Deliverable 3.1: State-of-the-art assessment and specification of data requirements for electrical system architectures

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Abstract

This deliverable will consist of two major parts:

- A comprehensive review (Chapters 1-4) of all the electrical infrastructure technologies between the converter and the point of connection to the onshore electrical grid, including technologies currently used in offshore electrical networks, as well as those foreseen to be deployed in the near future.
- A set of operating regimes of the ocean energy conversion arrays in terms of their output power (given as a statistical representation and as a set of representative time series), for the scenarios to be considered in the next tasks, as defined by WP1 and WP2 (Chapter 5).

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1 Introduction

This deliverable (D3.1) represents the first outcome within Work Package 3 (WP3) in DTOcean (Optimal Design Tools for Ocean Energy Arrays).

According to the description of work (DoW) of the whole project, the aim of WP3 is "to develop a methodology that proposes technically and economically optimal configurations for the offshore electrical network". In Figure 1 there is the overall structure of DTOcean project and in particular the position of WP3, which is a technical work package.

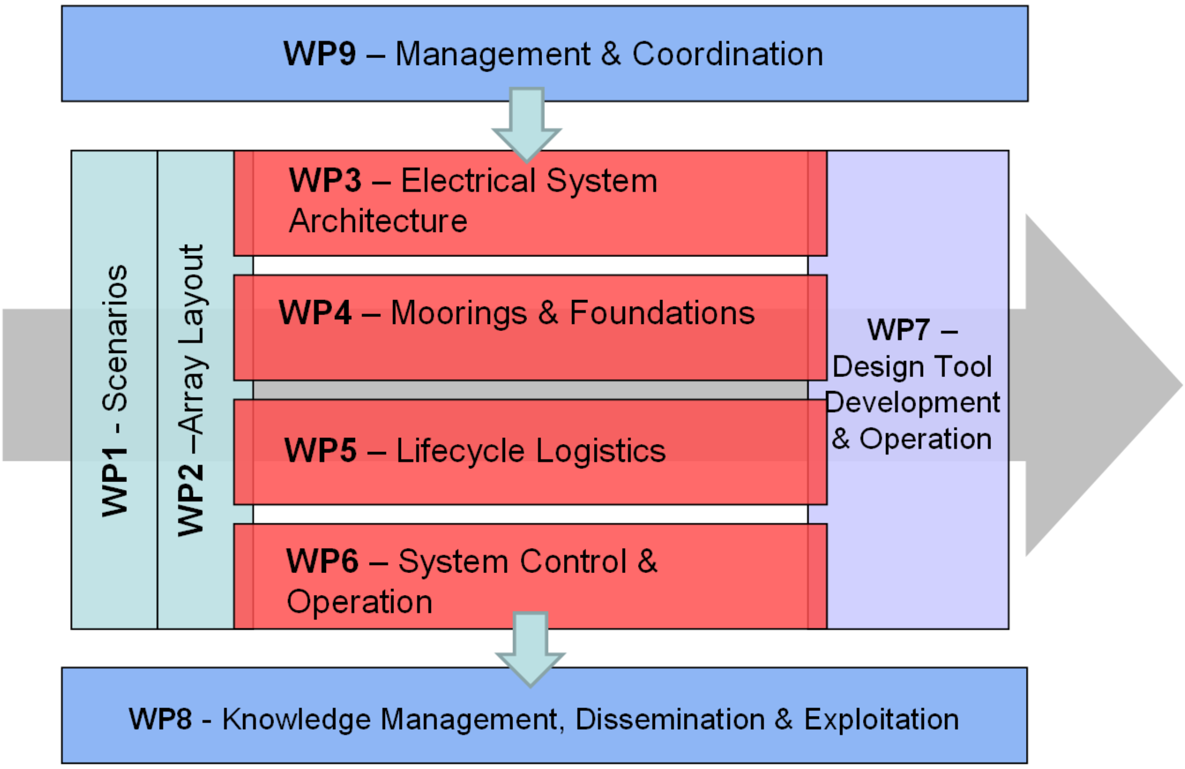


Figure 1: Operational structure and interrelation of the Work Packages in DTOcean

Evidently, the above mentioned major target of this WP can be achieved by fulfilling a series of interrelated objectives. The starting point is to analyze the various components and configurations of the electrical subsystems, pointing out which are the possible advantages and performing a critical qualitative assessment of the risks associated with any choice in terms of costs and reliability. For any configuration, the computation of the electrical efficiency must be evaluated after defining a proper methodology; reliability analyses are required, too, in order to predict the failure probabilities and estimating the mean time between failures. Once such a modelling activity is complete, a global design tool will be generated, encapsulating reliability, performances, costs and also environmental aspects related with the architecture of the electrical system. Of course, the configurations to be examined within this WP are the most relevant in terms of possible exploitation in the next 10 years for Ocean Energy Converter Arrays and they include all the components and subsystems of the electrical architecture: the umbilical, the subsea cables, the offshore substation including transformers, switchgear and power conditioning, and finally the link to the onshore grid.

D3.1. is a public report and essentially it collects the outcomes of the first two tasks developed in WP3 (Task 3.1 and Task 3.2). In D3.1., first, a state of art of all the electrical subsystems used for Ocean Energy Converters will be illustrated, starting from the technologies currently used in offshore electrical networks, as well as those proposed by the research community, aiming to a comprehensive assessment of the available and proposed offshore network technologies. Subsequently, the experience from previous projects (EPSRC Supergen Marine 1-2, FP7 MARINA etc.) will be collected in order to identify the operating regimes of the ocean energy conversion arrays in terms of their output power, for each of the scenarios defined in the WP1 and WP2. The objective is to define the electrical power output of each converter and the farm as a whole to be provided as inputs to the rest of the Tasks of WP3. In this sense, the methodology to define the power output characteristics of OECs will be illustrated within D3.1.

Essentially D3.1 follows the same structure. It can be separated into two major parts:

i. A comprehensive review of all the electrical infrastructure technologies between the converter and the point of connection to the onshore electrical grid, including technologies currently used in offshore electrical networks, as well as those foreseen to be deployed in the near future. In this section, experience and models from offshore wind energy research and industry, being more advanced, has been taken as an example critically, evaluating possible applications for wave and current marine energy farms.
ii. A set of operating regimes of the ocean energy conversion arrays in terms of their output power (given as a statistical representation and as a set of representative time series), for the scenarios to be considered in the next tasks, as defined by WP1 and WP2.

D3.1. consists of 7 major chapters, each of them divided into paragraphs and other partitioning as needed:

1) Chapter 1 is the present introduction, which elucidates the objectives of WP3 within DTOcean, but also the content of D3.1 and its structure.
2) Chapter 2 is entitled “Offshore Electrical Network Technologies”. In it, the state of art of electrical subsystems is included. In particular, specific attention is given to:

cables (transmission and umbilicals); connectors; ancillary components; hubs (subsea without transformers and offshore substation); transformers & switchgears; storage systems; reactive power compensation; HVAC and HVDC.

3) Chapter 3 is entitled "Offshore Electrical Network Architecture" and it is mainly a topological chapter describing layouts, costs and reliability of the possible inter-array cluster distribution.
4) Chapter 4 is a very short Chapter, herein included just for the sake of completeness, about the architecture of the onshore electrical network
5) Chapter 5 constitutes mainly the second major part of D3.1, which elucidates the methodology to define the power output characteristics of Ocean Energy Converters (OECs) for tidal and wave resource.
6) In Chapter 6 some conclusions will be presented with the perspective of the work to be done in the other tasks of WP3 and the interconnections with other WPs.
7) Finally, in Chapter 7 a list of References is included.

2 Offshore Electrical Network Technologies

2.1 General Description

Marine energy devices must be electrically connected to the onshore grid system in order to make use of the energy generated. The marine environment both above and below the water surface poses particular challenges in terms of the harsh environmental conditions that the connection equipment must withstand. In addition, access to the equipment for inspection, maintenance and repair will probably be weather-dependent and therefore sporadic and unpredictable. Access costs will be high due to the requirement for sea-going vessels and divers and/or submersible vehicles.

From a theoretical point of view any marine energy device might be directly connected to the grid without any additional element, assuming that a proper power converter is installed on board. However, for efficiency and economic reasons, it is likely that power produced by arrays of converters will be collected and transformed before transmitting it on-shore. Another option is to deliver the energy extracted from several devices through a cable into a submarine hub. This can be achieved in several ways and through several possible configurations that will be introduced in the rest of this document.

In particular, the following chapter will deal more specifically with the components of an offshore electrical network:

1) Cables (transmission and umbilicals), taking into account technical (such as for example materials, capacity, design technologies) and economic issues;
2) Connectors;
3) Ancillary components (bend stiffeners, bend restrictors, buoyancy elements and marker buoys)
4) Hubs (subsea substations and offshore substations)
5) Transformers and switchgears;
6) Energy Storage Systems (mechanical, electric and electro-chemical devices)
7) Power transmission options (HVAC and HVDC).

The following chapter will deal more specifically with the voltage level of connection to the inter-array network and the electrical layouts. Finally in chapter 4 the architecture of the onshore electrical network is presented. This is illustrated in Figure 2.

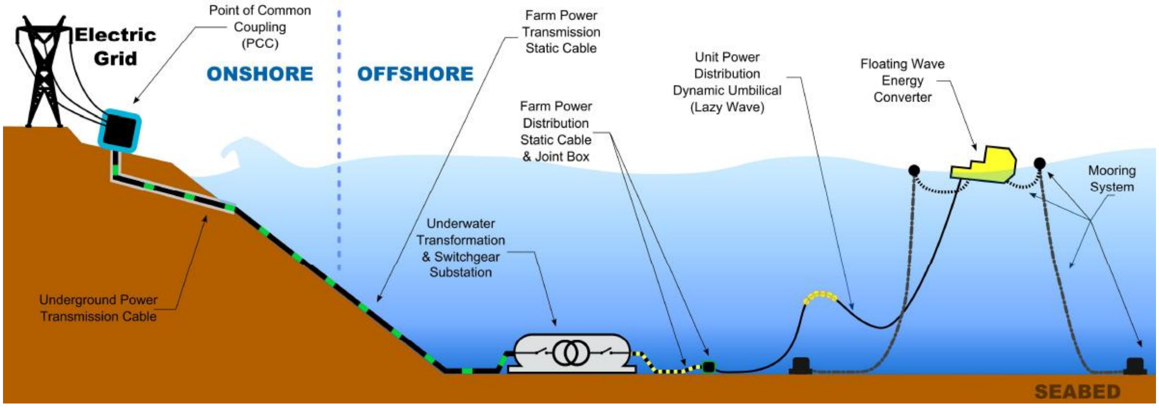


Figure 2 Example of electrical connection of wave energy converter [1]

2.2 Cables

Herein a state of the art of submarine cable technologies available today for the implementation of the future Ocean Energy Farms is presented.

Mainly, there are two major groups of cables within an Ocean Energy Farm:

- *Transmission cables*: used to export the integrated energy from the farm to the grid connection point; they can be used also inside the farm for internal connection of several devices to the transmission cable (interconnection cables)
- *Umbilical Cables*: used to interconnect two ocean energy devices or one with any other element in the energy transmission chain.

Different technologies are available, that may be chosen as a function of the voltage and power to be transmitted.

2.2.1 Transmission Cables

a. Submarine cables

The cable and cable laying costs in the marine environment are higher than their onshore counterparts. The most direct cable routes need to be established from the offshore substation locations to the proposed landfall points [2].

It is questionable if full redundancy (e.g. two cables of the same rating connecting a farm to the shore) for marine energy farms is economic, especially for small farms. Djapic and Strbac [3] recommends (for offshore wind farm) the use of a minimum number of submarine cables required for the power transmission with no redundancy. It also adds that the capacity of the cable can be less than the farm capacity by X% [3], being X a factor obtained by dividing cable capacity by wind farm capacity (see Table 10 in [3]). This approach has been accepted by the Crown Estate in the Round 3 offshore wind farm development too [2].

It is likely that a cost benefit analysis done for marine energy farm transmission options would provide very similar recommendations. Gardner et al. [4], through an economic study of offshore wind farms, proves that a redundancy of certain kinds (e.g. dashed link, of the same capacity as the other cables in the system, in Figure 3 is economically more valuable than having an additional connection to the shore. This is likely to hold true for marine energy farms too.

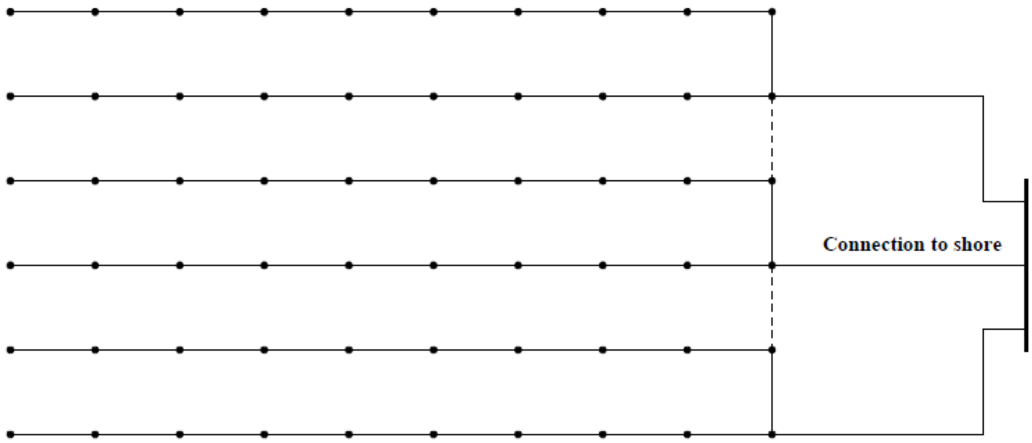


Figure 3: Cable redundancy in an offshore farm [4].

The gap in knowledge here is with respect to medium voltage transmission of power, which has not been dealt with in the recommendations for offshore wind farms. Transmitting the power at MV (33 kV in the UK) may be an option for small marine energy farms. The Wave Hub test site, 26 km from the shore and rated at 20 MW, uses a 33 kV transmission cable to the shore. Technical details of the cable used are available in [5]. The cost benefit analysis completed for the offshore wind industry will provide the framework for a similar analysis for marine energy farms, including the option of transmitting power at MV.

The voltage used to transmit the power to the onshore substation depends on the size of the marine energy farm and its distance from the shore. The power transfer limits of AC cables over long distances are: (132 kV up to 250 MW, 400 kV up to 2000 MW) [3]. The 400 kV cables are single core cables and require considerable amounts of reactive power compensation and may not be a viable option. A similar model for transmission at MV needs to be identified for marine energy farms. Irrespective of the voltage level, three-core cross-linked polyethylene (XLPE) cables have been the preferred choice for offshore wind farms ([2] and [6]) and may continue to be the choice for marine energy farms too.

Energy losses in the cable, due to ohmic losses in the conductor and the metallic screen, can be reduced by using a larger conductor [7]. This has not been considered in the work completed for offshore wind farms [3] and might not prove to be an economically viable option for marine energy farms. Dielectric losses of the XLPE insulation, also present at no load, depend on the operating voltage and can be significant over 100 kV [7]. Dielectric losses in XLPE cables are lower than for Ethylene Propylene Rubber and fluid-filled cables [7].

The IEC 60287 series of standards on submarine cables recommends:

- One three-core cable or one three-phase group of single core cables
- Temperature in sea bed 20°C
- Laying depth in sea bed 1.0 m
- Sea bed thermal resistivity 1.0 K x m/W

Not many models for estimating costs are available in scientific literature. Among all, one of the most adopted reference is [8], and subsequent models are based on . Costs were derived for different components in a wind park, but for the electrical components it could be assumed that the same may apply to the marine energy field. However, no reference to the sources such models are based on is made. All the constants and costs reported in [8] are expressed in Swedish Krona as for the year 2003, so when using the constant they should be adequately actualized.

For cables in AC, the cost function according to [8] follows the law:

$$\boldsymbol{Cost_{AC} = A_p + B_p exp \; \frac{C_p S_n}{10^8}} \quad 1$$

Where

$$\boldsymbol{S_n = \sqrt{3} U_{rated} I_{rated}} \quad 2$$

and

$Cost_{AC}$ is the cost of AC cables [SEK/km]

U_{rated} is the rated voltage of the cable, line to line [V]

I_{rated} is the rated current of the cable [A]

S_n is the rated power of the cable [W]

$A_p, B_p and\ C_p$ are the cost constants, generally depending on the rated voltage U_{rated}.

In case of cables in AC, then, it turns out that

i. Costs depend linearly on the length

ii. Costs increase exponentially with the rated power of the cable

For cables in DC, the cost law is the following:

$$\boldsymbol{Cost_{DC} = A'_p + B'_p S_n} \quad \textbf{3}$$

Where

$$\boldsymbol{S_n = U_{rated} I_{rated}} \quad \textbf{4and}$$

and

$Cost_{DC}$ is the cost of DC cables [SEK/km]

U_{rated} is the rated voltage of the cable, pole to pole [V]

I_{rated} is the rated current of the cable [A]

S_n is the rated power of the cable [W]

A'_p and B'_p are the cost constants, generally depending on the rated voltage U_{rated}.

In case of cables in DC, then, it turns out that

i. Costs depend linearly on the length
ii. Costs increase linearly, too, with the rated power of the cable

Of course, installation costs must be taken into account as well. It can be assumed [8] that generally installation in sea is three times higher than on land.

b. Load Capacity

Most cable systems will be registered with rated load in MVA or MW when built. The challenge of designing or choosing the right cable cross section is the variation of the ambient conditions for the cable system. The cable manufacturers define the cable load for the specific cable based on knowledge of the surroundings, e.g. buried in the seabed, water, air, steel tubes, at platforms, etc. The thermal resistivity of the surrounding material influences on the capability of getting rid of the heat generated by the current in the cables (an example of ABB submarine cable ratings [9] can be seen in Table 1).

