Cable solutions for Ocean Energy: Latest design configurations, failure modes, and monitoring methods

H. Marcollo, A. Eassom, D. Sirianos, C. Thomas and J. Gumley

Abstract— **Subsea cables are critical system components that enable operation of ocean energy technology devices. For technology demonstration of ocean-based energy systems through to commercial arrays of devices, due consideration must be given to the cable architecture to reduce single points of failure. This paper discusses potential cable architecture options applicable to i) three wave energy converter types; ii) two tidal energy types; and iii) ocean thermal energy converters. Risks, lessons learnt, historical failure data, and analogous experience from the offshore wind and oil and gas sectors are presented and interpreted for the aforementioned ocean energy converter systems. Finally, monitoring solutions and integrity management of subsea power cables systems are discussed in the context of pre-commercial projects.**

This paper is intended to provide a summary of the subsea cable technologies available and guidance for researchers and developers who are contemplating the first or subsequent deployment of a marine energy concept that includes power export to shore.

Keywords—**Ocean Energy Technology, Marine Energy Technology, Ocean Energy, Subsea Cables, Wave Energy Converters, Tidal Energy Converters, Ocean Thermal Energy Converters**

I. INTRODUCTION

The ocean's energy can be harnessed in many ways. Ocean Energy Technology (OET) devices refer to the systems used to capture energy from the ocean, with the main categorizations being Wave Energy Converters (WECs), Tidal Energy Converters (TECs) and Ocean Thermal Energy Converters (OTECs).

Within each of these three broad types of OET, dominant systems showing promise can be categorized into the following types:

1) WECs
   - Attenuators (ATT) (floating)
   - Oscillating Wave Surge Converters (OWSC) (fixed)
   - Point Absorbers (PA) (fixed or floating)
2) TECs
   - Fixed
   - Floating
3) OTECs (floating or shore-based)

Determination of whether the OET systems will be floating (moored) or bottom fixed is not only dependent on the underlying technology, but various field-specific factors such as water depth, metocean, seabed sediment type, size of the project, regulatory requirements, and insurance requirements. Specifically for floating systems, the design of the mooring system will be a key driver for selection of the power cable design and hence the energy export system. This is analogous to the oil and gas (O&G) experience of designing for oil, water and gas riser systems, where an iterative or coupled design approach is often required for the riser (cable) and mooring systems [1].

As most ocean energy concepts are yet to be deployed commercially at scale, cable designs can leverage from the body of knowledge already developed from the O&G and fixed bottom wind sectors. O&G assets, while relevant, are not often deliberately subjected to high energy environments. The innovations within the rapidly developing floating offshore wind sector provide the closest analogue to the cable system requirements for many other types of OETs, as this sector is predicted to have developments with dozens of moored floating units, necessitating complex cable systems interconnecting the units and offshore substations [2]. Telecommunications cabling is another potential source of guidance and experience for the OET sector; however, an analysis of this industry sector has been excluded from this paper due to the relatively small cable diameters which result in a significantly different set of challenges.

Using experience from the aforementioned industry sectors, this paper will first discuss the mechanical construction of power cables (Section II), before proposing

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a few likely single-unit cable configurations for both floating (Section III) and fixed systems (Section IV). Key considerations for other site-specific factors are next presented (Section V) before a discussion of potential failure modes (Section VI) and the required integrity management and monitoring approaches (Section VII).

For multi-unit arrays, a distinction can be made between inter-array cables and export cables. Inter-array cables are distinguished as those that connect the units together within the array or those that connect a unit and an offshore substation. Export cables are cables that connect offshore substations to the shore.

Inter-array cables may have both dynamic and static cable sections. Dynamic cables are designed to allow for axial, bending and torsional loading from continuous motion, whilst static cables are used for sections of a cable arrangement with minimal anticipated mechanical loading. Inter-array cables are also smaller in diameter and voltage rating (typically no larger than tens of kV) relative to export cables that are typically larger in diameter and rating (hundreds of kV for multiple units).

The target audience for this paper includes developers aiming to design their first systems with successful power export.

A. *Abbreviations and acronyms*

The following are the abbreviations and acronyms used throughout the paper:

ALS: Accident Limit State
ATT: Attenuators
AUV: Autonomous Underwater Vehicle
CAPEX: Capital Expenditure
CPS: Cable Protection System
DAW: Drag to Weight Ratio
EPCI: Engineering, Procurement, Construction and Installation
EPR: Ethylene Propylene
FLS: Fatigue Limit State
FOWT: Floating Offshore Wind Turbine
MBL: Minimum Breaking Load
MBR: Minimum Bending Radius
MWA: Mid Water Arch
MWS: Marine Warranty Surveyors
O&G: Oil and Gas
OET: Ocean Energy Technology
OPEX: Operational Expenditure
OTEC: Ocean Thermal Energy Converter
OWSC: Oscillating Wave Surge Converter
PA: Point Absorber
ROV: Remotely Operated Vehicle
TE: Tidal Energy
TEC: Tidal Energy Converter
ULS: Ultimate Limit State
WEC: Wave Energy Converter
VIV: Vortex Induced Vibration

II. Cable Mechanical Design

For the designers of OET devices, the chosen power cable design is likely to come from a known subset of designs already developed by other offshore energy sectors. These cables consist of helical metallic components as well as polymer layers. A typical cable cross-section is shown in Fig. 1. The centre of the cable consists of copper or aluminium conductors surrounded by various insulating layers. The insulating layers may degrade over time due to the stresses caused by temperature, electrical, chemical or mechanical means. These insulating layers are protected by the metal or polymeric sheaths which provide compression and tension stability, in addition to mechanical protection which is necessary especially for the installation process.

