limited time windows. Additionally, the three phases do not have to be connected individually nor separately from the optical fiber cables. For a more detailed review of wet mate connectors, please check [32]. Another possible future innovation comes with self-connecting and disconnecting cables. This would avoid the time intensive connection via the transition joint either on the ship or with a ROV on the seabed [17].

Inspection & Monitoring

As seen in 5.2.2 maintenance work is mainly based on an inspection schedule. After installation, tests and inspections are conducted in an as-laid inspection to record the first condition of the laid cable. It should be kept in mind, that damages occurring during installation are often the direct cause of failure in the later service life. To ensure a long operational life, despite danger through the dynamic environment (review 5.2.3) there are three types of long-term inspections which differ from the trigger of the maintenance work. The most efficient method is the condition-based maintenance, where the condition of the cable is automatically monitored mostly via optical fiber cables in the interstices of the power cable. Through the recorded data, a remaining life time can be estimated, and the offshore repair work can be planned in advance. Common monitoring techniques are the Distributed Temperature Measurement System (DTS), explained in 5.2.5.1, and the Distributed Acoustic Sensing (DAS), covered in 5.2.5.2. If the estimated life time is not in an acceptable range, it is most likely to replace the dynamic cable in its entirety due to its relatively short length.

With advancing information technology, like the Internet of Things (IoT), pervasive networked sensors are becoming more common in manufacturing operation. This will likely happen in the offshore wind sector as well. Real time monitoring and data recording becomes more accurate, data software will help to detect subtle changes in parameters, so that repair work can be even more accurately scheduled [17]. In section 5.2.4.2, Partial Discharge Measurement was presented as an offline inspection method. Due to the required high-voltage to identify minor damages it is not yet used for continuous monitoring on dynamic cables. But research is aiming for an online PD measurement in the future. Next to PD monitoring, online OTDR monitoring and the related DSS (Distributed Strain Sensing) are promising techniques to monitor the cables condition in the future. For a more detailed view into DSS please check [33]. All these monitoring techniques are being developed or are already in use to measure fatigue on the cable, which is crucial for dynamic power cables.

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