Table 1: Example of ABB Submarine Cable Ratings [9]

Conductor [mm^2]	Cable diam. [mm]	Mass in air [kg/m]	Ratings at 33 kV			Losses at full load Per phase, [W/m]
			Seabed temp [ºC]	Current [A]	Power [MVA]	
185	107	17	10	480	27.4	32.5
			20	449	25.7	28.4
240	111	19	10	549	31.4	33.7
			20	513	29.3	29.5
300	117	22	10	611	34.9	34.9
			20	572	32.7	30.5
400	122	25	10	681	38.9	36.3
			20	637	36.4	31.7
630	138	33	10	830	47.4	39.2
			20	776	44.4	34.3
800	147	40	10	896	51.2	40.7
			20	838	47.9	35.7

Maximum continuous load at the landfall sections can be limited significantly due to the submarine cable laying in dry or moist soil with high thermal resistivity. The cable load capacity can be decreased up to 200A for an 800 mm^2 cable [3]. The decreasing of load capacity can be limited by choosing backfill material with extremely low thermal resistivity.

In general, the cable installation is more expensive than the cable itself, which encourages choosing a larger cross section instead of having two cable systems in parallel.

c. Cable Type

The High Voltage (HV) submarine power cable is built up with three single-core cable (three phases) surrounding by filling material and covered by armouring (see Figure 4). The cable will also include one or more optical fibre cables for communication or protection purposes, if requested.

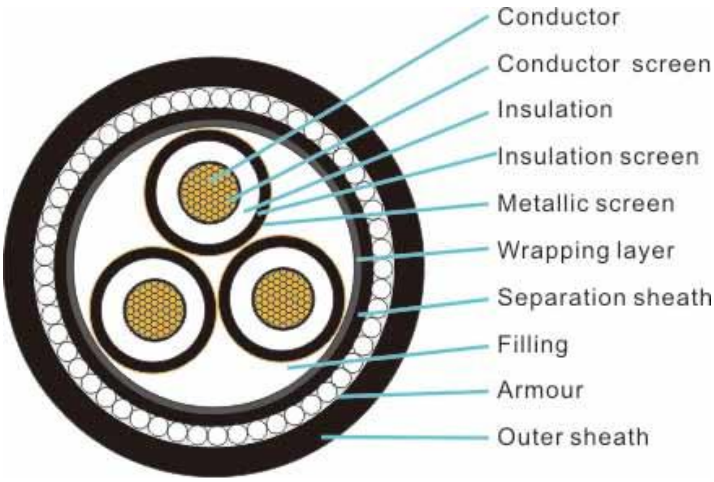


Figure 4: Three-core XLPE cable [10]

d. Conductor

The HV power cable conductor could be copper or aluminum. The cable manufacturers generally offer copper conductors even though aluminum is less expensive. The copper conductors have the benefit of having a higher load capacity per square millimetre than aluminum. To reach the same load capacity, an aluminum cable will need a larger cross section which results in a submarine cable with a larger overall diameter.

Cables with aluminum conductors have a lower weight than similar cable with copper conductor. For submarine cables with smaller cross sections, this could give challenges during installation, since the cable is too light to fall into the seabed by itself.

The conductors can be solid, stranded or specially designed. All conductors will be watertight by using swelling powder between the conductor cores.

e. Insulation

The cable insulation provides an effective barrier between potential surfaces with an extreme potential difference. It is very important that the insulation system is absolutely clean and even. Furthermore, the insulation wall must be mechanically robust, and resistant to temperature and aging.

- **Self-Contained Fluid-Filled Cable Systems**

  Self-contained fluid-filled (SCFF) cables have been used for underground and submarine power transmission for at least 70 years. The insulation of a SCFF cable is composed by multi-layers of pure cellulose paper tapes impregnated by fluid oil under pressure. More recently, pure cellulose paper tapes have been replaced by composite tapes, which are a sandwich of cellulose and polypropylene film, named paper–polypropylene laminated (PPL) tape that offers some improved properties in terms of capability.

SCFF cables have an excellent record of reliability in service and for many years have represented the only solution for difficult connections.

SCFF cables are mainly composed by the oil channel (see Figure 5), the conductor, the oil impregnated paper, maintained under pressure by the oil in the channel, and impervious lead or aluminum metallic sheath, and an overall protective sheath. In addition, submarine cables are also armoured in order to improve their mechanical performances.

Oil reservoirs shall be placed at the terminations and, for long connections, also along the route in order to maintain the suitable oil pressure inside the cable; for long submarine lines, a pressurizing oil pumping plant is necessary at one or both ends.

One of the disadvantage of this system is that requires a permanent oil pressure monitoring throughout its whole life. Indeed, such a monitoring and proper maintenance for these kinds of cables must be taken into account, as they can result in tension drop of the cable and environmental impact.

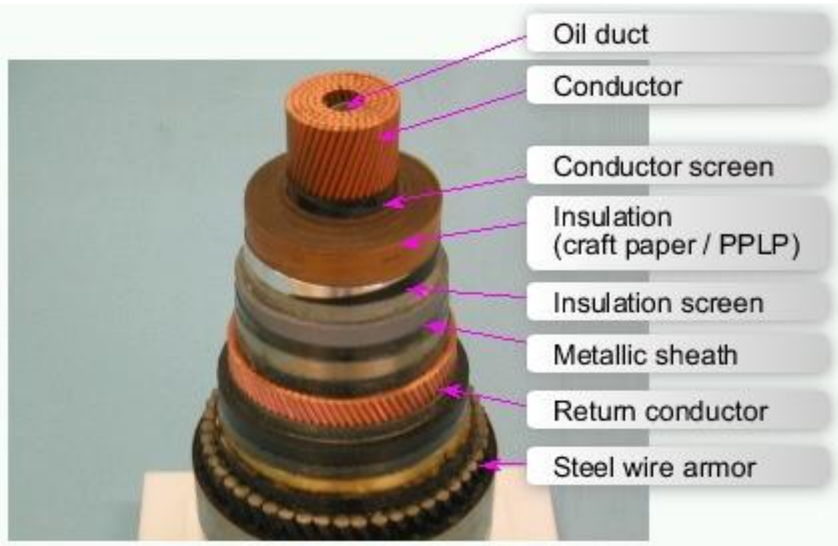


Figure 5: Submarine Oil-filled Cable (Courtesy of EXSYM)

- **Extruded Dielectric Cable Systems**
  During the last three decades, important evolutions in process technology and in materials have made possible the adoption of extruded insulation for transmission cables at 150 kV voltages and, in the last 10 years, up to 420 kV and 550 kV voltages.

Extruded insulated cables are mainly composed of the copper or aluminum conductor, the extruded polymeric conductor screen, the insulation (a layer of extruded cross linked polyethylene (XLPE), see Figure 6), the extruded insulation screen, the metallic screen and the outer sheath.

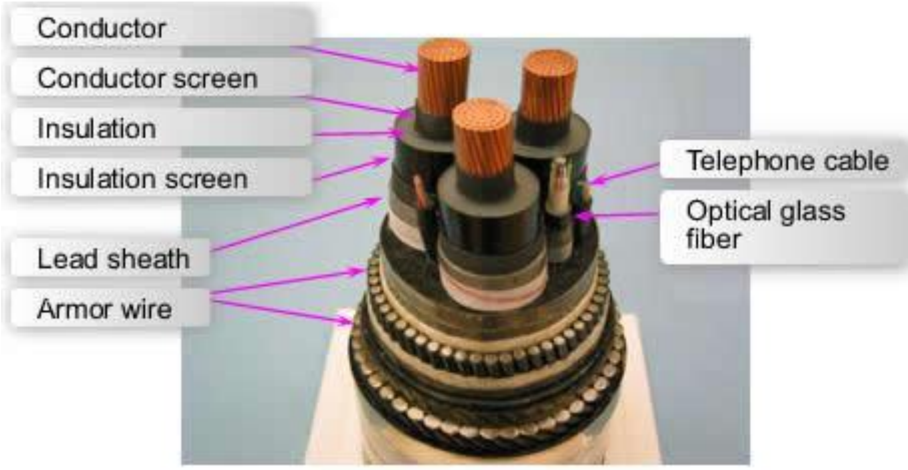


Figure 6: Submarine XLPE Cable (Courtesy of EXSYM)

The absence of a hydraulic circuit, lower dielectric losses, together with a more simplified construction process of the system due to the availability of prefabricated accessories, make extruded insulation cables systems more attractive than SCFF ones also from the point of view of the total cost of ownership.

f. Cable Screen

For submarine cables at voltage levels at 132kV or above lead alloy is used as cable screen and radial water tightness. With respect of the environment, the 33kV cables are developed without lead alloy by using a screen of copper wires, copper tape or a combination of copper wires with aluminum foil which is glued or otherwise mounted over the cable conductor, insulation and screen to make it totally watertight. 66kV submarine cables could be manufactured with lead alloy, but it would be interesting to encourage the cable manufacturer to develop these cables without lead alloy.

- **Short-circuit current:**
  The cross section of the cable screen must be designed to carry the full short-circuit current, which may occur in worst case fault scenario in the screen. The maximum short-circuit current and time of the fault must be calculated in the grid analysis and be given to the cable manufacturer before final design of the cable.

The short-circuit current will normally not influence the cross section of the cable conductor, since the cable conductor will normally carry a high load during normal operation and have a significant size.

g. Wet / Dry Design

Export cables at high voltage levels at or above 132kV are always of the dry type. Discussing advantages and disadvantages of wet and dry design for submarine array cables, the concern is to have water ingress into the insulation and hereby reduce the insulation effectiveness.

In principle, this is a question for the individual cable manufacturer to document that the used insulation material has the electrical withstand throughout the cable lifetime even if wet design is offered. References to similar cables in operation or tests must be provided.

In general, the HV cables are longitudinally watertight which avoids water to ingress more than one metre into the cable during possible cable damage.

The other issue is radial water tightness where the possibility for the polyethylene to absorb water during the lifetime even though this will take years. By adding an extruded lead alloy screen around each cable core, the radial water tightness is achieved.

h. Subsea Cable Protection

To ensure reliable and continuous operation of the offshore electricity network, submarine cable protection is necessary. Cable reliability data from 1985 shows a figure of 0.32 failures per year per 100 km [4] and 53% of the submarine cable failures occurred due to ship anchors or fishing gear [4]. Depending on the type of seabed, transmission submarine cables (between the offshore and onshore substations) are mostly buried to protect them from the above mentioned issues [4]. The cables are normally buried between 1-3 m below the seabed using ploughs (in sands and soft and stiff clay) or using water jetting [2], [11]. In areas where cables cannot be buried, either due to a rocky sea bed or due to unavoidable subsea obstacles such as gas and oil pipelines, the cables are protected using concrete mattresses or rock dumping [6] (see Figure 7).

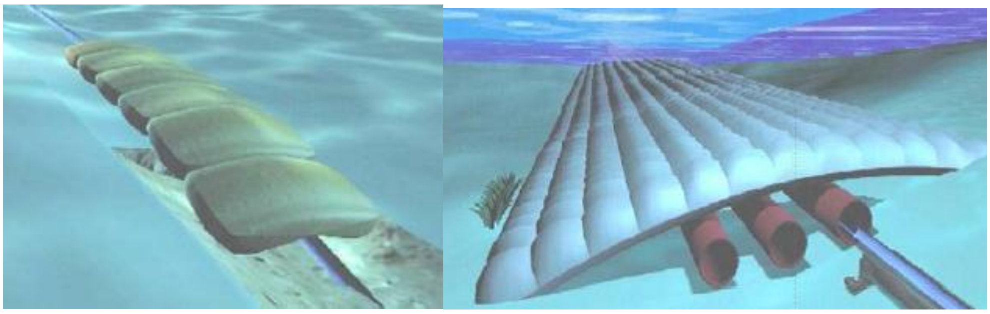


Figure 7: Concrete bags protection (left) and Mattress protection (right). (Pictures courtesy of Malcolm Sharples)

Since the distance between the marine energy converters will not be very large, it is likely that the area with a marine energy farm would be off limits for shipping and fishing activities. Under such a scenario, burying (and in turn protecting) the submarine cables that constitute the inter-array network may not be required for arrays of WECs. In Figure 8 there is an example of the marine chart symbols commonly used in order to signal the presence of submarine cables, cable areas, or where anchoring or fishing is prohibited.

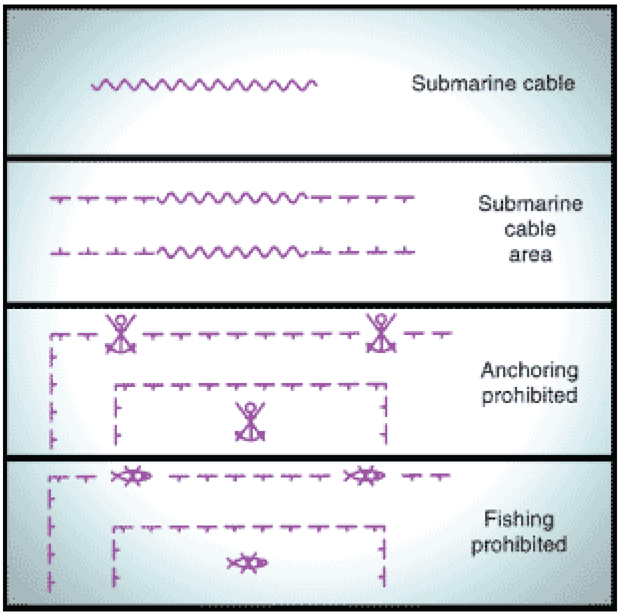


Figure 8: Marine Charts: Symbols Relating To Submarine Cables (pictures courtesy of New Zealand Boating Website [12])

When the spacing between the marine energy converters in an array is regular, spare sections of cables of the appropriate length may be stored at a shore depot or on the offshore substation platform [4].

To protect the submarine cable against mechanical damage during installation and handling, the submarine cable is protected by armouring wires. Steel is generally used, but also HDPE could be applied. The armouring must be designed strong enough to secure the cable against damage, but not bigger than needed since the electrical losses in the armouring increases with a larger cross section of the armouring (see for example armouring in Figure 9). Another issue is the weight of the cable which increases with bigger armouring.

Figure 9: Well-protected submarine cable (Picture courtesy of Nexans Cables [13])

In deeper detail, Zaccone [14] recommends one layer of armour for shallow water applications, while two layers of armour are suggested for deep water applications. The cable must be able to handle the mechanical stresses due to storage, handling, installation and recovery [14]. Figure 10 shows the safety factor that needs to be taken into account when installing submarine cables to overcome the additional tensions caused by the laying, recovery and dynamic forces on the cable.

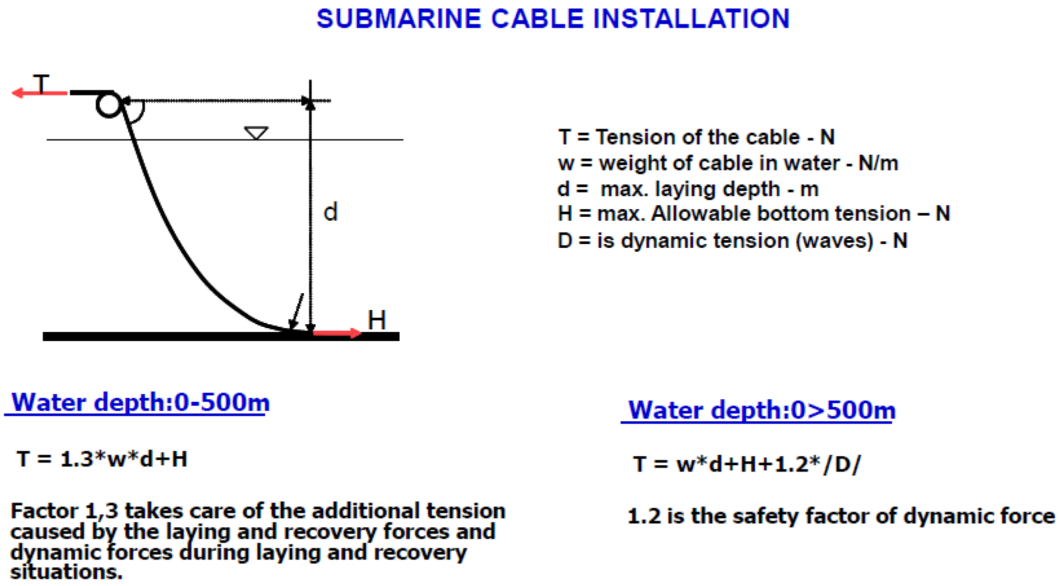


Figure 10. Submarine cable installation [15].

To protect the armouring against corrosion, the cable surface is applied with bitumen and a layer of yarn or an extruded polyethylene sheath.

2.2.2 Umbilical Cables

Umbilicals, in the marine industry, are cables that connect a subsea source/sink of a consumable to an apparatus on or above the sea surface. In the field of marine renewables, umbilicals essentially are cables that transmit the power extracted/generated by wave or tidal energy converters and possibly communication signals to the subsea electricity/communication network that then carries these consumables to the onshore network. Depending on whether the marine energy converter is a floating device or one that is fixed to the sea bed, the umbilical may be static or dynamic. This section explores these two types of umbilicals and draws from the experience and knowledge on this subject from the offshore industries (oil and gas and offshore wind), where umbilicals have been used for a considerable period of time (see, e.g., an example of scheme of connections in Figure 11).

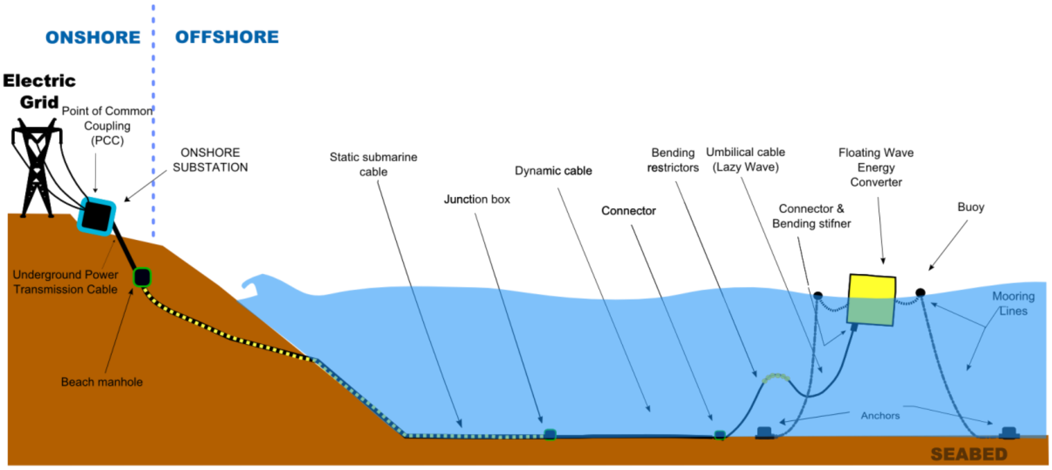


Figure 11:Scheme of connection [1]

a. *Oil and gas industry umbilicals*

The oil and gas industry (O&G) has used static/dynamic umbilicals in fixed/floating oil platforms in deepwater (water depths between 500 and 1499 metres) and ultra deepwater (water depths more than 1500 metres) [16]. The technical know-how for marine energy devices fixed to the seabed, which would be in depths far below those seen in the oil industry, would come from the O&G sector.