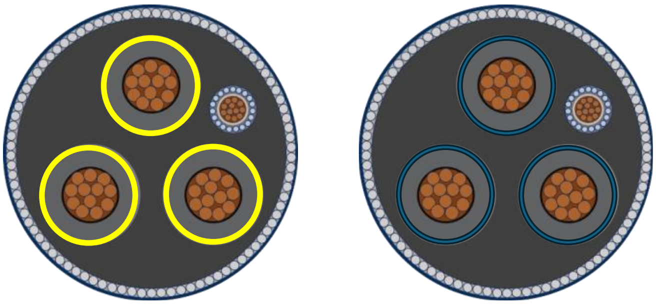


Fig. 1. The construction layers of a ‘dry’ cable (left), containing an impermeable lead pipe sheath, compared to a ‘wet’ cable (right), containing a polymer layer allowing moisture ingress.

Cable designs are usually classified as “wet” or “dry” designs. In a dry design, the cable typically has an extruded impermeable lead sheath (shown in yellow within Fig. 1) [3], whereas wet designs have a polymer layer (shown in blue within Fig. 1) and the ingress of moisture is possible. This results in the wet design being able to tolerate a larger range of dynamic motion and being much less likely to suffer from mechanical fatigue damage. Therefore, dynamic inter-array cables are usually wet designs, with static cables being traditionally dry designs. Typical materials such as polyethylene sheaths with water blocking tapes can be used to protect against water damage in a wet design as seen in the 33 kV inter-array cables in the Kincardine offshore wind farm [4].

Inter-array cables are typically AC (usually three phase) due to their relatively short lengths, with voltage levels ranging from 11 kV [5] to 66 kV [6]. Increases to 132 kV are expected due to the higher power of offshore renewables currently under development and the benefit of these higher voltages having reduced electrical losses [7].

For single unit OET demonstrators, floating systems will likely adopt a wet cable construction, as it is unlikely that the cable motions could be decoupled from the motion of the floating unit due to the ocean environment. For fixed systems, a dry cable may be an acceptable solution; however, great care would be required to avoid any sections becoming dynamic over time due to scour (see Section V).

III. Single Unit Cable Configurations for Floating Ocean Energy Systems

There are many possible configurational arrangements for the power cable of a floating OET device; this paper presents three options: steep wave, lazy wave and simple catenary. This section outlines the elements a developer may need to consider when selecting between the different cable configurations, as well as the design implications for each configuration. Fig. 2 presents the conceptual profile of each of these configurations for an arbitrary floating OTEC unit.

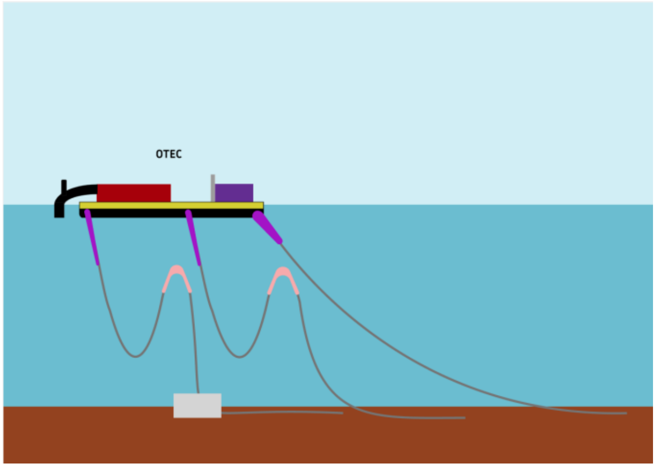


Fig. 2. A steep-wave (left), lazy wave (middle) and simple catenary (right) configurations accompanying an OTEC.

1) *General design considerations*

Unlike static cables, dynamic cables are required to withstand the impact of the induced motion of the OET in response to wind, waves and currents. They are also subject to the direct effects of wave and current. The result from both of these conditions is induced dynamic tension, bending and twisting cycles, thus the dynamic cable must withstand a higher magnitude of mechanical loading.

A. *Design parameters*

The selection of the cable configuration for floating OET systems is typically governed by the required compliance of the cable to remain within the design limits of its construction, given both the motions of the floating unit and the water depth available to accommodate these motions. In general terms, the ratio of maximum offset range to water depth (expressed as a percentage) is a governing design parameter. Whereby the maximum offset relates to the maximum excursion of the floater from its design mooring centre when exposed to design environments. This parameter is a function of the floater response and the mooring system configuration. Analogous experience for riser design from the O&G sector relates to the use of unbonded flexible risers, which are deliberately constructed to allow for dynamic bending, and the authors' project experience has dealt with acceptable floater maximum offsets up to 30% of water depth. These compliant riser configuration designs in shallower water can be more challenging than in deep water, due to the limited space between the floater and the seabed, and the wave environment having a greater direct loading contribution on the riser system.

The design limits of the cable are typically categorised into two physical quantities: tension and bending. Tension is the axial load through the cable, whereas bending describes the moments induced in the cable as it undergoes curvature. Most cable constructions will specify both a Minimum Breaking Load (MBL) for tension and a Minimum Bending Radius (MBR) for bending. Both MBL and MBR checks are required for all design conditions predicted to be experienced by a floating OTEC device, including maximum operating conditions, storm survival conditions, damaged conditions such as the device sinking or being detached from its moorings, and temporary states such as during installation or recovery of the device.

The above discussion specifically refers to Ultimate Limit State (ULS) and Accident Limit State (ALS) conditions which could result in cable damage or loss if the allowable tension and bending limits are exceeded. However, these events may not be governing for the design of the cable and thus may not ultimately impact the choice of configuration. Fatigue, which is the repeated loading and unloading of the cable, may be the governing parameter, as has been seen for many floating units. This has been identified as a specific issue for floating wind [8]. For cables, both tensile and bending fatigue are important design considerations.

Tension and bending are not constant throughout the length of a cable, thus there are multiple locations on the cable which are typically governing in terms of the design. These locations include:

1) The hang-off point, i.e. the interface between the floating unit and the cable,
2) The touchdown point, where the cable first contacts the seabed, and,
3) Local inflection points, where buoyancy is used to introduce further compliance into the cable system.

Ancillary components within the cable configuration, such as bend stiffeners at the cable hang-off point, are often used to provide further support to the cable and reduce the magnitude of bending the cable is required to endure.

Tension and bending are also not constant throughout the cross-section of a cable, as each element within its construction (conductors, armour wires, fibre optics) can experience different stress ranges and have different fatigue resistance properties. Cable construction may need to be reviewed for systems where fatigue analysis has identified a low fatigue life.

The discussion thus far has primarily referred to the cable design's compliance to the dynamic motions of the floating unit. However, both the direct wave and current loading on the cable itself is another key parameter that will also influence the magnitude of both tension and bending within the cable. Diameter-to-Weight ratio

(DAW) is another key design parameter for cable systems. Generally, lower DAW values result in a cable configuration that is more stable [9].

While OET development remains at a less mature stage, OET devices will tend to be installed in shallower waters that are closer to shore. In these waters, the wave and current environment will have a greater impact across the full water depth, and cables will also be in closer proximity to mooring lines or other cables. In this arrangement, cables with high DAW would be more susceptible to over-bending, clashing with other lines and seabed instability. As such, selection of a cable with an appropriate DAW can be a critical design decision to maintain the integrity of the cable.

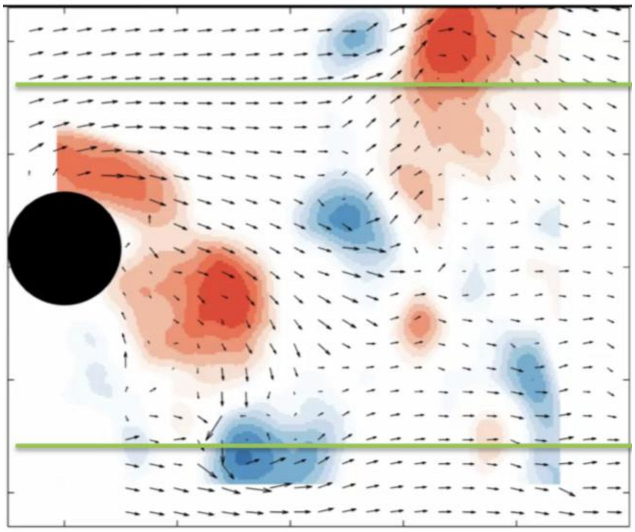


Fig. 3. Example low-and high-pressure eddies (in blue and red respectively) forming behind a slender structure that results in VIV. Fluid flow is from the left-hand side, with the vectors showing the streamwise velocity of the fluid after being disturbed by the cylinder. The green lines indicate the amount of movement the cylinder is undergoing due to VIV and the vortex shedding behind it. Sourced from authors' own physical experiments (units removed) performed at the Monash University Flair Water Channel by AMOG Consulting.

Finally, and specific to slender structures like dynamic cables, is the impact of Vortex Induced Vibration (VIV), a drag induced phenomena which can have a major impact on cable fatigue life. VIV forms when a slender structure is subjected to a persistent fluid flow, e.g. current, and oscillating eddies are generated behind the structure. These eddies result in oscillating low pressure regions downstream, as shown in Fig. 3, inducing motion in the structure. These VIV induced motions result in dynamic bending stresses within the cable that contributes to the bending induced fatigue damage in the cable. VIV can be driven by ocean or tidal currents, with the latter being particularly relevant to Tidal Energy (TE) devices that experience predictable and large currents. However, VIV may also be driven by motions of the device(s) to which the cable is attached, which in turn induce significant motions in the cable itself; for example, the vertical movement of a floating OET may generate heave-induced VIV.

B. *Modelling approaches*

To determine whether a proposed dynamic cable design meets all the design criteria, several different modelling approaches are used throughout the design process.

A global fully-coupled numerical model built in any of the numerous industry-specific software will traditionally include the floater, the mooring system and the cable itself. The numerical model will have the ability to simulate the motions of the floater in six degrees of freedom when subjected to wind, wave and current loading, and output the resultant loads in the cable system. In addition, the effect of the power take-off on the global motions of the floater, including any accidental states, must also be accounted for in the model. However, these models are computationally expensive; as such, the mooring design and cable design may be decoupled.

As the cable system has minimal influence on the restoring force applied to the floater, the mooring system can be assessed without requiring modelling of the cables. A mooring system analysis can be used to identify the governing floater motion and offset limits. Offsets may be directionally dependent, in which case floater maximum offsets can be specified as near, far, transverse and/or quartering relative to the cable system. Once the governing environmental conditions and the floater excursion envelope has been identified from the mooring analysis, a cable analysis can be performed. This cable analysis can be performed with a decoupled model, i.e. without modelling the mooring lines, and applying the governing floater motions at the bounding floater excursions. This approach can reduce computational runtimes and allow faster design iterations to converge on a suitable configuration.

These decoupled cable models may also be extended to include the assessment of VIV and risk of seabed scour. These assessments may also require additional third-party software packages such as SHEAR7 [10] and/or different analysis approaches.

The cable and mooring system design is generally an iterative process to eventually find an optimal solution in terms of long term system integrity, cost and meeting the design criteria. Unfavourable configurations can be excluded through the use of preliminary quasi-static analysis of the cable within the early stages of the workflow. More variables can then be added so that the optimal cable configuration can be identified for the given site conditions, floater information and ancillary equipment information. This stage would also include an interference check, ensuring that the cable does not contact the mooring or other subsea equipment, which would represent a significant integrity risk to the system.

Local models of the cable itself may also be adopted to ensure that the cable's construction can withstand the bending and tension forces, which would result in stresses in the metallic components. As discussed in Section II, cables consist of helical metallic components as well as polymer layers, which have tighter Minimum Bending Radii than standard cylindrical piping, but are generally more likely to experience failure from dynamic loading. The stress experienced can be highly nonlinear due to the inter-layer friction and can be also affected by the water depth and thermal effects [10].