Umbilicals have been used in the O&G industry for multiple functionalities - to transfer high and low pressure fluid supply, to transmit low/medium voltage electricity power and electrical/optical communications, to transport chemical injection fluids, for gas lifts etc. [17]. To meet these requirements, they normally have steel tubes or thermoplastic hose fluid conduits, optical fibres and low/medium voltage electric conductors [17]. The low (typically below 3 kV) and medium voltage electrical conductors (with polyethylene insulation) in the umbilical have traditionally been used to power pumps and other electrical equipment on the sea bed. The umbilical is designed with high axial tensile and compressive strengths to maximise conductor fatigue resistance during umbilical installation and dynamic service [17]. Medium voltage power cables up to 36 kV and conductor size up to around 400 mm^2 have traditionally been used [17].

A Norsok standard [18] lists the different components in a subsea production control umbilical in the O&G sector and also specifies their technical requirements. The major components dealt with, relevant to the marine energy industry, are: terminators, jointing and electric power cable. Some of the relevant technical requirements are as follows:

- *Terminators, both at the platform end (here marine energy converter) and the subsea end, need an approved method to prevent water ingress in the cable.*

- *Electrical terminations shall have two independent barriers against water ingress, which shall be separately tested during qualification and final product assembly.*
- *The axial load requirements shall not allow structural damage to the termination or template landing structure.*
- *The J-tube seal shall withstand 100 year maximum wave and internal pressure from the filled up J- tube.*
- *Sufficient cushioning shall be provided to prevent damaging of the copper conductors, insulation and sheeting during umbilical manufacturing processes, installation and its operational life.*
- *All electrical conductors shall be insulated with an appropriate thermoplastic material suitable for subsea operation.*

Please note that considering the short lengths of umbilicals necessary for marine energy application, it is not envisaged that umbilical jointing would be required.

The standard also discusses different mechanical loading tests - torque balance, tensile test, bending and tensile test, bend cycling test - and the required umbilical performance from these tests. These would be relevant for umbilicals in the marine energy industry too.

b. Devices piled onto the ground

In the marine energy industry, umbilicals will only have electrical conductors and fibre optic communication cables. For devices fixed to the sea bed (e.g. tidal current turbines and offshore substations on monopiles or similar structures) the umbilical would be taken to the subsea unit using the structure itself. The umbilical is, thus, not dynamic and may only have to deal with the wave and current loads on it. The umbilical requirements for offshore substation platforms would be very similar to the requirements for marine energy converters fixed to the sea bed.

The point where the umbilical cable enters the structure (which depends on the type of structure and the loads on the cable) needs careful design, because this can determine the cable rating [4]. J-tubes are often used here and the cables that run through J-tubes will need to be de-rated [2]. The Norsok standard [18] mentions the design requirement of J-tubes (in the O&G industry). They have been listed in the preceding section.

The offshore wind and the oil and gas industries have used static umbilical systems for decades now and would be the best source of any design information.

c. Floating Devices

With respect to floating wave energy converters (WECs, TECs) or floating tidal devices (TECs) designing the umbilical system would be more challenging since the umbilical here has to endure bigger forces and stresses due to loads from waves, currents and marine energy converter induced motions. The forces due to induced motions of energy converter would be very different from the forces on umbilicals used in offshore floating O&G platforms. O&G platforms are designed to remain as stationary as possible. The main features of umbilicals for floating devices can be resumed as follows:

- The cable must withstand, without deterioration, the severe bending under tension, twisting and coiling which may occur during operation, manufacture and installation.
- The cable must also withstand, without significant deformation, the external water pressure at the deepest part of the route.
- The cable should be designed in such a way that its dynamic behaviour has a minimal effect on the global performance of the device.
- The weight of the cable in water must be sufficient to inhibit movement on the sea bed under the influence of tidal currents. Movement would cause abrasion and fatigue damage to the cable.
- Cable components and terminations (including connectors) should be designed taking into account possible economic constraints (oil and gas solutions might not be cost-effective for application to marine renewable energy)

To meet the mechanical flexibility required for such an operation, the voltage of these umbilicals may need to be restricted to 6 kV or below [6]. Oversized rated conductors will also not be used [6]. Table 2 shows the voltage level options being considered for marine energy converter farms.

Table 2: Voltage level options in farms of marine energy converters [6].

Stage	Voltage Level [kV]	
Local Collection System (Cluster)	3, 6 (Umbilical Cable) 10, 20, 30 (Static Cable)	
Transmission Options	AC	33, 132, 150, 220
	DC	±80, ±150
Point of Common Coupling	Depends on the feed-in point (150, 220, 400)	

For mechanical flexibility, thus, a limit on the voltage (and hence insulation thickness) of umbilicals is required. It is only recently that umbilicals, used in the O&G industry for high voltage power supply and control hydraulic tubes, have seen a combination of higher voltages (24 kV) and longer lengths (26 km) [19].

ABB has recently installed the longest (1.5 km long) dynamic three-core power cable connecting the Goliat platform to the static AC cable 350 metres below the surface [20]. An innovative corrugated copper sheath has been used for mechanical strength [20]. The umbilical, before installation, was tested in one of MARINTEK's advanced rigs for six months and no damage to critical components was found [21].

The hydrodynamics of different flexible umbilical configurations for floating structures were studied in [22]. Figure 12 shows the three options considered. The study focused on the mechanical loading regimes and fatigue life of umbilical cables for floating WECs. It concluded that most mechanical failures occur at the attachment/hang off point of the umbilical. Considering the type of umbilical operation required for floating wave energy converters, such as buoyancy devices on umbilicals, to reduce stresses, will need to be studied further.

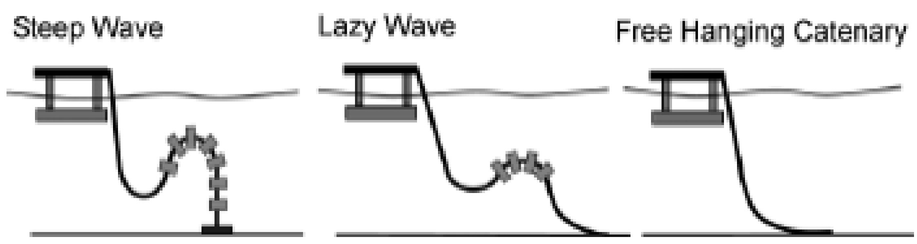


Figure 12: Umbilical arrangements for floating structures [22].

d. Composition of Power Umbilical Cables

Power umbilical cables are generally made up of several layers, whose composition and relative importance is changing dependent on the application.

Since the primary function is the transmission of electrical power (and possibly communication or measurement signals) the cross-section (see Figure 13) is generally composed by one or more central cores containing the conductor.

Each core would require appropriate insulation and possibly a screening layer to keep the electrical field stress homogeneous. The whole ensemble is typically enveloped within a sheath.

Armouring is usually required for protection and structural support. Steel armours are practically always necessary for subsea dynamic cable configurations due to the high occurring loads. An outer oversheath, generally polymeric, is also necessary for protection from corrosion of the armour.

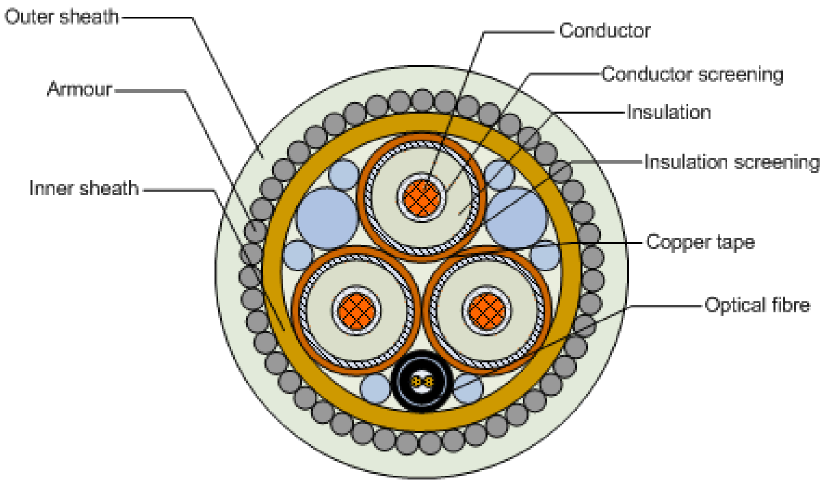


Figure 13: Typical umbilical power cable cross section

2.3 Connectors

Information about connector is available throughout all of the Marina FP7 Project [23].

For floating marine energy converters, electrical connectors should be used to allow their easy connection/disconnection, with the aim to reduce maintenance costs. Essentially they enable the electrical connection between two cables or between one cable and one device.

Electrical connectors also give some flexibility in terms of power ratings, voltage levels and the aggregation of a number of converters in an array/farm [15]. These connectors may be classified, based on whether they are mated (connected) in a dry or a wet environment, as dry and wet mate connectors.

When choosing a connector for marine energies some characteristics must be taken into account:

- Easy connection and disconnection procedure.
- Minimum offshore working time.
- Low demanding meteorological requirements for the connecting operation.
- Low maintenance.

Nowadays there is a wide range of commercial connectors due to Oil & Gas, Military and Oceanographic industries. Most of those companies have developed their own products for marine renewable energy, however, their technological background entails some disadvantages and challenges for marine renewable energy.

Examples of connectors can be seen in Figure 14, Figure 15 and Figure 16.

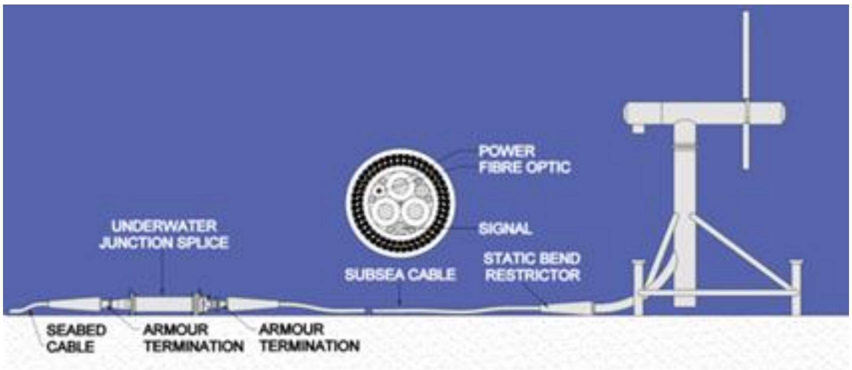
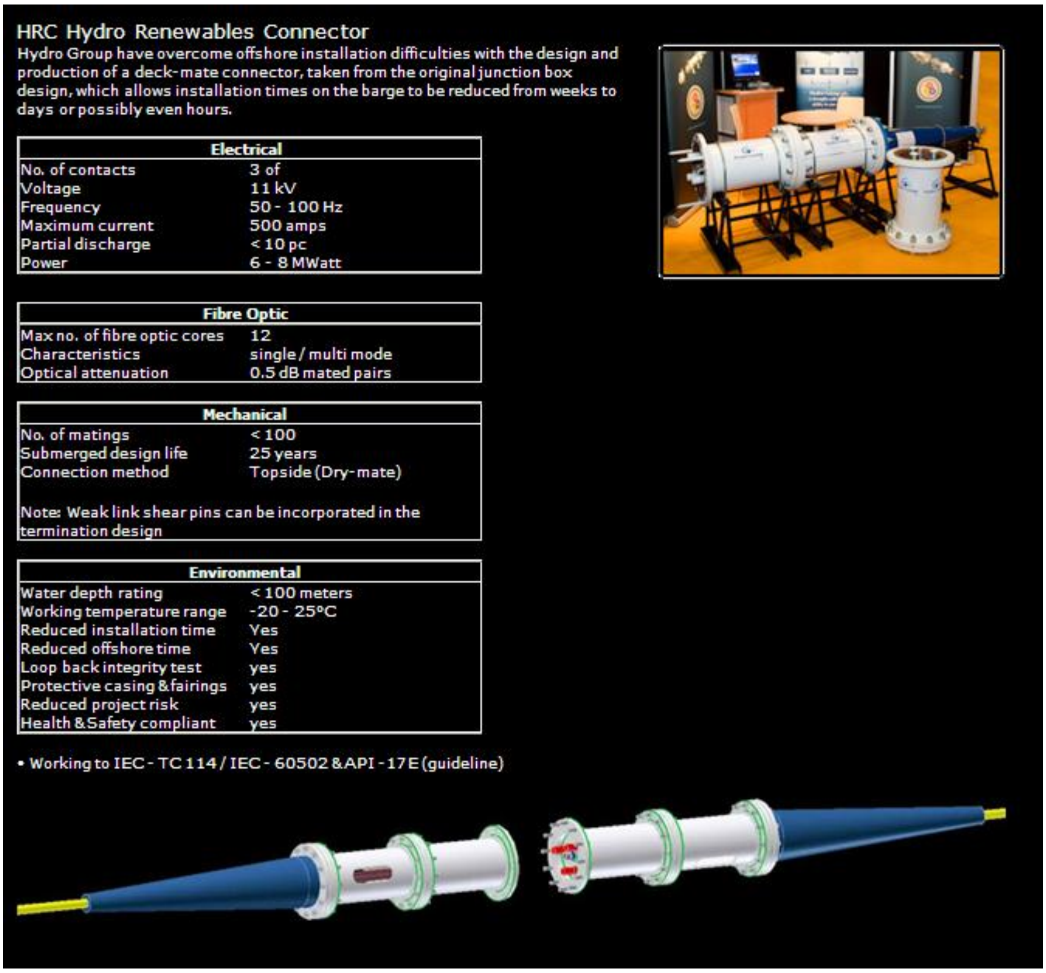


Figure 14: Hydro Group Connector (courtesy of Hydro group plc. [24])

There are two types of connectors:

- Wet-mate Connector: they work under water but connection / disconnection can be performed either in dry atmosphere or under water. Wet mate connectors with a voltage and current rating of 30 kV and 1300 A respectively (approximately 67 MVA) have been used in the oil and gas industry and are commercially available [19]. Wet-mate connectors are more expensive than dry-mate and they are also less developed for the same voltage and power. The advantage is that they can be connected under water, however expensive and specific ROVs (Remotely Operated Vehicle) or specialist divers are needed and only up to limited depth.
- Dry-mate Connector: they work under water but connection / disconnection is performed in dry atmosphere. Dry mate connectors of more of less the same rating have been used and are commercially available. The Ormen Lange subsea compression system will move the limit to 132 kV/145 kV [19]. The main disadvantage of dry-mate connectors is that they must be connected in dry conditions; this entails procedures and resources for refloating operations.



HRC Hydro Renewables Connector

Hydro Group have overcome offshore installation difficulties with the design and production of a deck-mate connector, taken from the original junction box design, which allows installation times on the barge to be reduced from weeks to days or possibly even hours.

Electrical	
No. of contacts	3 of
Voltage	11 kV
Frequency	50 - 100 Hz
Maximum current	500 amps
Partial discharge	< 10 pc
Power	6 - 8 MWatt

Fibre Optic	
Max no. of fibre optic cores	12
Characteristics	single / multi mode
Optical attenuation	0.5 dB mated pairs

Mechanical	
No. of matings	< 100
Submerged design life	25 years
Connection method	Topside (Dry-mate)

Note: Weak link shear pins can be incorporated in the termination design

Environmental	
Water depth rating	< 100 meters
Working temperature range	-20 - 25°C
Reduced installation time	Yes
Reduced offshore time	Yes
Loop back integrity test	yes
Protective casing & fairings	yes
Reduced project risk	yes
Health & Safety compliant	yes

- Working to IEC - TC 114 / IEC - 60502 & API - 17E (guideline)

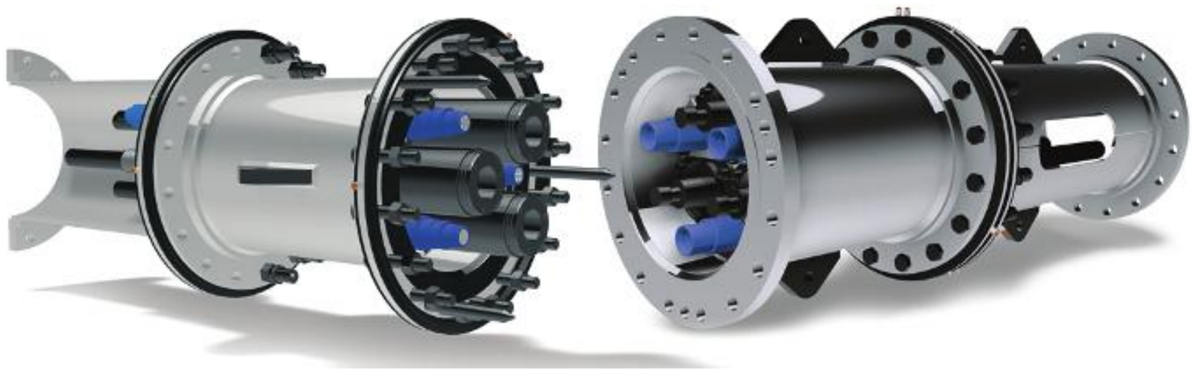


Figure 15: : Hydro Group 11 kV Dry-Mate Connector [24]

Figure 16: MacArtney 11 kV Wet-Mate Connector (courtesy of MacArtney Technology [25])

A terminator is another option to connect two cables. This solution is based on a fixed connection between two cables but it requires longer period of time for the installation since the joint must be sealed and encapsulated. The connection / disconnection must be performed in dry atmosphere.

Table 3 includes a non-exhaustive list of the manufacturers of wet and/or dry connectors.