C. *Physical testing*

Finally, physical testing is undertaken once both the cable sectional design and dynamic cable configurations have been selected. Physical samples of the cable are mechanically tested so that their expected performance in bending and tension is understood and within expectations for the design. An example of a test may be a fatigue test within a dynamic rig. For example, test rigs have been built for physical testing to explore the structural and material damping [11] as well as algorithms developed to understand the torsion behaviour that comes from testing [12].

2) *Lazy wave cable configurations*

The lazy wave cable configuration consists of a cable being installed with distributed buoyancy modules, creating the wave-like shape as shown in Fig. 4. The terminology "lazy" refers to the tangential incidence angle of the cable to the seabed.

The lazy wave design enables the cable to have a level of flexibility and compliance, reducing the cyclic loading induced by metocean conditions which in turn reduces the fatigue damage caused by vessel motions [13]. This configuration has been utilised throughout the FOWT and O&G sectors as a cost-effective method for increasing stability in challenging environments.

When designing the cable configuration and associated bend stiffeners, the hang-off inclination angle is a key design parameter, as this angle will drive both strength and the fatigue performance of the configuration [14].

Additionally, the placement of the buoyancy modules affects the stress and fatigue experienced throughout the cable configuration. Proper placement of the buoyancy modules reduces the overall tension experienced by the cable, as the load is spread more effectively, as well as providing a more compliant shape able to tolerate larger floater excursions. The placement of the buoyancy module also affects the natural frequencies of the system.

The lazy wave cable configuration is however more susceptible to the effects of VIV as the natural frequencies are lower than the more tensioned configuration options, leading to more potential overlap with vortex shedding frequencies. The specific lazy wave shape chosen does change the cable's susceptibility to VIV [13]. However, the propensity to VIV is also strongly dependent on the direction of the current relative to the lazy wave configuration. Lazy waves that are perpendicular to the current flow are more likely to experience fatigue damage in comparison to when the lazy wave is parallel to the current direction [13].

The inter-array cables within these systems can be connected in either of the following ways:

1) A single continuous dynamic cable that connects the OET systems.
2) A static length of cable connected to a length of dynamic cable for each floating system. These are connected to each other using either field joints or connectors.
3) A single cable assembly that uses dynamic cables at either end or a static cable in between. These are connected using factory joints. These are effectively manufactured and installed as a single length [15].

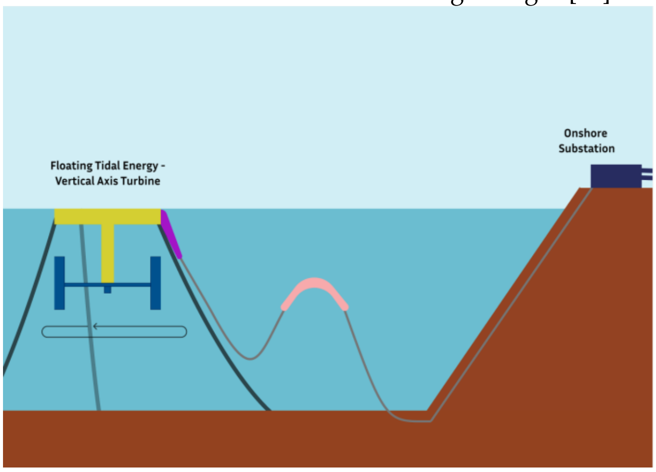


Fig. 4. A lazy wave configuration accompanying a floating vertical axis tidal energy turbine.

In selecting between the three options, a designer needs to factor in the relative cost of the static and dynamic cables, alongside the added cost of utilising field joints or connectors, as well as the introduction of additional potential points of failure at these locations. Additionally, pre-made assemblies cannot be adjusted onsite for length, resulting in potential problems if the positioning of any of the OETs differs from the expected design. For developments involving arrays of OETs, cable configurations that can ensure the rest of the farm is operational and exporting electricity successfully when one system has failed is a major consideration for the insurability and financial viability for the project.

A. *Lazy wave variations – W-shape*

Specific lazy wave configurations such as the W-shape provide potentially more attractive economic options for inter-array connections in very deep waters where the costs of having full length water column cables that touchdown to the seabed and rise back up to the next unit become very expensive. Here, the cable runs higher within the water column between the two OET systems using clamped ballast or buoyancy modules so that the cable shape resembles a 'W'.

B. Lazy wave variations – mid water arches "Lazy-S"

The other variation often adopted for a lazy wave configuration "Lazy-S" is to replace the midline buoyancy with an anchored mid-depth buoy across which the cable lays, i.e. a Mid Water Arch (MWA). Typically tethered to the sea floor, MWAs may also be fixed structures, although this is more relevant for O&G facilities which use them to accommodate several risers at once.

While more expensive than midline buoyancy attached to the cable itself, the MWA gives additional compliance to the system and is used to decouple the motions of the cable at the hang-off point from the touchdown point. MWAs are often used in shallower waters, especially for floating units which have significant motions.

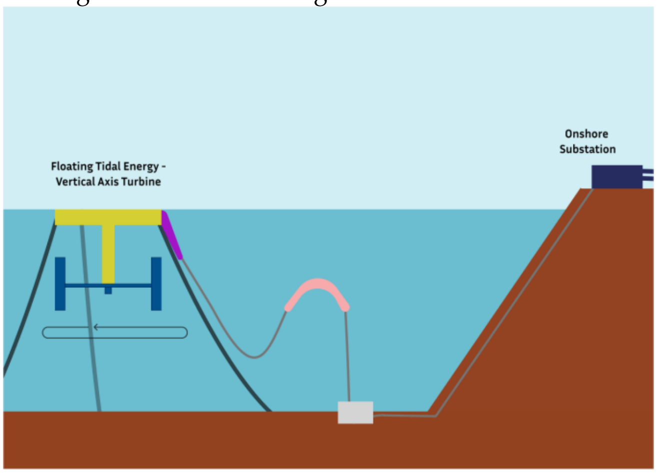


Fig. 5. A vertical axis tidal turbine with a steep wave cable configuration.

3) Steep wave cable configurations

A steep wave configuration is similar to the lazy wave in that the buoyancy modules allow for a hump-like shape to form; however, the terminology "steep" refers to the near-perpendicular incidence angle of the cable to the seabed, as shown in Fig. 5. Much like within a lazy wave, the buoyancy modules are also strategically placed to assist in managing the cable's weight and tension, thereby allowing movement while minimizing the strain experienced.

Steep wave configurations for cables are particularly advantageous in scenarios where there are large currents throughout the water column and there are increased risks of the cable being swept across the seabed.

These configurations were first adopted in the O&G sector for high-energy environments where there are higher magnitudes of vertical and horizontal loads, such as those with high frequency (short period) waves, or high current speeds. Steep wave buoyancy modules are often placed closer to the seabed end of the configuration so that cable transitions to the seabed in a near-perpendicular direction. This also makes a steeper curve, which means it can absorb and dissipate the metocean energy more effectively, reducing the risk of the mechanical stress and fatigue. Additionally, the steep wave allows for less interaction with the seabed in comparison to other configurations. Reducing the interaction with the seabed results in a reduced risk of failures due to abrasion, making it more suitable in regions with rockier or harsher seabeds or in regions with high currents.

However, the implementation of steep waves involves an increased cost for engineering efforts and materials associated with the seabed interface architecture and the precise placement of buoyancy modules, resulting in complexities in the installation phase. Increased costs are also incurred within the maintenance and inspection efforts as the buoyancy modules need to be inspected to ensure they have not moved or been impaired due to excessive marine growth.

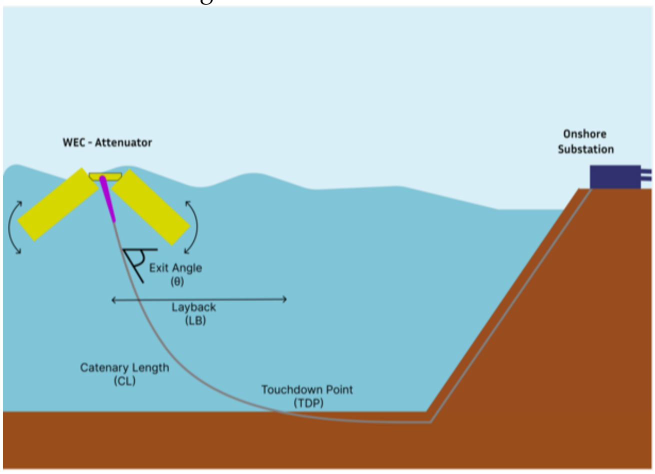


Fig. 6. A WEC Attenuator with a catenary cable.

4) Simple catenary cable configurations

A catenary is defined as the curve made by a cable or chain when it is suspended by its ends under the influence of gravity, as shown in Fig. 6. This configuration ensures that the suspended cable section has flexibility so it can adapt to the dynamic ocean conditions. Within subsea systems, a simple catenary can be used to maintain the structural integrity and functionality of cables within various metocean conditions by accommodating for the constant motions.

Simple catenaries are typically cheaper and easier to install than the other wave configurations discussed. However, they are less compliant to OET platform motions, risking exposure to overbending, fatigue or overload failures of the cable. Therefore, more advanced lazy waves or steep waves might be needed in harsher ocean conditions

The cables are laid from the floating structure to the seabed so that the optimal catenary can be formed. Both cable tension and bending need to be managed during the lay, and additional anchoring or temporary installation aids may be required to ensure the cable does not slip, become over-tensioned, or over-bent during the process.

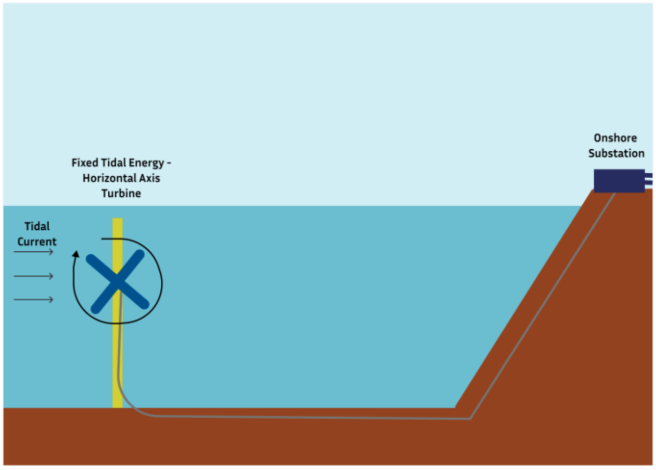
IV. CABLE CONFIGURATIONS FOR FIXED SYSTEMS

Within fixed devices, the cable exits the system via a J-tube and spans across to the seabed. Fixed systems include fixed tidal energy or point absorber (Fig. 7), and OWSC WECs. Notably, the cable configuration for each is similar, with the main difference being whether the cable is exposed above the seabed, or captive to the structure itself.

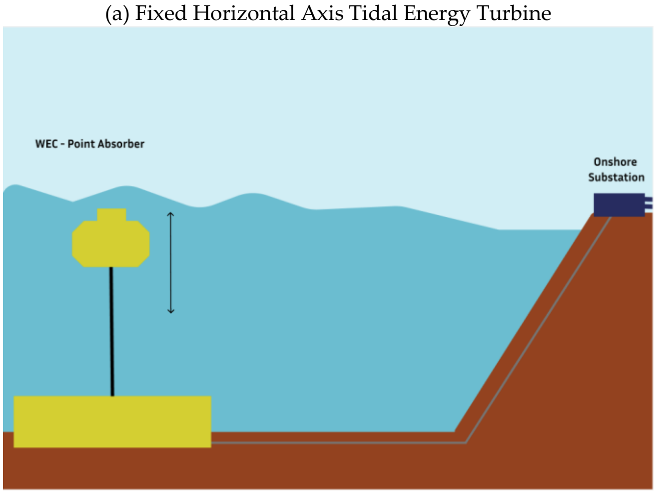
Within the suspended region of cable that is between the J-tube and the seabed, there is opportunity for the cable to effectively be dynamic when exposed to the water column. This can also result when the cable is subjected to phenomena such as scour or seabed movement, with loads such as wave action and Vortex-Induced Vibration (VIV) causing mechanical failures due to extreme or fatigue loading. Cable protection systems (CPS) are required to provide the cable with the necessary protection against these loads. CPS components include bend stiffeners and bend restrictors.