Table 3: Non-exhaustive list of the manufacturers of wet and/or dry connectors

Company	Website	Scope	Connection Type	Maximum capacity	Comment
MacArtney Under Water Technologies	www.macartney.com	Oil & Gas, Oceanographic Industry, Renewable Energy.	Wet-mate	11 kV / 400 A	- Developers and manufactures of USP´s connector for OPT.
Hydro Group (Hydro house)	www.hydrogroup.plc.uk	Oil & Gas, Oceanographic Industry, Renewable Energy, Military, Aquaculture Industry.	Dry-mate / Wet-mate	11 kV/500 A dry-mate 33 kV/ - A wet-mate 36 kV/- A dry-mate	- They worked with Pelamis Wave Power to develop a new umbilical connection, umbilical cable and subsea junction box.
Siemens Subsea	http://www.energy.siemens.com/hq/en/industries-utilities/oil-gas/applications/subsea.htm	Oil & Gas, Oceanographic Industry, Renewable Energy, Aquaculture Industry.	Dry-mate Wet-mate	15 kV/200 A 30 kV/1350 A	

Gisma	www.gisma-connectors.de	Oil & Gas, Renewable Energy.	Dry-mate	6,6 kV / 1000 A	- They are working on a 10/12 kV connector.
Teledyne D.G.O´Brien	www.dgo.com	Oil & Gas, Renewable Energy.	Dry-mate	1 kVAC/1,8 kVDC / 4 to 8A	- Wet-mate option available.
ODI	www.odi.com	Oil & Gas, Oceanographic Industry, Military.	Wet-mate	10 kV/220 A	
Vetco (General Electric Group)	http://www.ge-energy.com/products_and_services/products/subsea_power_and_processing_systems/	Oil & Gas, Renewable Energy, Military, Aquaculture Industry, Aerospace Industry, Biomedical Industry.	Dry-mate Wet-mate	145 kV/700 A 36 kV/500 A	
J&S Marine	www.jsmarine.co.uk	Oil & Gas, Renewable Energy, Naval Industry.	Dry-mate	Up to 36 kV	- J&S has installed nine electrical splice housings at the EMEC test facility in the Orkney Islands and four at BIMEP facility in Northern Spain.

At times, when a submarine cable is cut or damaged due to external causes (third-party damage), cable joints are used to repair it. A cable joint is a permanent connection and does not allow connection/disconnection manoeuvres (as submarine connectors) but they are cheaper (see Figure 17).

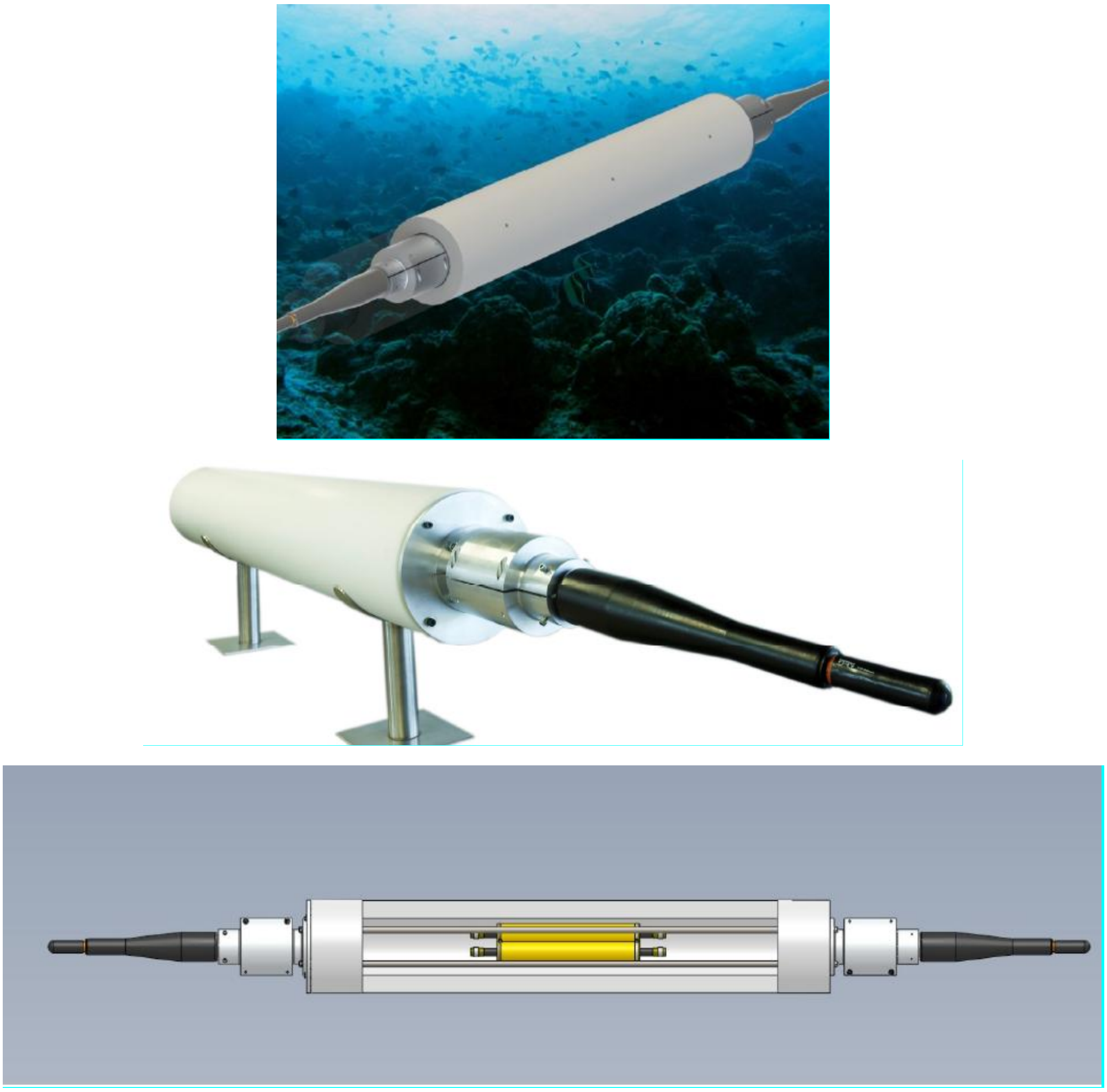


Figure 17: J+S Repair Joint for 36 kV submarine cable (see [26]) .

2.4 Ancillary components (bend stiffeners, bend restrictors, marking buoys)

2.4.1 Bend stiffeners (Taken from [1])

Power umbilical cables are generally connected to a rigid structure (wave energy device, offshore substation, junction box). External loads generated by the sea and the motions of the device determine large stresses on the umbilicals [27]. *The movement of the umbilical in combination with large axial loads may cause damage to its structure possibly because of over bending and/or fatigue* [28]. *Bending stiffeners are used to avoid this problem adding a local stiffness to the cable in order to limit bending stresses and curvature to acceptable levels. In Figure 18 an example of positioning of bending stiffeners and restrictors is shown.*

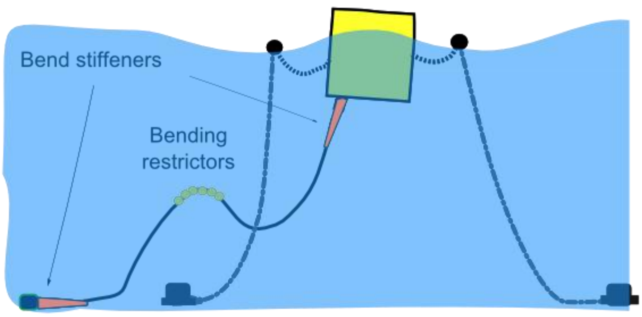


Figure 18:Bend stiffeners and bend restrictor example **[1]**

The bending stiffener (see [29] *and Figure 19) has a conical external profile and a central hollow cylindrical section allowing it to slide over the end of the umbilical. Each bending 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.*

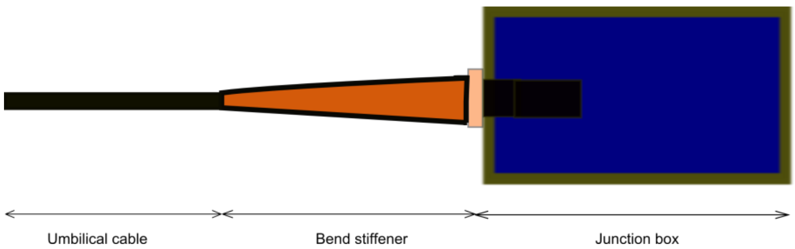


Figure 19: Bending Stiffener example **[1]**

There are two types of bending stiffeners:

- *Dynamic Bending Stiffeners: are designed to protect flexible umbilicals in applications where a long service life is required.*
- *Static Bending Stiffeners: are used primarily for over bend protection during installation.*

An alternative to the elastomeric bend stiffener is the Gimbal system [30] *which can accommodate large angular deflexion and high axial load, by separating the axial load capacity of the assembly from the components.*

The bending stiffener body is usually manufactured from moulded polyurethane elastomers. The typical choice of polyurethane elastomer is based on its low modulus and high elongation at break.

The main information required for the design of a bending stiffener includes:

- *Umbilical diameter*
- *Load cases (tensions vs angle)*
- *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)*

2.4.2 Bend restrictors (Taken from [1])

Within ocean wave energy industry, power umbilical cables provide electrical and optical connections different rigid structures such as the WEC and subsea devices (transformers substations, electrical hubs…). Bending restrictors (see Figure 20) might be required in order to prevent them from over bending at the interface between flexible and rigid structures.

A bending restrictor [28] *is specifically used where static (or quasi static) loads act on a cable, rather than dynamic loads when a bending stiffener would be more suited. Usually is used to give extra buoyancy to the umbilical.*

The restrictor usually comprises a number of interlocking elements which articulate when subjected to an external load and lock together to form a smooth curved radius known as the locking radius. The locking radius is chosen to be equal to or greater than the minimum bend radius of the pipe.

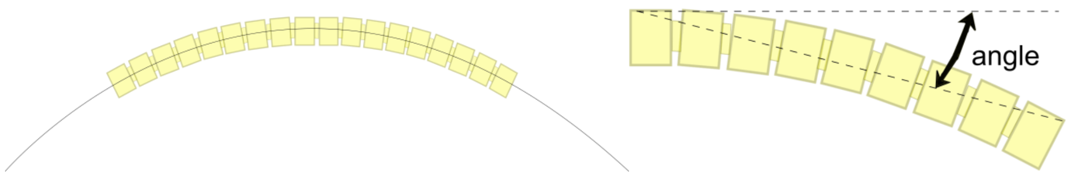


Figure 20: Bending Restrictors **[1]**

Once the elements have locked together the bending moment present is transferred into the elements and back through a specially designed steel interface structure into the adjacent rigid connection, therefore protecting the cables from these potentially damaging loads.

Bending restrictors need to follow some design criteria such as:

- *Split design, allowing installation of the restrictor after umbilical termination.*
- *Easy installation onshore and offshore.*
- *Neutral buoyant in water, eliminating self-weight loading on the cable.*

The main variables and cable parameters to take into account in order to select optimal bending restrictors for specific utilization are:

- *Minimum bend radius.*
- *Outside diameter.*
- *Loads (bending moments, shear loads).*
- *Length of coverage.*
- *Operating temperature.*

The materials used in the manufacture of the rending restrictor components are:

- *Elements - structural polyurethane.*
- *Element fasteners - super duplex stainless steel.*
- *Interface steelwork - high strength structured steel.*

The structural polyurethane and super duplex stainless steel fasteners are corrosion resistant in seawater. The interface steelwork is the part of the structure that requires corrosion protection. This can be provided by a subsea coating system and either connection to an adjacent cathodic protection system or by attachment of its own dedicated anodes. For polyurethane elements usually yellow or alternatively orange is used because both colours provide excellent subsea visibility.

2.4.3 Marking Buoys

Reference [31] highlights the issues to be taken into account when planning and undertaking voyages in the vicinity of offshore renewable energy installations (OREIs) off the UK coast.

Visibility will depend on the device type. Some installations are totally submerged while others may only protrude slightly above the sea surface. Marking will be based on IALA Recommendation 0-139 [32] on the marking of Man-Made Offshore Structures, including offshore wave and tidal energy devices, which states that:

"Wave and Tidal energy extraction devices should be marked as a single unit or as a block or field as follows:

- *When structures are fixed to the seabed and extend above the surface, they should be marked in accordance with the IALA recommendations contained in the marking of offshore wind farms – O-139.*
- *Areas containing surface or sub-surface energy extraction devices (wave and/or tidal) should be marked by appropriate navigation buoys in accordance with the IALA Buoyage System, fitted with the corresponding topmarks and lights. In addition, active or passive radar reflectors, retro reflecting material, racons and/or AIS transponders should be fitted as the level of traffic and degree of risk requires.*
- *The boundaries of the wave and tidal energy extraction field should be marked by lit Navigational Lighted Buoys, so as to be visible to the mariner from all relevant directions in the horizontal plane, by day and by night. Taking the results of a risk assessment into account, lights should have a nominal range of at least 5 (five) nautical miles. The northerly, easterly, southerly and westerly boundaries should normally be marked with the appropriate IALA Cardinal mark. However, depending on the shape and size of the field, there may be a need to deploy intermediate lateral or special marks.*
- *In the case of a large or extended energy extraction field, the distance between navigation buoys that mark the boundary should not normally exceed 3 (three) nautical miles.*
- *Taking into account environmental considerations, individual wave and tidal energy devices within a field which extend above the surface should be painted yellow above the waterline. Depending on the boundary marking, individual devices within the field need not be marked. However, if marked, they should have flashing yellow lights so as to be visible to the mariner from all relevant directions in the horizontal plane. The flash character of such lights should be sufficiently different from those displayed on the boundary lights with a range of not less than 2 nautical miles.*
- *Consideration should be given to the provision of AIS as an Aid to Navigation (IALA Recommendation A-126) on selected peripheral wave and/or tidal energy devices.*
- *A single wave and/or tidal energy extraction structure, standing alone, that extends above the surface should be painted black, with red horizontal bands, and should be marked as an Isolated Danger as described in the IALA Maritime Buoyage System.*
- *If a single wave and/or tidal energy device which is not visible above the surface but is considered to be a hazard to surface navigation, it should be marked by an IALA special mark yellow buoy with flashing yellow light with a range of not less than 5 nautical miles, in accordance with the IALA Buoyage System. It should also be noted that many tidal concepts have fast-moving sub-surface elements such as whirling blades.*

- *The Aids to Navigation described herein should comply with IALA Recommendations and have an appropriate availability, normally not less than 99.0% (IALA Category 2).*
- *The relevant Hydrographic Office should be informed of the establishment of an energy extraction device or field, to permit appropriate charting of same.*
- *Notices to Mariners should be issued to publicise the establishment of a wave and/or tidal energy device or field. The Notice to Mariners should include the marking, location and extent of such devices/fields.*

Example of marking buoys can be seen in Figure 21, referred to the BIMEP area, off the Basque Country coast in Spain.

Figure 21: BIMEP delimitation buoys (photography of Imanol Touzon, Tecnalia)

2.5 Hubs

Renewable energy power from offshore renewable devices once captured needs transferring to the power grid onshore. For many projects in the development stage, this has meant single inline terminations to export cables that transfer energy onshore. As projects progress, these single devices will be replaced by arrays of devices achieving an economy of scale in renewable energy capture. Underwater hubs, or UTUs (underwater termination units), placed on the seabed assimilate power input from several devices and transfer the renewable energy onshore.

2.5.1 Subsea hub (no offshore substation/transformer)

In the case of small marine energy farms close to the shore, the offshore collection point need not have a substation with a transformer it can be a subsea hub. The size of the farm would in this case be primarily determined by the largest feasible MV (or LV) submarine cable available [4]. The shore cable would be protected by switchgear at the shore end. The O&G industry have used process control hubs on the sea bed to control their electrical and hydraulic equipment. The design of such subsea hubs and their installation, therefore, can be reproduced in marine energy farms.

An example of an offshore subsea hub, without transformers, is available at the Wave Hub test site off the South West coast of England. Figure 22 shows a schematic of the test facility and also the subsea hub [33]. The hub (see the structure of the hub in Figure 23) was manufactured by JDR, a manufacturer of submarine cables, connectors and other subsea equipment [5].

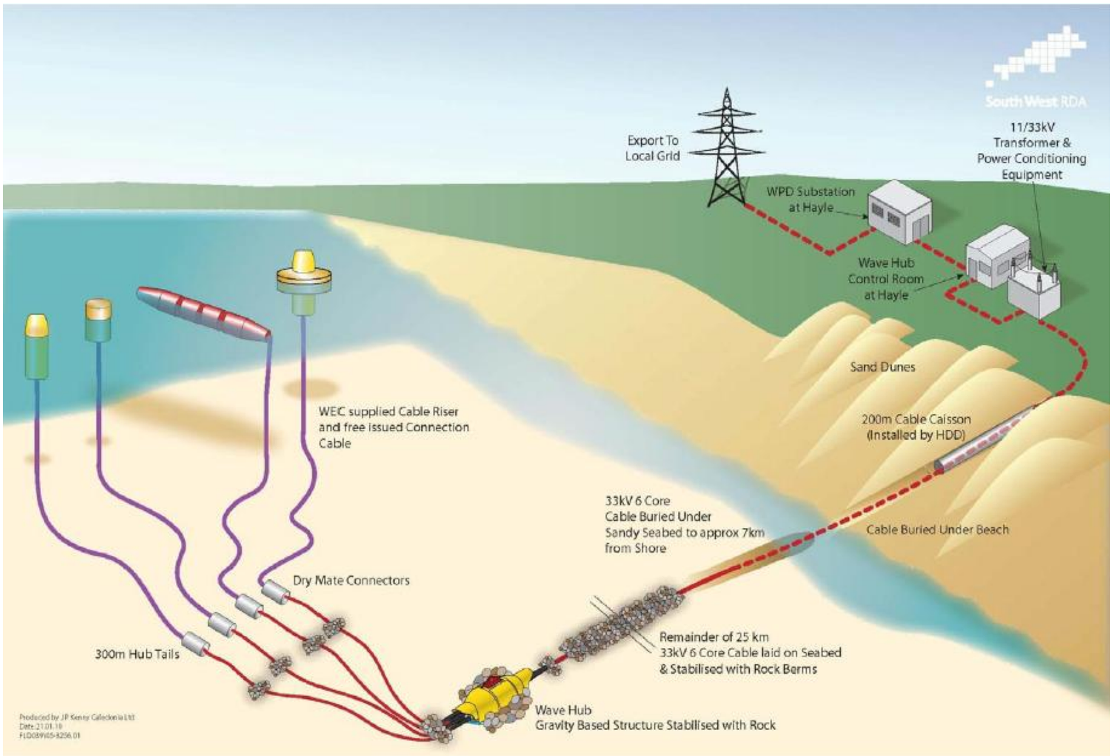


Figure 22: Schematic of the Wave Hub test site [33].

The Wave Hub chamber is the free-flooding, outer protection, carbon-steel structure, seen in the Figure 23. Within the chamber there are provisions for making watertight connections and also terminations for power and fibre optic cables [5]. Dry mate connectors connect the umbilical from the marine energy converters to the Wave Hub tails connected to the subsea hub. A 33 kV export cable from the subsea hub carries the power from the four marine energy converters to the shore.

Figure 23: Wave Hub structure [33]

MacArtney has also in the market a modular hub (see Figure 24) with the following specifications:

- Standard working voltage range: 6 - 36kV
- Up to 1250 amp.
- Conductor range: 35 – 630mm2
- Working depth: 100m
- Material: S355, painted and corrosion protected
- Other materials available on request
- Lifetime submerged: 5 years, depending on demands and maintenance scheduling
- Straight line pull SWL: 100kn per termination
- Pull out / lift SWL: 50t
- The hub can be supplied with switch gear or switch gear with protection
- The hub can be dry, oil, gel or nitrogen filled as required

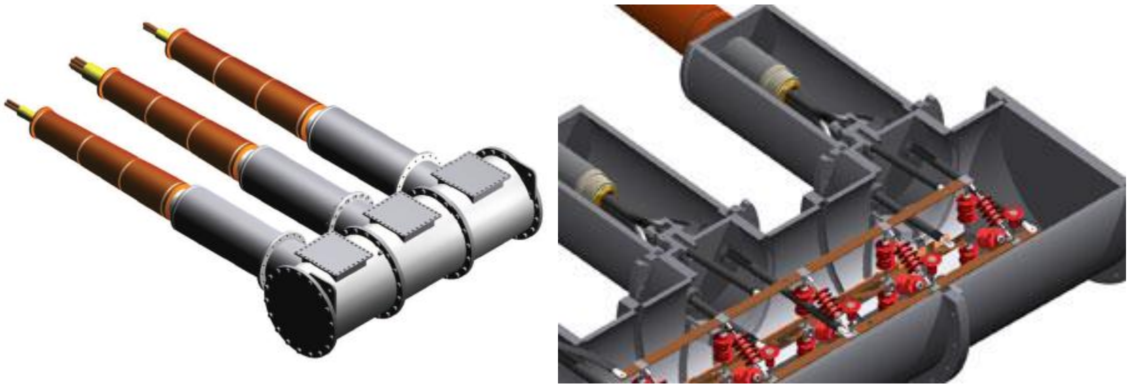


Figure 24: MacArtney Hub (courtesy of MacArtney [25])

2.5.2 Subsea Substations

The underwater substation concept (see Figure 25) is an interesting idea when the energy is generated far from the shore and a voltage transformation is needed to avoid excessive power losses. Such a concept was also analyzed within MARINA project [23].

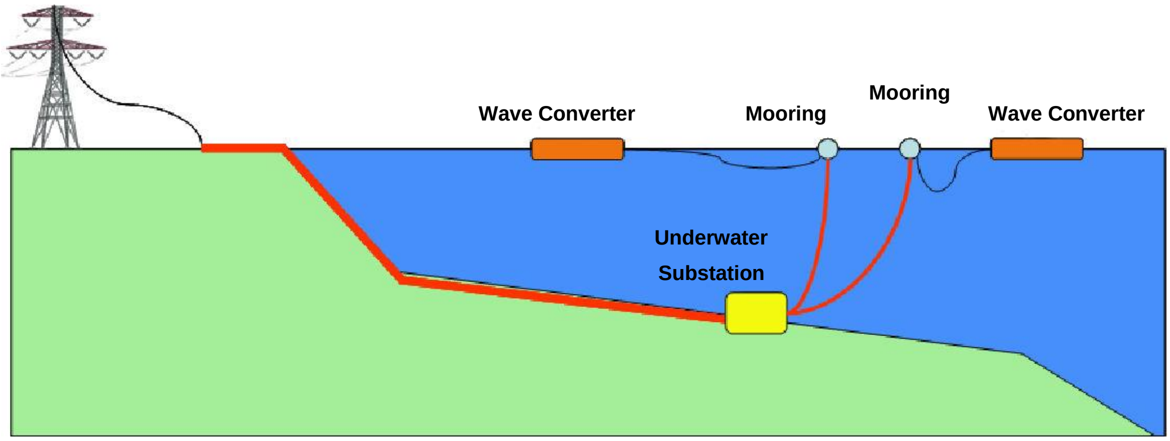


Figure 25: Wave Farm Layout with Underwater Substation

An underwater substation is placed over fixed seabed foundations in order to avoid sinking into the sediment. The substation consists of a pressurized tank containing the following elements: switchgear and protections, ancillary equipments and one or more power transformers. The tank must be capable of withstanding the hydrostatic pressure and the tightness must be guaranteed at all entry points of the cables.

Nowadays there is no underwater substation in any offshore wind farm in the world. The University of Uppsala group [34] (see Figure 26) have manufactured a low voltage power substation for wave energy converters and some companies such as OPT (Ocean Power Technologies) [35] are researching this concept (see Figure 27).

The Oil & Gas industry was first in developing underwater solutions to supply power to pumps and compressors up to 3,000 m depth. This entailed new researching lines in underwater power transformers, umbilical cables, connectors, switchgear, etc. Examples are shown in Figure 28, Figure 29 and Figure 30.

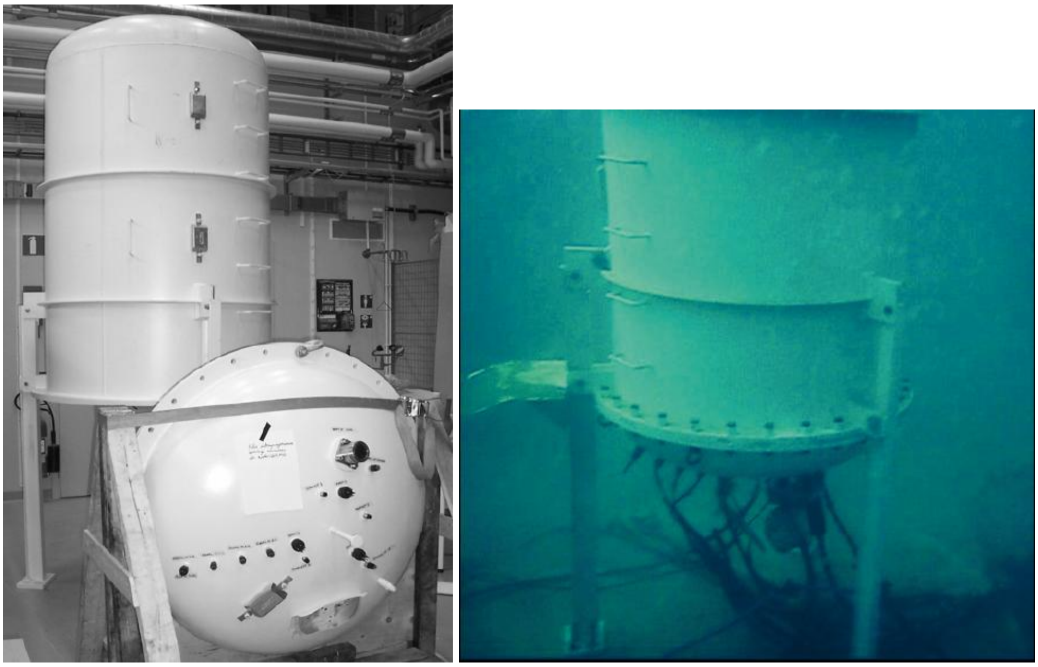


Figure 26: Uppsala Marine Substation for Lysekil Wave Power Project (96 kVA, 1 kV) [34]

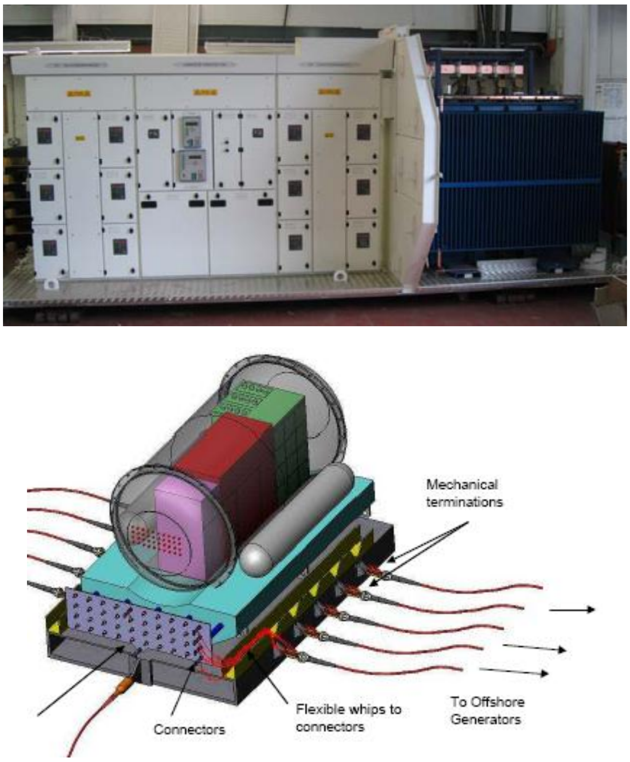


Figure 27: OPT Substation (1,5 MW, 11 kV) [35]

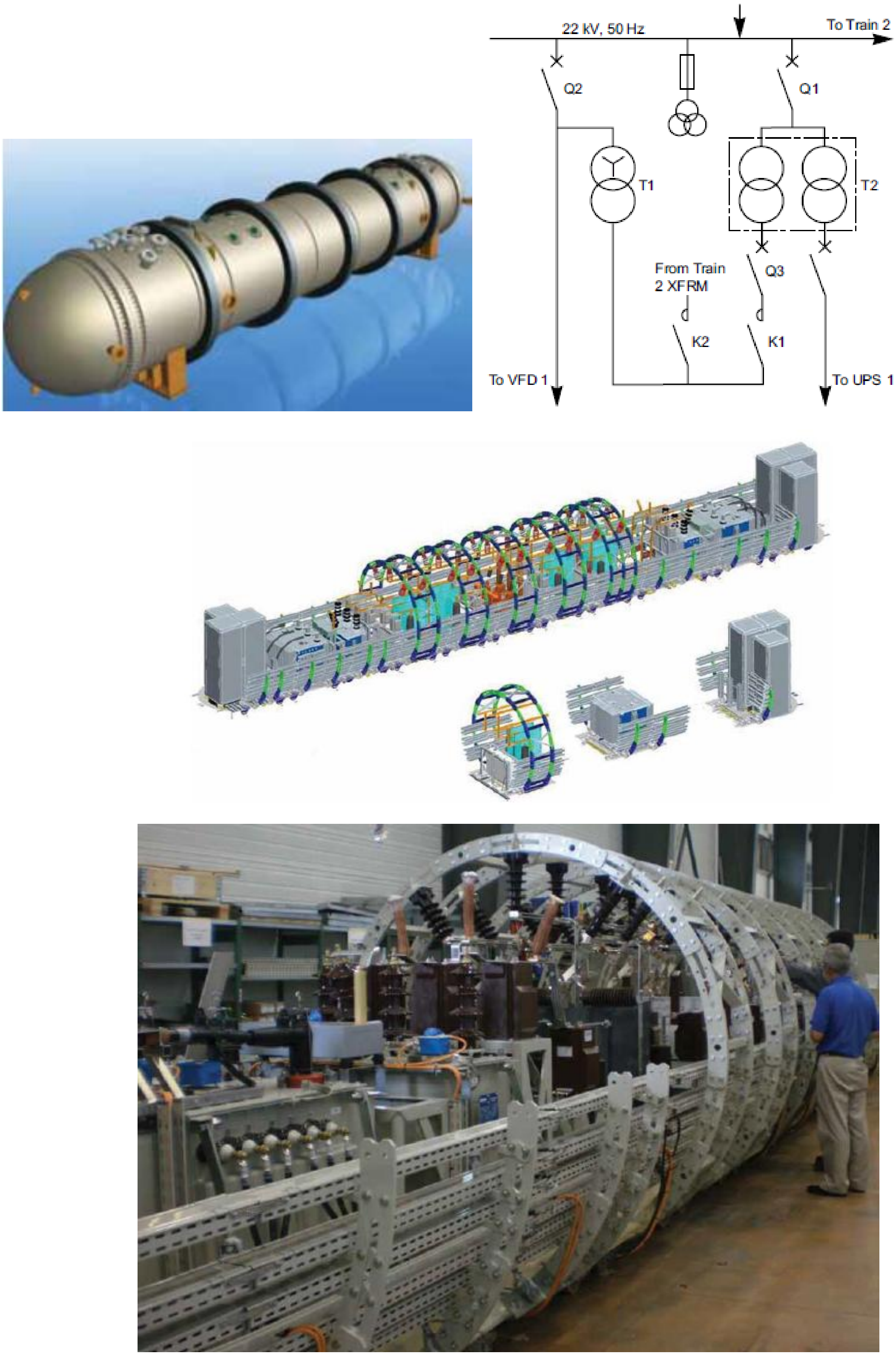


Figure 28: Schneider Subsea Power Distribution [36]

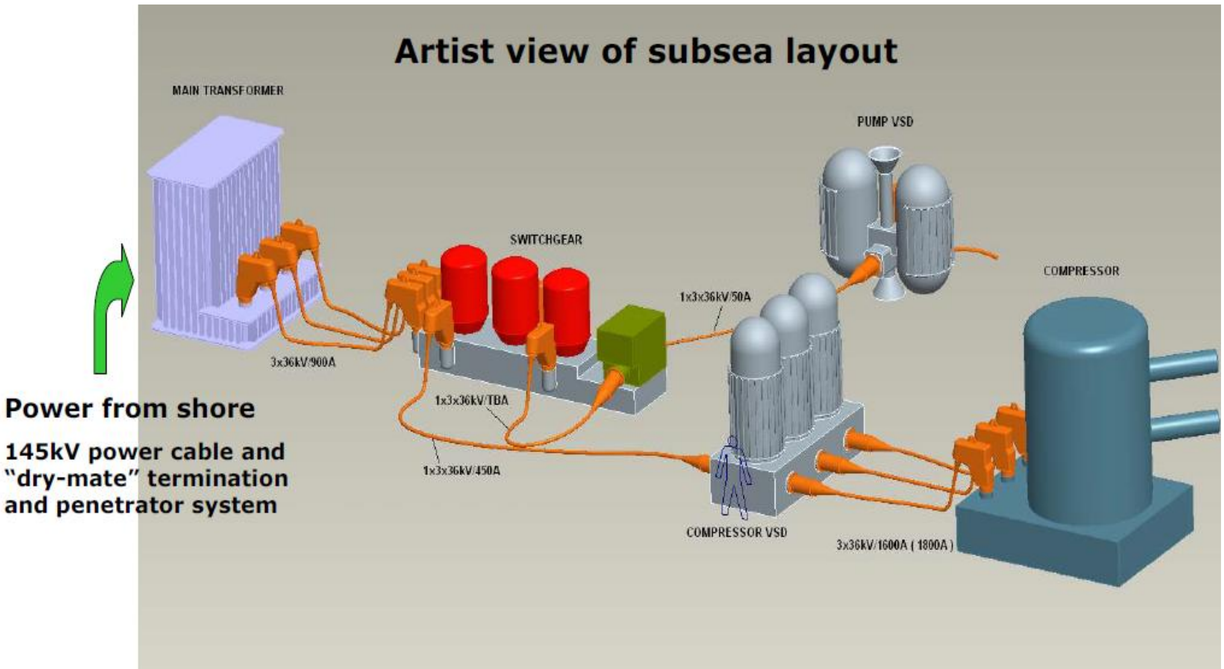


Figure 29: VetcoGray (General Electric) Subsea Power Systems [37]

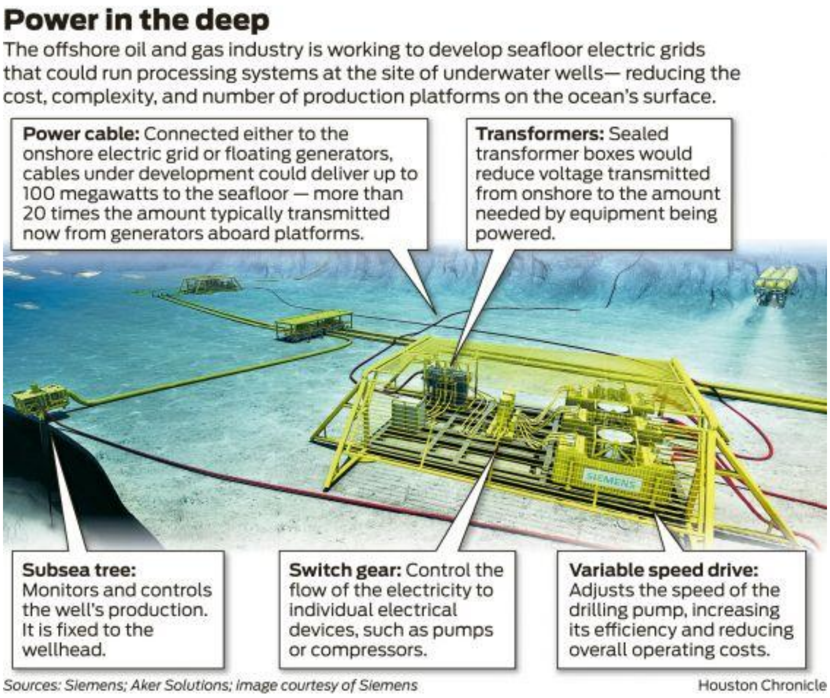


Figure 30 Siemens Subsea Power Grid [38] Offshore Substation (transformer and switchgear above water)

2.5.3 Offshore Substation (transformer and switchgear above water)

For large marine energy farms, further away from the shore, transmitting the power at medium voltage may not be possible because of excessive transmission power losses. In such cases, therefore, the collection point would be an offshore substation with transformers and associated switchgear. The optimal connection options for offshore wind farms of various sizes have been researched and a consensus seems to be present in the offshore wind industry regarding the same. Some of this technical know-how from the offshore wind industry can be directly applied within large marine power farms. Also, since many of the technologies and concepts that are used with the offshore wind industry will be used in marine energy farms the cost of such systems would be very similar [39].