Due to the dynamic nature of the "dynamic bend restrictor train" region (Fig. 8), a wet cable design is traditionally selected to account for fatigue induced by VIV or typical wave and current forces. However, if the dynamic bend restrictor train is expected to experience fewer dynamic motions due to more benign surrounding metocean conditions, it may be feasible to use a dry cable design for that region.

As the seabed surrounding the touchdown of the cable erodes, the exposed region of the cable span can grow, making it more susceptible to VIV and thus fatigue damage. This seabed loss is often attributed to scour, discussed in the next section.



(a) Fixed Horizontal Axis Tidal Energy Turbine



(b) Point Absorber Wave Energy Converter

Fig. 7. The fixed cabling associated with a Fixed Horizontal Axis Tidal Energy Turbine (a) and a PA WEC (b).

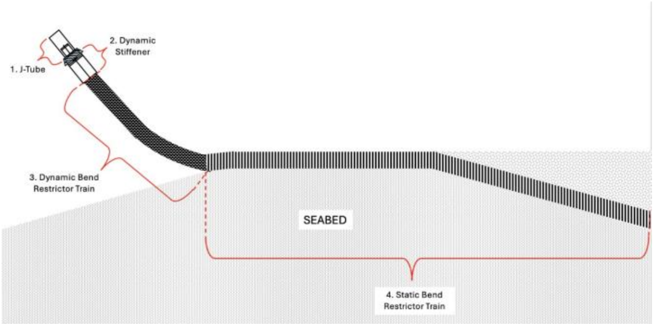


Fig. 8. Cross-sectional view of a fixed OET cable span

V. Site-Specific Environmental Data

The dynamic cables accompanying OETs must be able to withstand the various environmental factors within the project site. Along with the standard metocean conditions (wind, wave and current), there are two other key considerations discussed herein: marine growth and seabed stability or scour.

1) *Marine growth*

The marine growth that the cable is likely to experience is a factor in the cable life span, as it can add weight and drag to the cable, the latter being due to a greater cross-sectional area. This marine growth results in the cable experiencing greater loads than when growth is not present, and should be assessed at the design stage. The type and rate of marine growth tends to be very location-specific, depending on the nutrients, local species and organisms present, and temperature: both water temperature and cable skin temperature when operational. An example of marine growth is given in Fig. 9.

Throughout the design phase of the project, efforts should be made to collect robust site data to support the design of the cable configuration for the given OET device. Additionally, prevention measures, removal methods and the potential of the recyclability of the ecological matter need to be addressed.

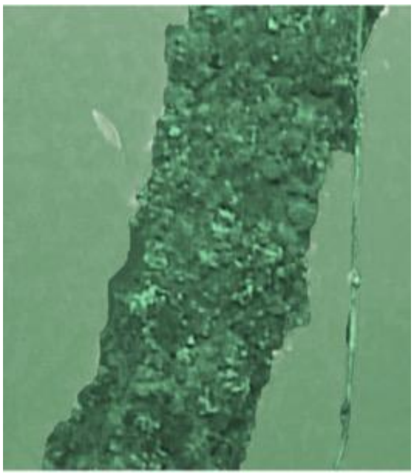


Fig. 9. A subsea cable with marine growth and fishing tackle.

Fig. 10. Scour Testing by AMOG Consulting at the University of Western Australia's O-Tube facility (authors' own). Upper figure is at t=0, lower figure after several hours of exposure to flow.

2) Scour and its effect on subsea cables

Scour is the phenomena when flow accelerates around an object, mobilizing the sediment surrounding the object and carrying that sediment into the free stream.

Scour is initiated by the boundary layer shear flow against the seabed and the parting of the flow as it travels around the monopile / structure that causes the introduction of vorticity into the flow near the intersection of the structure and the seabed. The vortices evolve into a horseshoe vortex pattern [16].

The formation of the vortices and its characteristics are determined, among other things, by the cable geometry and the Reynolds number [16].

Scour mitigation can come from changing the geometry that obstructs the flow, usually in the form of rock dumping surrounding the scour area or the addition of VIV suppression devices to minimise the occurrence of scour. If significant scour has already occurred, an intervention operation may be required to both rebury the cable and modify the design to limit the scour from reoccurring.

An image of scour testing is shown around a model monopile in Fig. 10.

VI. Failure Modes

1) Failures identified with static cables for ocean energy technology systems

It is estimated by the Carbon Trust that the average failure rate for static maritime renewable cables is between 1.9 x 10^{-3} failures/km/year and 2.13 x 10^{-2} failures/km/year [17]. The main causes of failure within the bottom fixed maritime renewable UK industry can be split into the following categories: development, manufacturing, installation, operation and external damage [18]. To mitigate these causes of failures, the OREC (Offshore Renewable Energy Catapult) suggest that the following aspects should be considered [18]:

1) Development: Over the duration of the development phase of the project, it was suggested that more comprehensive site surveys are required. The aim of these is to ensure the cables are design to be suited for the environment and the installation methodology.
2) Manufacturing: Experienced subsea cable experts should be a part of the cable design and witnesses to manufacturing process so that potential issues can be identified at the earliest possible point. Some of the problems that may be mitigated include serial defects, issues within the cable design or fabrication facilities and the manufacturing of the cables.
3) Installation: The selection of skilled installation contractors was noted as being an important factor to reduce installation failures. Particular attention is drawn to the joints and accessories of the cable, and the installation process should be monitored by high voltage cables experts. This monitoring complements the work scopes of the Marine Warranty Surveyor (MWS). The MWS ensures that the installation adheres to the warranty clauses from insurers, and typically surveys and verifies vessel and equipment selection, spooling operations, sea fastenings for transport and the installation campaign itself.
4) Operation: In the operations phase, these artificial ocean structures can become home to an ecosystem of marine life, sometimes leading humans to fish close to them, despite exclusion zones. It is very common for underwater inspections to find fishing lines wrapped around cables. Effective ways to eliminate fishing interaction are still sought.
5) External Damage: It is important to ensure that the survey data are of an acceptable quality and have a good understanding of the shipping traffic surrounding the sites. Cable burial risk analyses must also be conducted; these are applicable for both bottom fixed and floating maritime renewables.

The frequency of occurrence for many of the cable damage scenarios could be mitigated through public knowledge-sharing or other communication of failures experienced across the industry. Examples of this include sharing faults that occur within the fibre optic carrier tube and cable protection system [19]. Sharing high-profile issues allows for an increased awareness throughout the industry, thus leading to better risk mitigation in the longer term. Analogous sharing of failure data has occurred in the offshore energy sector, both for mooring integrity [20] and in the OREDA database [21] for subsea equipment reliability. Furthermore, offshore wind field owners and operators are sharing data to improve the collective experience through ORE Catapult's SPARTA initiative [22].

2) Installation faults within bottom fixed wind turbines

Installation failures make up almost half (46%) [18] of the cable failures within the maritime renewable sector; mainly occurring due to cables being mishandled and overbent. Finding the origins of installation failures is known to be a challenge especially if the failure occurs while the cable is operational. The five categories for installation failure are the following:

- Design
- Equipment
- Planning
- Engineering
- Human complacency

The design category in the above list does not include design flaws, faults of the cable cross-sectional properties, nor the configuration of the cable, but rather refers to flaws in the design of the installation process. This includes problems caused by incompatible vessel selection or installation methodologies, and encompasses failures related to cable accessories.

Equipment installation failures are those that occur when the equipment is unvalidated or not appropriate for the project. This could occur due to failure or poor performance of the tools, or may be due to lack of availability of the correct tools, resulting in inappropriate substituted equipment.

Planning failures occur due to timeline pressures or delays, coupled with insufficient contingency plans. This category also includes ill-definition of temporary storage or suspension of works due to weather that result in a cable failure during the subsequent handling or storage.

Failures due to engineering occur when the cable handling criteria is unclear, standards are not met or properly defined, the environmental basis of design is not representative of the field conditions, or changes to the design are not properly assessed or communicated. These can also occur when methods are unvalidated, unproven or executed according to the wrong or outdated standards.

Lastly, failures that occur due to human complacency are most common when workers experience at least one of: fatigue, poor communication, or workmanship. Poor workmanship may be due to under-qualification or poor-quality training.

Over the duration of the installation operation, there may be multiple transitions and other stop/starts which can create compound risks. The installation plan should be well-researched and widely understood, with work being conducted alongside experienced professionals to avoid problems in the interface management between the cable and the floater EPCIs.

3) *Cable failures across the offshore sector*

There has been an increase in demand for subsea cables due to the increase in offshore renewable energy projects, with the global demand for cables being estimated to grow to an expected 24,103 km of cables by 2021 [23]. It is also expected that many of the existing or recently deployed subsea cables could be in need of repair or imminent replacement. The maintenance of subsea cables within the offshore renewables sector is a subject of utmost importance, as failing cables cause significant financial losses. For example, GCube Insurance Services [24] reported that 55% of total claims they handled were due to cable failures. Additionally, interruptions in the power supply cause significant financial losses to the field owner or operator due to production downtime and repair costs, and have the potential to impact external stakeholders due to power unavailability.

As shown in Table 1 the historical data from Scottish and Southern Energy (SSE) PLC [25] over a fifteen-year period from 1991 to 2006 suggest that 8.3% of all subsea cable failures occurred due to faulty installation, in contrast to the 46% failure rate due to installation which is specific to bottom fixed wind turbines discussed previously.

Furthermore, most of the failures are due to environmental (47.5%) or third-party damage (26.7%). The environmental failures are broken down into armour and sheath failures and are likely wear-out failures due to phenomena like corrosion or abrasion. Third-party failures are more random in nature, with these consisting of specific events such as anchor drag, shipping incidents or other dropped objects causing cable failure.

The estimated cost of locating and replacing a damaged section of cable can be in the range of €0.7– 1.5 million for European based projects.

TABLE I
ROOT CAUSES OF SUBSEA CABLE FAILURE
BETWEEN THE YEARS 1991 AND 2006
(SOURCE: SSE PLC [25])

Symbol	Quantity	Number of Failures	% of total
Environment	Armour Abrasion	26	21.7
	Armour Corrosion	20	16.7
	Sheath Failure	11	9.1
Total Environment		**57**	**47.5**
Third Party Damage	Fishing	13	10.8
	Anchors	8	6.7
	Ship Contact	11	9.1
Total Third Party		**32**	**26.7**
Manufacturing/ Design Defects	Factory Joint	1	0.8
	Insulation	4	3.4
	Sheath	1	0.8
Total Manufacturing/Design Defects		**6**	**5**
Faulty installation	Cable Failure	2	1.6
	Joint Failure	8	6.7
Total Faulty Installation		**10**	**8.3**
Not Fault Found (NFF)	Unclassified	10	8.3
	Unknown	5	4.2
Total NFF		**15**	**12.5**
Total		**120**	**100**

VII. MONITORING SOLUTIONS

Ensuring the integrity of an OET's cable systems requires strong inspection and monitoring strategies. This is a common challenge across all subsea cables, and indeed most aspects of floating technology in general. Both the frequency and fidelity of inspections are important factors. Additionally, the two strategies are best considered side-by-side, as credible monitoring may allow for additional insights into the cable system and thus support more targeted or risk-based inspection campaigns.