The offshore substation requires a support structure and would hold transformers and protection equipment. These platforms can also serve as stores and workshops. Each substation will have several clusters of marine energy converts connected to it. Ultra-large farms may have multiple offshore substations, each of them having a separate connection to the shore. Often the transmission voltage is determined by the voltage at the onshore network connection point.

The amount of power that can be accumulated at one offshore substation (in case of wind farms, see Figure 31), and hence the number of offshore substations required for each farm will be dictated by [2]:

- the power carrying capacity of the onward transmission medium
- the power carrying capacity of the array cabling
- the number of wind turbines
- the distance from the platform to the furthest wind turbine in the array, (as using excessive lengths of 33 kV cable to connect an array can lead to onerous power losses).

Figure 31: Baltic 1 Offshore Wind Farm (Germany)

2.6 Transformers & Switchgear

2.6.1 Transformers

Recommendations on transformers used in offshore substations and in the device [4] (from the offshore wind industry):

- The IEE offshore regulations forbid oil-filled transformers, because of the risk of fire. Other liquid-filled transformers must have a bund to prevent discharges to sea.
- The GL rules prefer dry-type transformers, but do not forbid oil-filled units for offshore wind.

  Offshore wind farms built to the date of the reference have used both liquid and dry-type transformers [3]. In the future though, it is envisaged that cast-resin transformers, with a narrower structure easier for integration or removal, will find widespread use in the offshore wind. The experience with respect to offshore substation transformers from the offshore wind industry will play a vital role in the development of marine energy farms too.

Through a detailed cost-benefit analysis study of offshore wind farms of different sizes it was found that the maximum rating of a single transformer substation for offshore platform is 90 MW [3]. The minimum rating for a multi-transformer substation is 50% of the wind farm rating. References [3] and [2] recommend no full redundancy, with respect to offshore substation transformers, and ask for the installation of the minimum number of transformers required. They also add that the capacity of the transformer can be less than the farm capacity by a factor X% being X a factor obtained by dividing the capacity of the transformer and the wind farm capacity [3].

Lundberg [8] saysthe cost of transformers depends mostly on the rated power. Also in this case, he [8] refers the costs in Swedish krona (SEK).However, in this case, a non-linear model is suggested, following the law:

$$\boldsymbol{Cost_{TR} = A''_p + B''_p P_{rated}^{\beta}} \qquad \mathbf{5}$$

where

$Cost_{TR}$ is the cost of the transformer

P_{rated} is the rated output power [W]

A''_p is the offset constant.

B''_p is the slope constant

β is a best-fit exponent.

It turns out that in such a non-linear model the offset constant is negative: this means that the model does not have physical meaning for small plants.

2.6.2 Switchgear & Protection equipment

Switchgear is an expensive and bulky component within marine energy farms and its cost increases rapidly with an increase in the voltage level. This section examines the switchgear used within the inter-array network of marine energy farms, but also a model for cost analysis.

Figure 32 shows a switchgear arrangement suggested for use within offshore wind farms [4]. A similar arrangement can be used within marine energy farms too. For relatively short feeders, like that would be seen in marine energy farms, it may be adequate to provide only one circuit breaker in the turbine at the ''shore'' end of each feeder [4]. The switchgear can be operated from the shore via SCADA systems. Manually operated equipment to isolate transformers and individual generators will also be necessary. Gas-insulated switchgear has demonstrated a good performance in offshore applications.

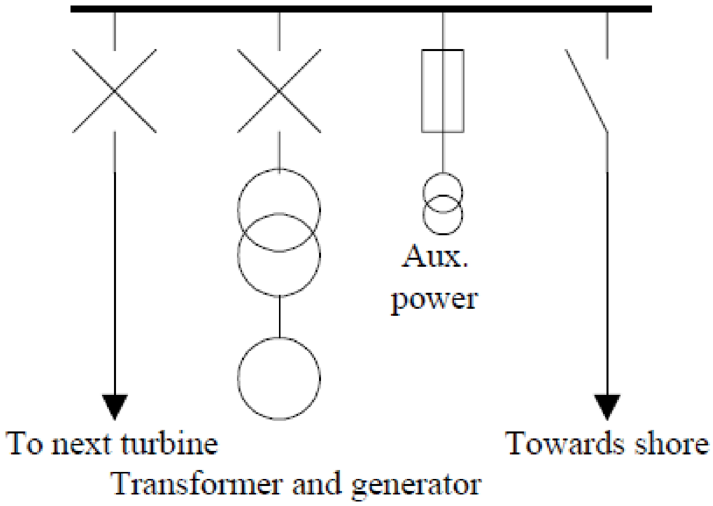


Figure 32: Turbine switchgear arrangement [4].

Figure 33 shows an example of a fault protection scheme [15], which shows redundant cables, switchgear and protection equipment for alternate routing during fault conditions. Such schemes, readily obtained from existing offshore wind farms, can be used with marine energy farms too.

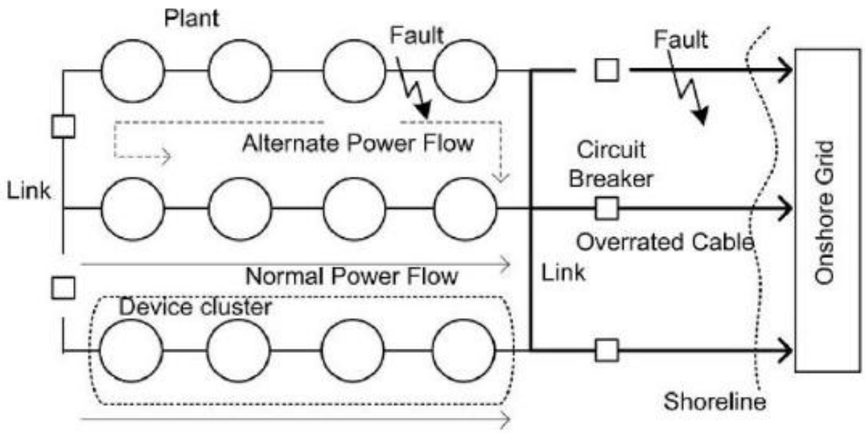


Figure 33: Farm switchgear arrangement [15].

All the offshore switchgear used was taken to be Gas Insulated Switchgear (GIS) in [2]. Page 34 of [2] shows the exact layout of a round three offshore wind farm substations and switchgear. It is likely that the substation and switchgear arrangement for marine energy farms would be very similar.

Reference [8] suggests also a cost model for the switch gear. Essentially it could be approximated with a linear relation depending on the voltage level.

2.6.3 Subsea Transformers and Switchgear

The option of having the transformer and switchgear on the seabed can be considered in the future, based on developments in subsea oil and gas production [4]. Subsea electricity distribution systems have been installed in various parts of the world, mainly aimed at powering pumps and other equipment in oil/gas production units. In most of these installations, subsea transformers rated between 2 - 5 MVA have been used [19]. The Ormen Lange subsea compression unit (see Figure 34) will move this limit to 70 MVA [19], which still falls short of the need in the marine energy industry. Since the power and voltage levels of the subsea technology would need to be higher than what is available today, a major technical development is needed before this option becomes viable [4].

Figure 34: ABB Subsea Transformer for Ormen Lange gas field [40]

Though there are companies manufacturing subsea switchgear (e.g. [41]), there is no subsea switchgear in operation today [19].

Earthing requirements and lightning protection are other considerations for the electrical design of Marine Energy systems, but will come under the heading of electrical protection.

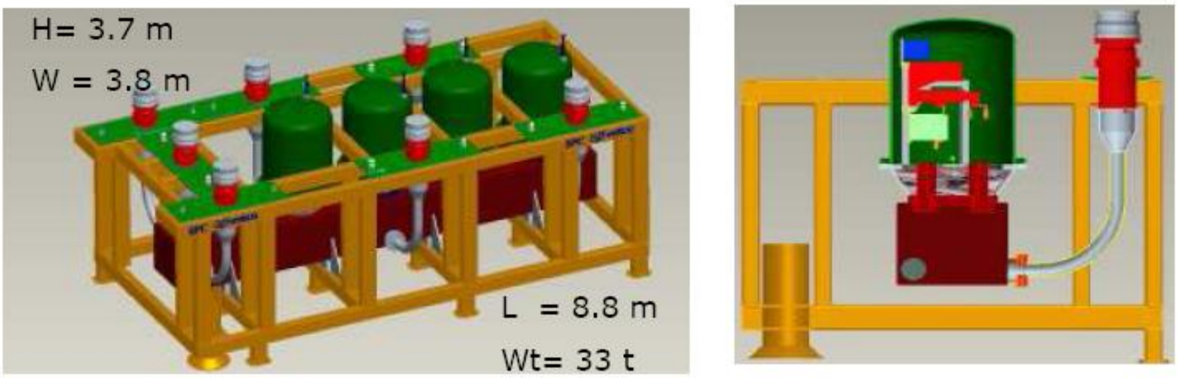


Figure 35: ABB Subsea Circuit Breaker (24 kV / 500 A) [23] based on patent [42]

Figure 36: Bennex Anguila Changeover Switch (7,2 kV / 275 A) [43]

2.7 Energy Storage Systems

The intrinsic intermittent nature of energies extracted in marine environment (current and wave) opens the doors to the possibility of storing the produced energy in order to fulfil better the requirements in terms of power consumption in the local power system. The following review about energy storage technologies and applications in marine environment are freely based on [44].

A well-designed energy storage system should guarantee (see [45]) an optimized solution in terms of:

- Power quality (in terms of continuity)

- Bridging power (continuity of generations when switching among different power generators)
- Energy management, because of the lag between generation time and consumption time.

Energy Storage Systems can be classified according different criteria:

- Time Scales (see [46])
  - Short Term Scale (STS, time scale of seconds or minutes/hours), due to the oscillating properties of wave/current motions, which is regular enough and therefore somehow predictable in statistical terms;
  - Long Term Scale (LTS, scale of hours/days) and Very Long Term Scale (VLTS, scale of months), which can be analyzed in terms of long-term statistics. Due to the regularity of wave phenomena, also such scale can be predicted thanks to long- term statistical analyses, and it is object of on-purpose research.
- Size of the installation
  - Storage systems coupled to single WEC, generally for STS (see [47]). The choice of a proper device is often critical and based on several prerequisites, such as life cycle and reliability (maintenance can be performed only during specific weather windows). Recommended maintenance period is five years [48]. Other problematic issues are related to size and harshness of the marine environment, as these devices must be installed in situ.
  - Storage systems acting at a farm level, both for STS and LTS. They have higher power ratings with respect to the systems coupled to single WEC and they could be installed onshore. For this reason most of the design issues above mentioned become irrelevant and major problems are related to grid integration as for other renewable.
- Storage Mechanism
  - Mechanical Energy Storage
  - Electrical Energy Storage
  - (Electro-) Chemical Energy Storage.

If at the beginning of the development, Mechanical (Hydraulic) solution were preferred, nowadays direct-driven All-Electric (electric or electro-chemical) solutions are preferred. This is indeed the trend also of the technologies nearest to the market stage, such as OPT Technologies [35]. Such a design choice is aimed at improving the reliability and efficiency of the system. However, a further possible approach is to use hybrid solutions by coupling supercapacitors with batteries, see [49].

2.7.1 Mechanical Energy Storage

a. Pumped Hydroelectric Storage (PHES)

Pumped Hydroelectric Storage principle (see Figure 37) is based on the height difference between two reservoirs. During off-peak hours, water is pumped from the lower to the higher reservoir and then, during peak hours the direction is inverted passing through a turbine; it allows large capacity (30-4000 MW, [50]). The strong dependence on the site, the initial costs, the high power and energy capacity does not make this principle generally suitable for energy storage not even in LTS.

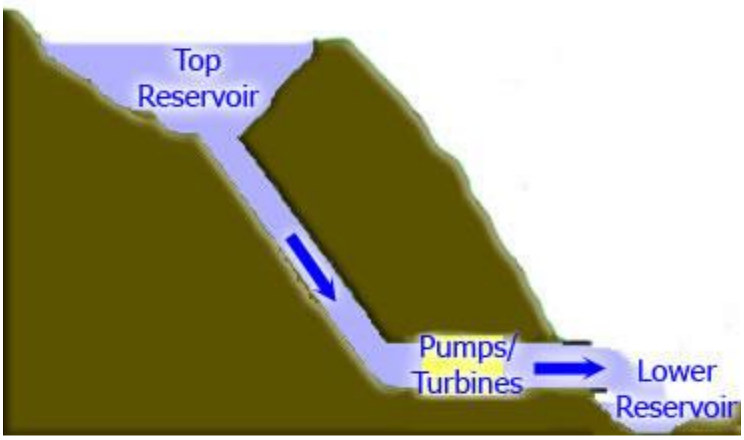


Figure 37: Working principle of a PHS (from [51])

b. Compressed Air Energy Storage (CAES)

The working principle is illustrated in Figure 38, and as for PHES, it is valid for LTS. Compressed air is accumulated during off-peak hours in a sealed cavern and then, during peak hours, compressed air with natural gas is injected into multiple stage gas turbines in order to produce energy. This can be a valid alternative for energy storage in the field of marine renewables, as shown in [52]; however it could be a solution only for medium-large farms, because of the high capacity of the plant, and the very high initial costs can influence significantly LCOE.

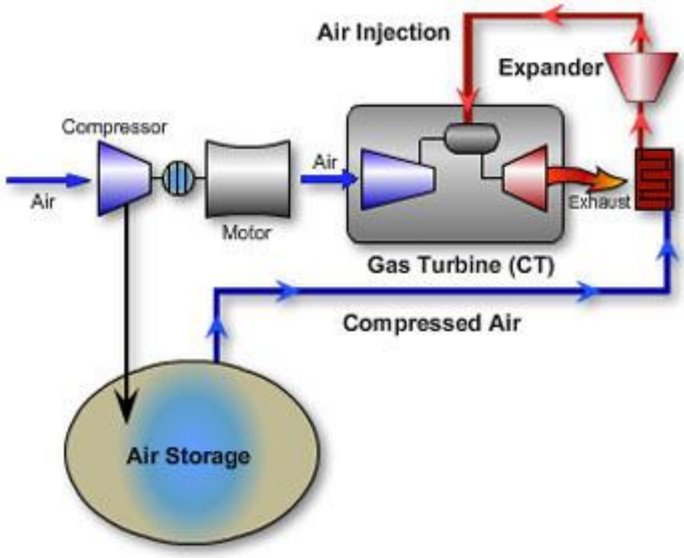


Figure 38: Working principle of a CAES (from [53])

c. Flywheel Energy Storage (FES)

A flywheel can be used to store kinetic energy in rotating mass around a shaft (see Figure 39). Increasing the rotational speed of the flywheel, these devices may be able to provide energy for longer time, albeit with much lower power limits. Main disadvantages are the low-energy density and high self-discharge ratio. They are usually adopted for short term energy storage in wave energy applications (see, for example [54] and [55]). It could be convenient to use an external flywheel instead of using the rotating mass of the turbine in order not to interfere with the control law of the turbine. Moreover, when in presence of a flywheel, control strategies are sea-state based (and this might be crucial for point absorbers). No problems at all in installing flywheels at a farm level (onshore), as the only criticalities are related to grid integration applications [56].

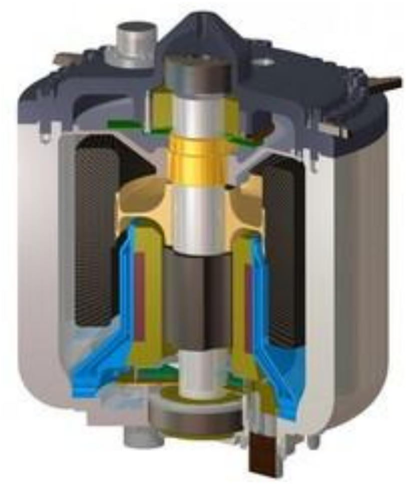


Figure 39: Pentadyne GTX Flywheel, from [57].

2.7.2 Electric Energy Storage

a. Supercapacitors

The working principle of supercapacitors is the same than traditional capacitors, i.e. storing energy in an electric field; however, by using porous materials, distance between the plates can be reduced to few molecular diameters. They have high power density and long lifecycle, but low energy and high cost. They may be used for STS and their applications have been analyzed recently; for example in [48] where the case of a supercapacitor in a single grid full scale OWC is analyzed, showing a terrific withstanding in terms of lifecycles. Similar results, under different initial grid set-point (supercapacitor not working at any wave cycle) and for a direct driven point absorber, were shown in [58] and [49].

b. Superconductive magnetic Energy Storage (SMES)

The working principle of SMESs is to store energy in the magnetic field generated by DC current flowing into a superconductive coil, kept cool by using liquid helium or nitrogen. They have power capacity of 2 MW and efficiency (though sensitive to temperature) estimated as 95-98% [50], but with low energy density. This principle could be applied for STS, also for farms; however its development stage, the complexity of the system and the harshness of marine environment does not make it a competitive technology for energy storage in the field of marine renewables.

2.7.3 (Electro-)Chemical Energy Storage

a. Battery Energy Storage

A battery consists in one or more electrochemical cells that convert the stored chemical energy into electrical energy. The two electrodes are plunged into an electrolyte allowing ions to move between the electrodes and terminals. These terminals allow current (electrons) to flow out of the battery through an external circuit to perform work.

There are several types of standard storage batteries:

- Lead-Acid (LA) batteries, using lead dioxide for the cathode and lead for the anode in sulphuric acid as electrolyte. They can reach efficiency levels up to 75-85%, low life-cycle capacity, power up to 10MW and energy capacity up to 40MWh [50].
- Nickel-based batteries have nickel hydroxide for the cathode, aqueous solution of potassium hydroxide for electrolyte and different material as for anode (cadmium, metal hydride or zinc). In general they have lower efficiency than lead-acid batteries and higher self-discharge rate.
- Lithium-based batteries, which have higher energy density, higher energy efficiency and lower self-discharge [59].
- Sodium Sulphur batteries, characterised by high efficiency, and high life-cycle. They can reach 200MW of power and energy capacity of 1200 MWh [50];
- ZEBRA (Sodium Nickel Chloride) batteries, classified as high temperature batteries, as for Sodium Sulphur batteries, have very high energy density.
- Flow batteries (Vanadium Redox, Polysuphide Bromide, Zinc Bromine), in which power and energy capacity are decoupled. For this reason they can reach high values in power and capacity (see [50]). They have fast reaction time, no self-discharge and no degradation from deep discharge.