Guidelines from Classification Societies on the frequency of inspections tend to be prescriptive, however there are gradual changes occurring with transitions to risk-based frequency inspection strategies such as those described for mooring failures in [26]. The risk-based approach compares the value of the inspections against the inspection costs and the risks which the inspection is attempting to mitigate.

Measures such as condition monitoring of cables could be used to enable those working on a project to collect data remotely and devise informed risk mitigation plans such as undertaking further inspections, conducting pre-emptive repairs or removing marine growth. The holistic consideration of inspection strategies in conjunction with condition monitoring can therefore provide an optimised cost throughout the lifetime of the asset in addition to providing the necessary risk mitigation.

A good monitoring strategy can be a key aspect of achieving or extending the life of the cable, or simply minimizing downtime. Monitoring allows for forecasting and prediction of cable integrity, and therefore optimised sparing strategies, i.e. advanced planning for the ordering of new equipment or parts to in turn enable optimised inspection and repair periods.

During operation, a large amount of data are likely to be generated and thus needs to be properly filtered, analysed, interpreted and stored. Data collection should focus on sections of the cable that are most likely to experience problems (as identified in Section VI), such that the governing (lowest) design life utilisation can be identified and recorded. A downside of monitoring is that false positive anomaly identifications may occur, in which case an argument will need to be mounted, or proof gathered, that the identification was incorrect [7].

Although the utilisation of monitoring systems increases the CAPEX of the project, the benefits of these systems, such as increased operational visibility, should theoretically improve the project's OPEX. For larger arrays (10s of units) a sampling strategy for instrumentation may improve CAPEX without significantly impacting visibility into the condition of the field. A sampling strategy involves instrumenting only a subset of units, and then extrapolating these learnings across the entire array. This monitoring technique requires a well-justified selection of instrumented units which accurately represent the entire system health in order to provide the appropriate assurance to both insurers and Classification Societies. Although there is a potential OPEX reduction that accompanies this technique due to the added flexibility gained for inspection or repair activities; there are uncertainties in the way immediate fault interventions are guaranteed following an incident notification.

1) Distributed fibre optic sensing

One proposed monitoring method is distributed fibre optics. These systems can measure mechanical stress factors (bending, strain, pollutants and heating) and electrical stress factors (transience and harmonic) experienced by the cable. Solutions include:

- DAS: Distributed Acoustic Sensing
- DTS: Distributed Temperature Sensing
- DSS: Distributed Strain Sensing

The utilisation of distributed fibre optics does not require any active sensors throughout the entire cable route. A laser is pulsed through the fibre from a device that is situated at one end of the cable, and the reflected light provides information on the magnitude of the bending, amplitude, and frequency of vibration of the fibre [27]. The placement of the hardware, as well as the amount of hardware needed, is dependent on the configuration of the farm's configuration, as a single interrogator can be used to monitor the cables of multiple energy generation sources provided it is within the limits of cable length coverage for the device (50-125 km [28]). Optical loss can occur when the fibre optics are spliced, thus it is generally beneficial to reduce the number of connectors along the cable.

2) Additional monitoring or inspection options

Other options for monitoring or inspecting the cable integrity include accelerometers and gyroscopic rate sensors, which work with accessories mounted to the cables. Other alternatives include ROV (Remote Operated Vehicles) or AUV (Autonomous Underwater Vehicles) fly-by with camera and or sonar detection methods [29]. These sources can be used in conjunction with environmental (metocean) data in order to validate machine learning or numerical models (Section III.B) using real-life conditions, creating digital twins that assist in identifying failure modes, fatigue and other problems that may arise over the system's life. This digital twin may be a cable-only uncoupled model driven by measured motions of the floater, or may include the floater and mooring system in a coupled model. The advantage of the latter option is that this can then take metocean data as an input to the digital twin, rather than the more complicated gathering of floater motions.

VIII. Conclusion

Through the discussion in this paper, there is a significant body of knowledge that the commercially nascent OET sector can rely upon for designing and managing both static and dynamic cables. Many lessons come from the O&G and offshore wind industries for both fixed and floating systems.

Floating OET systems are likely to adopt one of three major categories of cable configurations: lazy wave, steep wave and simple catenary; with all three being applicable in different conditions and projects. Simple catenaries are the cheapest and easiest to install but provide less compliance to the cables and are therefore not recommended to be used where challenging metocean conditions are expected. Lazy wave and steep wave configurations exhibit similarities due to the presence of buoyancy modules to add compliance to the system. However, a lazy wave cable is laid tangentially to the seabed, whereas conversely a steep wave has an almost vertical touchdown, often connecting to a subsea base to enable greater suitability in regions with harsher seabed conditions or high wave or tidal forces.

Fixed devices traditionally have cables that travel down the fixed structural system or tether and then exit the structure and span across to the seabed. Even through the OET structure is fixed, there can be a dynamic span that is exposed to the water column and thus to VIV-related failures and scour in the region of sediment surrounding the touchdown zone.

The associated failure modes for these cables can arise due to design and process issues in the following stages: development, manufacturing, installation and operation, or may be due to external sources of damage. Most failures occur due to phenomena such as abrasion, corrosion or sheath failure that is triggered by environmental factors; thus, numerical modelling should be conducted to examine the behaviour and performance of the cable within the full range of conditions it is likely to experience over its life.

Despite best endeavours during design, it is important to prepare for incidents of cable failures to ensure they can be managed and responded to, in order to minimise downtime and cost to the project. Monitoring solutions, including distributed fibre optics, have been proposed for detecting and possibly predicting cable failure. Effective monitoring strategies can enable both risk-based inspections, and more efficient ordering of replacement parts or operational planning.

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