Only few papers have treated battery storage as a solution for wave energy converter farms both for LST and STS. However battery systems are the canonical solution for autonomous point absorbers [49].

b. Hydrogen Energy Storage

Just for the sake of completeness, this technology is included here: indeed, at the present stage this concept is immature. It does not consist of a self-contained device; indeed it would be better to talk about as a whole system of devices, including hydrogen creation system, hydrogen storage system and hydrogen use system. For this reason it is unpractical in marine energy field.

2.8 Power transmission options: HVAC and HVDC

Based on the type of power transmission between offshore and onshore locations, a first distinction can be made according to whether the electrical energy is transported by alternating current (AC) or direct current (DC).

For offshore plants the choice of whether to use a DC or AC transmission line is mainly determined by the distance to shore and the installed capacity ([60], [61], [62], [63]*). For projects located far from the grid connection point, or of several hundred megawatts in capacity, AC transmission becomes very expensive or, in some cases, practically impossible due to cable-generated reactive power using up much of the transmission capacity.*

In such cases, high voltage DC (HVDC) transmission is becoming an option. Such a system requires an AC/DC converter station both offshore and onshore; both stations are large installations whose building and operation might impose a number of engineering and economical challenges.

Currently most of the existing offshore transmission systems use HVAC for the transport of electrical power from the farm to the shore. Usually, an offshore substation is used to increase transmission voltage and therefore limit losses. Nevertheless, when the farm is not very distant from shore and the energy generator voltage transformer is high enough, offshore transforming substations may not be necessary. (Taken by [1]*).*

There are two different preliminary issues to take into account for selection of the transmission options: capital costs associated with the initial investment and the efficiency of the transmission line (transmitted power divided by power produced). A general feasibility analysis should primarily include the understanding of these two parameters. Other evaluation criteria should be considered as well but might be strongly site-specific and therefore difficult to accommodate under a general approach.

Figure 40 shows the cost and efficiency comparison of these two options. It is evident from the figure that for farms less than approximately 100 km from the shore the HVAC solution still is more cost effective. Other publications give similar figures for this breakeven point (50 km in [6] and 100 km in [2]).

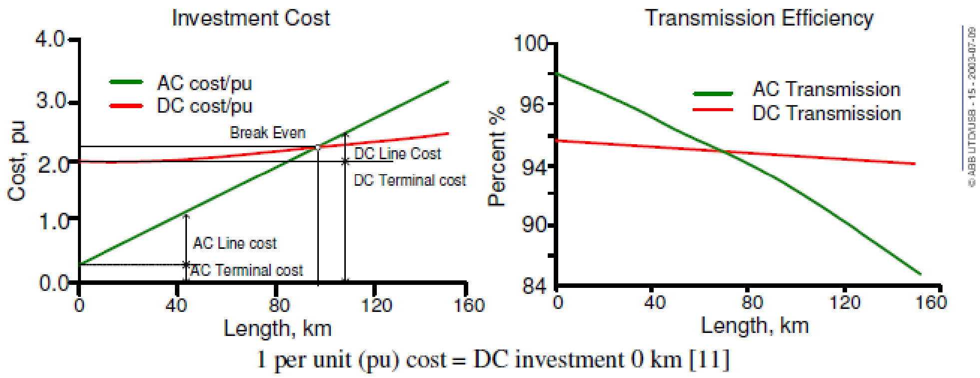


Figure 40: HVDC vs. HVAC costs and efficiency [15].

From the electrical losses point of view, for distances up to approximately 70 km, the HVAC solution leads to lower losses (see Figure 41). However, other aspects like number of cables required, reliability, life cycle costs, integration with the onshore power system, etc. will need to be studied before an informed design choice can be made [64].

The charging current in AC cables, due to the capacitance between each phase conductor and earth, is a challenge when the length of the cables and the voltage levels increase [2]. This challenge can be addressed by providing shunt reactive power compensation at points on the cable. For extremely long cables, the compensation may be needed at regular intervals, which may not be a viable option considering the technological and financial cost of making such installations in the offshore environment. Having compensation at the offshore and/or onshore substations is the next best option and the one widely used today.

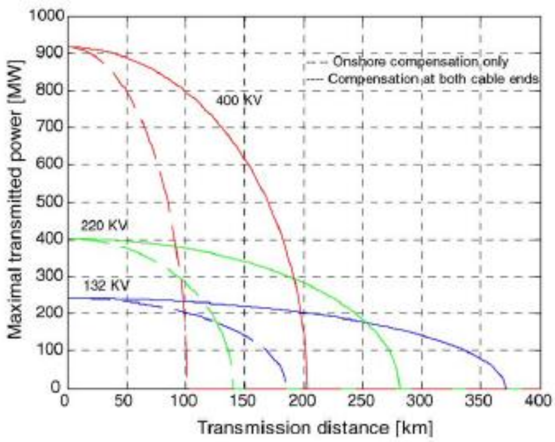


Figure 41: Transmission capacity of different HVAC cables and voltage levels [64].

The optimum reactive power compensation for a transmission at 275 kV was listed, for different offshore wind farm size and distances from the shore, in [2]. Here, the compensation was applied only to compensate for the capacitive charging current in the transmission cable and to maintain a unity power factor at the receiving end. In addition to this compensation, the owner of an offshore energy farm above a particular size is obligated to prove reactive power capability of 0.95 lead to 0.95 lag at the interface point with the onshore transmission network (in the UK) [2]. The values for the reactive power compensation required for other voltage levels and distances will need to be identified for use with marine energy farms.

The main components of an HVAC system are [6]:

- AC collection system at the platform
- Offshore transformer substations
- Onshore transformer substations
- Three-phase submarine cable
- Offshore and/or onshore reactive power compensation

Figure 42 shows these components in an example AC collection system. References [3] and [2] do not recommend any full redundancy in the platform, offshore cable, onshore network and onshore substation because of the significantly higher costs of undersea cables, absence of demand offshore, relatively low load factor and low capacity value.

HVDC is an option that will play a significant role, though not in the near or mid-term, once the cost of the converter stations reduce and the size of marine energy farms and their distance from the shore increase. HVDC transmission may become the preferred solution for certain marine energy farms having an offshore HVDC grid nearby. Whether traditional HVDC Line Commutated Converters (LCC) submarine transmission has only been used for connection of high voltage grids and there is no single converter station located in the sea, HVDC Voltage Source Converters (VSC) systems would play a major role in the expansion of ocean energy conversion during the next decade, when the array size will grow to many 10s of converters, installed at locations more than 100 km far from the shore. They allow independent and total control of active and reactive power at each end of the line and power transmission can be controlled with high flexibility.

Table 4, which has been freely taken from [65], includes a synopsis of the main characteristics of the three different power transmission technologies herein examined.

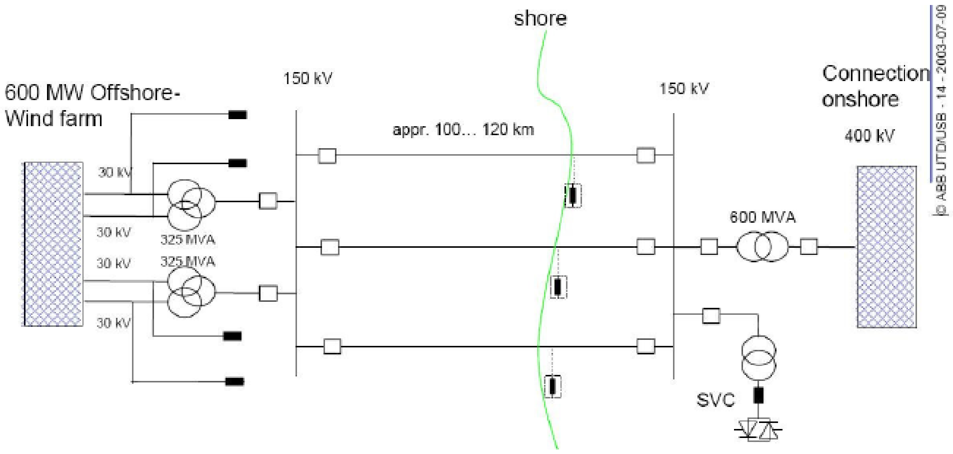


Figure 42: AC collection system example [15].

Table 4: Synoptic Comparative Table Among different Power Transmission technologies (AC vs. DC LCC vs. DC VSC)

AC	DC	
	LCC	VSC
Possibility of avoid offshore platforms	Needs an offshore platforms	Needs an offshore platforms
Avoid switching losses (converters)	Switching losses at AC/DC converters	Switching losses at AC/DC converters
Need reactive power compensation	Don´t need reactive power compensation	Don´t need reactive power compensation
Faults in main grid affect the offshore grid and vice versa	Electrical decoupling between the AC offshore grid and the main grid	Electrical decoupling between the AC offshore grid and the main grid
Charging currents reduce the transfer capacity	There are not charging currents	There are not charging currents
Power transmission capability in both directions	Change direction in the power flow need to change the polarity	Power transmission capability in both directions
Mature and reliability technology in offshore applications	Well proven technology but in other applications	Well proven technology but in other applications
Less cost due to the use of standard components	Needed a minimum of reactive power to work, even without energy production	High cost

3 Offshore Electrical Network Architecture

3.1 Voltage level of connection to the inter-array network

In the onshore wind industry, the practice is to step up the voltage to the voltage of the network to which the wind farm is to be connected [4]. This is normally done using dedicated turbine transformers. Presently the highest voltage used to inter-connect turbines is 33 kV (medium voltage) in the UK, both for onshore and offshore wind farms [4], [2]. Above this voltage level, the cost of transformers and its associated switchgear increases rapidly [4]. Moreover, no wind turbine manufacturer has shown an interest in generating directly at medium voltage [4]. Higher voltage inter-array networks may be required as the number of wind turbines and the length of the radials increase, to counter the power losses in the cables [2].

For the sizes of marine energy farms and arrays that will be seen in the near to mid-term, a medium voltage (33 kV in the UK) inter array network would be used. The fast-paced development of the offshore wind industry (which uses the same voltage level for their inter-array network) means that the supply chain for electrical equipment (at this voltage level) may already be in place or is likely to be in place in the near future. Additionally, data regarding the failure rates for some of the offshore equipment (like cables and connectors) may be obtained from the offshore wind experience. Moreover, unlike offshore wind farms where the spacing between neighbouring turbines may be large (500 m or so), the spacing between marine energy converters will be smaller, because of the less amount of space needed by the device itself. This means that power losses in the inter-array network may not justify the use of a higher voltage above say 33 kV. It must be noted that pilot demonstration projects and small marine energy farms close to the shore may have their inter-array networks at a lower voltage and may also use the same voltage at which the power has been generated (typically low voltage in the range of 400 - 690 V). A cost-benefit analysis needs to be done to determine the size of the farm and the distance from the shore that warrants the use of a medium voltage inter-array network. Higher voltages (say 132 kV) for the inter-array networks for floating marine energy converters may not be an option today due to space constraints in the marine energy device for the on-board transformer [6].

3.2 Electrical layouts

A generic farm layout normally consists of [6]:

- Clusters (medium-voltage local collection system), collecting the power of several marine energy converters
- An integration system, raising if necessary, the voltage from medium to high voltage

- A transmission system (AC or DC) transferring the marine power to shore (to the grid integration point or point of common coupling)

3.2.1 Cluster layouts

Connecting individual wave or tidal power converters to the shore using a power cable each is the most reliable connection option for farms of marine energy converters. The implementation of a complex offshore hub or an offshore substation is avoided using this approach. The excessive cabling and cable laying costs in this approach would make it cost prohibitive, which means that the individual marine energy converters would need to be integrated into a common local collection system, or clusters, from where the power is transmitted to the shore. Even for the four-device Wave Hub test site in South West England (26 km from the shore) such a cluster has been used to transmit the power to the shore [5].

As discussed earlier, clusters in marine energy farms would be a medium (or low) voltage collection network. The following types of cluster layouts may be used [6], [1]:

Connecting individually the different devices to shore will not be an acceptable option in the majority of wave farms, mainly because cabling and transmission efficiency losses. There are several types of clustering (kept from [1]):

- *String clustering without redundancy (see Figure 43): The devices are connected in parallel along a single collection cable. The main advantage is that if one arm of the system breaks the overall system continues working. This option is one of the most used in wind farms.*

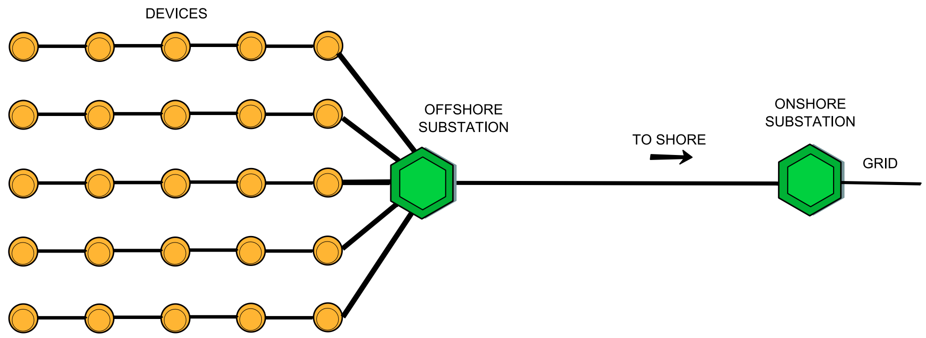


Figure 43: String Series Cluster. Medium and Large Farms (AC and DC) **[1]**

- *Star clustering (see Figure 44): The devices are connected independently to a cluster nodal platform. The advantage is that several parts are independent one to each other so that in case of failure the overall infrastructure will continue working.*

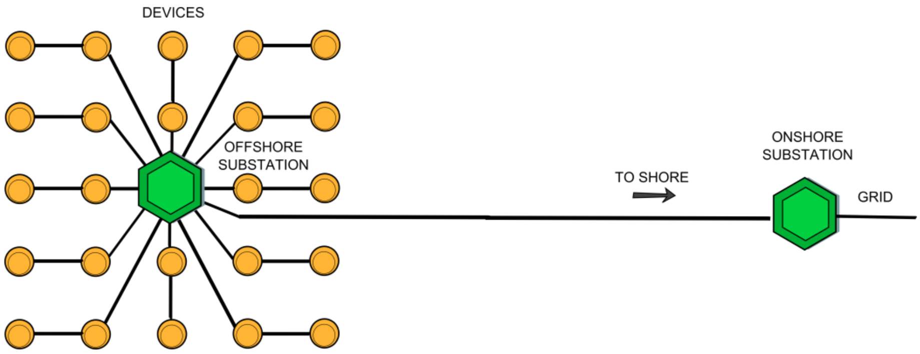


Figure 44: Star (Radial) Cluster [1]

- *String without redundancy (see Figure 45): The system only has one transmission cable. If the system has any kind of failure the overall farm could keep out working.*

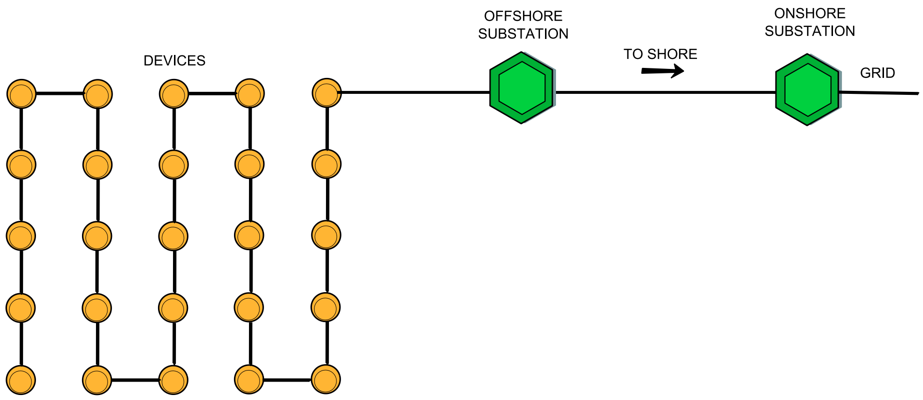


Figure 45: Full String Cluster [1]

- *String with redundancy (see Figure 46): The devices are connected in parallel along a closed loop collection cable and a switch controlling the power flow in the cluster. Many other redundancy designs might be implemented.*

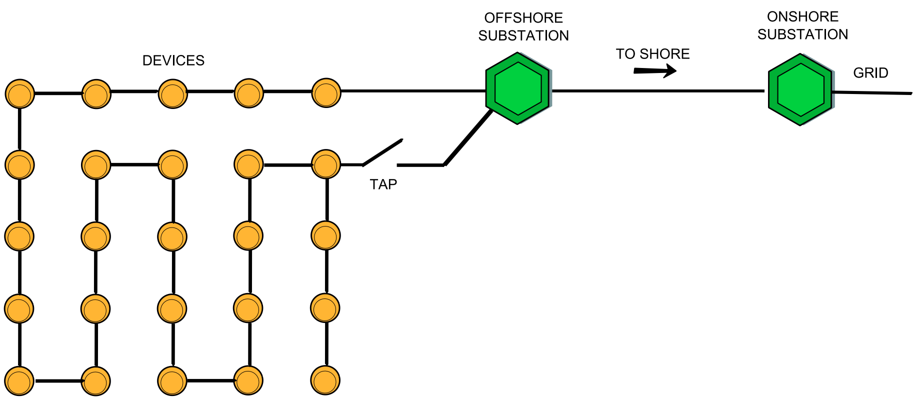


Figure 46: Redundant String Cluster (AC & DC) [1]

- *DC-series clustering (see Figure 47): The devices are series-connected in various branches. This configuration is only used in DC clusters technologies. In offshore wind energy depending on power installed and distance to shore DC transmission is becoming an important option.*

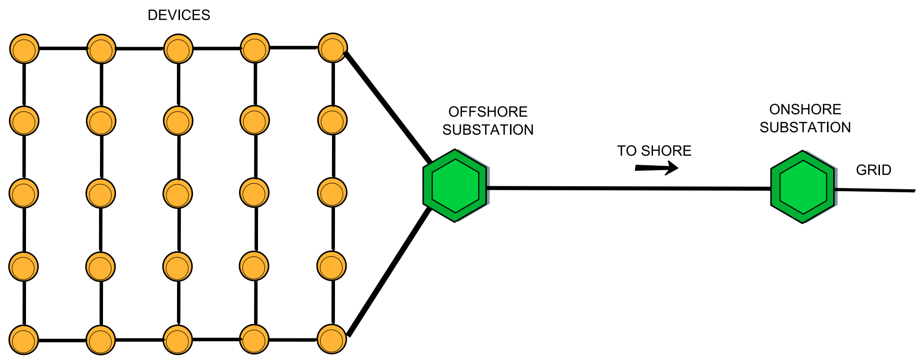


Figure 47: Series DC Cluster. **[1]**

The radial or the string arrangement (*Figure 44*)has been the most commonly used cluster layout and is considered the optimal configuration for offshore wind farms [4] (see Figure 48). Redundancy can be introduced in the radial cluster type (see *Figure 44*). In a work on offshore wind farms, using probabilistic means and failure rates for the offshore electrical components, it was shown that having this redundancy only improved the 20 year production of a wind farm by 0.026 % [4]. Since we are dealing with very similar failure rates, it is unlikely that this redundancy will improve energy production by much in the case of marine energy farms.

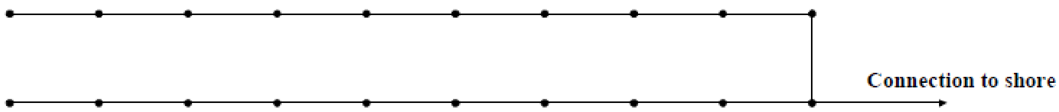


Figure 48: Radial cluster type with no redundancy [4]

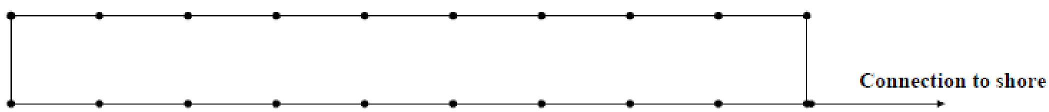


Figure 49: Radial cluster type with redundancy [4].

The star cluster layout (*Figure 44*) is a variant of the radial cluster type. The shorter feeder lengths (even if the total length is the same as a radial network) results in reduced electrical losses. The star cluster layout may be the option for closely spaced marine energy converters. The string cluster (*Figure 45*) is again a variant of the radial cluster type, with just one radial. The redundant string cluster (*Figure 46*) is similar to the radial cluster with redundancy discussed earlier. Cluster layouts, which use a combination of two of the basic structures discussed here may also be used. For example, a radial cluster with each point on the radial being star clusters may be an alternate possibility.

The rating of the cable and the electrical losses in the cable (and in turn the distance between neighbouring generators) determine the number of generators within each cluster [4] and [6]. Depending on the number of generators, there may be a requirement of more than one cluster in a marine power farm. Having more than one cluster also aids in the gradual, phase-by-phase development of marine energy farms, which, considering the supply chain, is the most likely means of installing large marine power farms. These clusters are then integrated together at offshore substations for power transmission to the shore. As mentioned earlier, the distance between two marine energy converters will not be as large as that between two offshore wind turbines. Therefore, electrical losses will not be a major issue to be considered when designing the cluster layout.

The arrangement of the clusters within a marine energy farm needs to be designed taking the availability of the individual devices, the cost benefit of the arrangement, the redundancy, fault protection and accessibility for maintenance into account [6] and [15]. For example, in a string cluster type the main cable is the same for all the devices. The availability appears better in a radial cluster or a star cluster.

The series DC cluster (*Figure 47*) has been proposed for use in marine energy farms where DC generators are used for the power generation [1].

In the case of tidal turbines network design may not be an issue since most of the significant tidal resource is in constrained passages, inlets and channels, fairly close to the shore [15].

3.2.2 Transmission to Coast

The individual clusters, depending of their rating, can have individual submarine power cables transmitting the power to the shore. Another option would be to combine the power exported by multiple clusters at an offshore substation and then use one submarine cable to transmit the power to the shore. Figure 50 shows the different transmission options discussed so far.

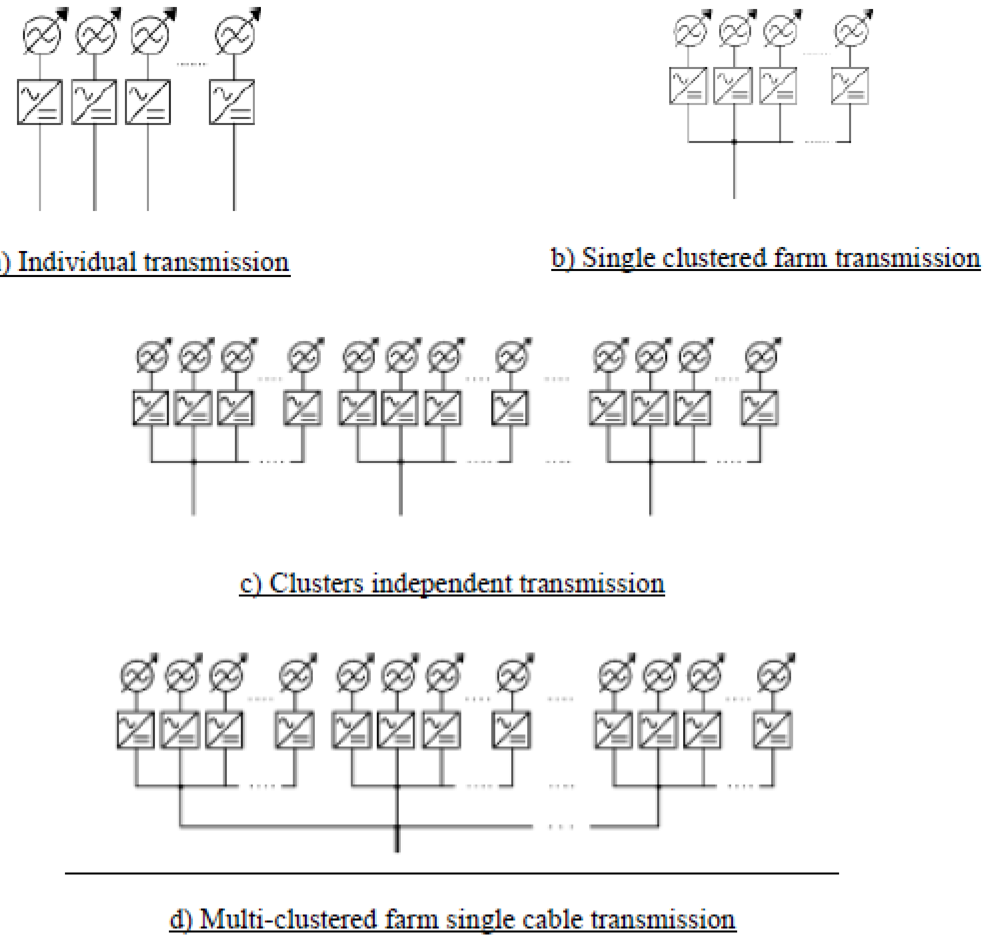


Figure 50: Marine energy farm integration topologies [6].

4 Onshore Electrical Network Architecture

4.1 Onshore Substation

References [3] and [2] recommend the use of a single transformer up to 120 MVA. For larger arrays, with multi-transformer substation, the minimum rating is 50% of the farm rating. These are figures obtained from the cost-benefit analysis completed for offshore wind farms, but it is likely to hold true for marine energy farms too.

If the onshore network voltage is the same as the transmission voltage, then no transformer is needed onshore [6].

No redundancy is recommended for the onshore substation [3].

4.2 Onshore Network

Table 5 and Table 6 show the decision making process with regard to the installation of a single or a double circuit, with respect to farm size, for a 132 kV and 220 kV overhead transmission system [3]. These are tables obtained from the cost-benefit analysis of offshore wind farms, but it is likely to hold true for marine energy farms too. It is also recommended to minimize the onshore cable length [2].

No redundancy is recommended for the onshore network [3].

Table 5: Choice of a Single Circuit (SC) or Double Circuit (DC) for a 132 kV overhead line [3].

Length [km]	Wind farm capacity (MW)		
	150	**250**	**400**
1	SC	DC	DC
10	SC	SC/DC	DC
25	SC	SC	DC
50	SC	SC	SC/DC

Table 6: Choice of a Single Circuit (SC) or Double Circuit (DC) for a 220 kV overhead line [3].

Length (km)	**Wind farm capacity (MW)**				
	400	**600**	**800**	**1000**	**1060**
≤2	DC	DC	DC	DC	DC
≤4	SC	DC	DC	DC	DC
≤8	SC	SC	DC	DC	DC
≤25	SC	SC	SC	DC	DC
≤50	SC	SC	SC	SC	DC

5 Power generation as input to the design of the offshore electrical network

The aim of this project is to develop a techno-economic decision making tool, suggesting the offshore electrical network layout and design for tidal and wave energy converter farms, based on the levelised cost of electricity generation. The levelised cost of electricity generation is defined as the ratio between the total cost of a generating plant, including the capital and operational costs, and the total energy yield expected over the plant's lifetime [66]. For such a techno-economic decision making tool, the power generation from the farm is required as an input. Accessing the reliability and the expected energy constraint associated with the different layout options also requires this information.

Considering that the energy yield over the lifetime of the plant is required, the expected or a forecasted time-series of the power generated by the marine energy converter farm with an acceptable resolution is needed. The resolution of this time-series needs to be decided depending on the question being addressed and its computational intensity/feasibility. Since the lifetime of a marine energy converter farm may be between 20-30 years, a time-series with power generation values estimated every 30 minutes or an hour would be appropriate. The resolution suggested here has been used in similar techno-economic work completed for the onshore and offshore wind industries [3], [85].

The power output of marine energy converter farms depends both on the resource characteristics (current velocity and direction in the case of tidal current devices and significant wave height, average/peak wave period and wave direction in the case of wave devices) and the power extraction/generation characteristics of the device, which should also include the effects of control. The resource characteristics for both tidal and wave are expected to be statistically represented, based on historic measurement archives and modelling based forecasts made at sites where the farms are being considered.

There are many individual tidal and wave energy converters that have been tested in tanks and in real seas. Additionally, a lot of computer based numerical modelling work, with both individual and arrays of wave and tidal devices, has been completed. Experience obtained from these sources will be used to determine the power output characteristics of the different wave and tidal devices selected for each of the scenarios defined by WP1 and WP2. The resource characteristics and the device power characteristics, once available, can be used to obtain the power output of the wave or tidal device and also of farms of these devices. This information may be represented either statistically or as a set of representative time-series.

This section examines how the power output data from both wave and tidal energy converter farms (and also individual converters) can be represented for use as input to the techno-economic decision making tool. The current draft does not deal with the particular scenarios (device types and locations) defined by WP1 and WP2, but builds a generic framework. It is envisaged that this framework can employed, with minor modifications, for any wave and tidal energy converter farm including the scenarios identified as a part of the DTOcean project. The procedure described here for single wave and tidal converters closely matches the power assessment of wave and tidal energy converters suggested in [87].

5.1 Power generation from tidal energy converter farms

5.1.1 Resource characteristics

The power output from a tidal energy converter (TEC) depends on two main factors – the tidal current speed normal to the power capture surface and the direction of the tidal currents [67]. In restricted channels and narrows, the tidal currents are almost bi-directional [67], while in open seas the direction of flow needs to be taken into account by using a cosine correction to the velocity (making the velocity normal to the turbine) [67]. For turbines with a facility for yawing, this would not be required since the yaw facility would ensure that the current velocity will always be normal to the turbine. The velocity of the tidal current varies with depth and also with the width of the channel and how these effects are to be incorporated is discussed in [68]. Tidal currents are also sensitive to bathymetry changes and to bottom friction [68]. Thus, depending on where and at what depth the tidal current velocities were measured, the velocity readings will need to be modified to make it suitable for predicting the power output of a TEC.

Therefore a time-series (or a combined distribution) of the tidal current velocities and directions, over the life time of the farm, is required as an input to the present study. Figure 51 shows a generic frequency distribution of tidal current speeds. Hagerman et al. [68] and ECI [69] have used such distributions, generated from actual measurements, to calculate the power output of TEC farms.

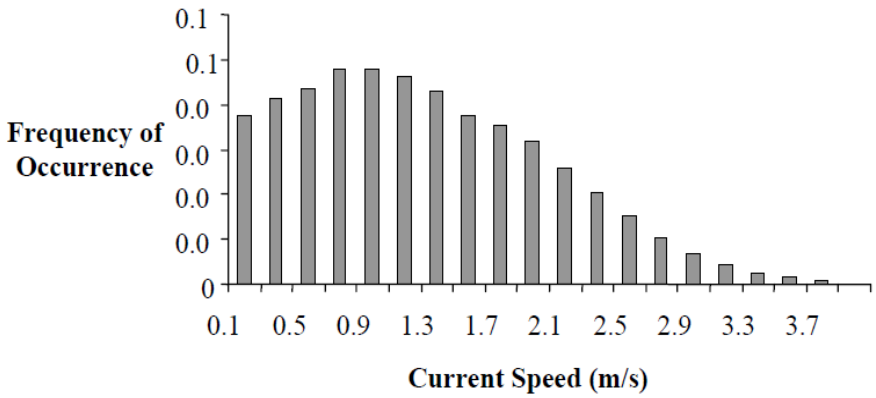


Figure 51: Generic tidal current speed distribution [68].

5.1.2 Power characteristics of a single device

The power characteristics of the different types of TECs being tested and deployed today – horizontal axis turbines, vertical axis turbines, oscillating hydrofoils, Venturi effect devices etc., have been represented by power curves. The power curves are generated using either measured data or from modelling of the device, and relates the electrical power produced by the TEC to the value of the simultaneous incident resource [70]. In the case of TECs, the incident resource of interest is the tidal current velocity.

The power available from the kinetic energy across the power capture area of the TEC can be calculated from the measured/modelled current speeds using :-[70], [71]:

$$\boldsymbol{P_{KE} = \frac{1}{2}\rho A U^3}, \qquad \textbf{6}$$

where ρ is the density of the fluid (here sea water), A is the power capture area and U is the speed of flow of the tidal current normal to the power capture surface. The maximum power that can be extracted by a single TEC in unconstrained flow is a fraction (0.59 for both vertical and horizontal axis TECs) of the power available P_{KE} [71]. In all tested horizontal axis TECs, the fraction, called the power coefficient C_p has been found to be lower (between 0.3-0.5 [71], [72]). The power coefficient C_p is a function of the tip-speed ratio (ratio of the speed of the tip of the device rotor, to the speed of the current) [70], [73]. Control of the rotational speed of the TEC, through blade pitch control or electrical generator speed control, is applied to optimise the power extraction at different current speeds [72], [67]. Figure 52 shows the maximum power point tracking function for a TEC, which has been accomplished in the work [72] using speed control of the electrical generator that the turbine is connected to.

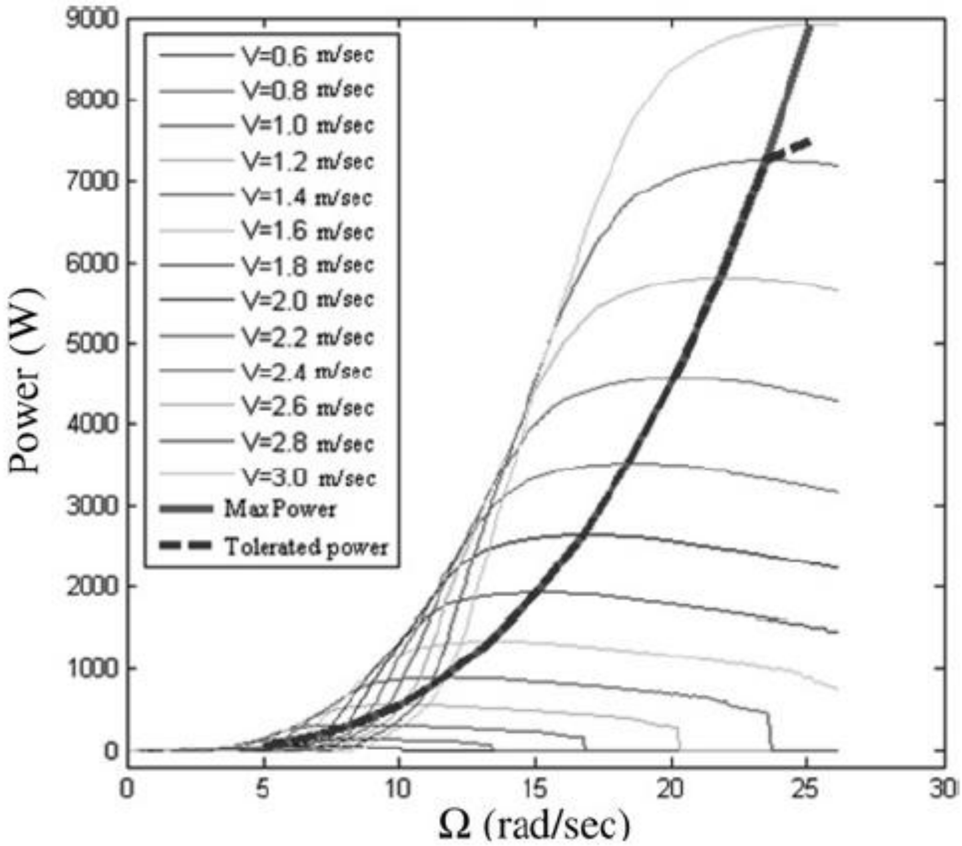


Figure 52: Power curves for different tidal current speeds [72].

Swift [70] specifies the detailed procedure to be followed to produce a power curve for a tidal device and the recommended approach is similar to the one used in the wind industry [74]. Figure 53 shows a typical power curve for a TEC, which is very similar in shape to the dashed curve shown in Figure 52. The power curves of different types of tidal current turbines have been generated from actual tests and modelling and have been presented in [75], [76], [77], [69]. Figure 54 shows the power curve of the full-scale SeaGen turbine that was tested at the Strangford Narrows. The power curves shown in these figures appear similar to the power curves of wind turbines, except that there is no cut-off speed (at extremely high current velocities) because of the limited and known velocity range of tidal currents [69].

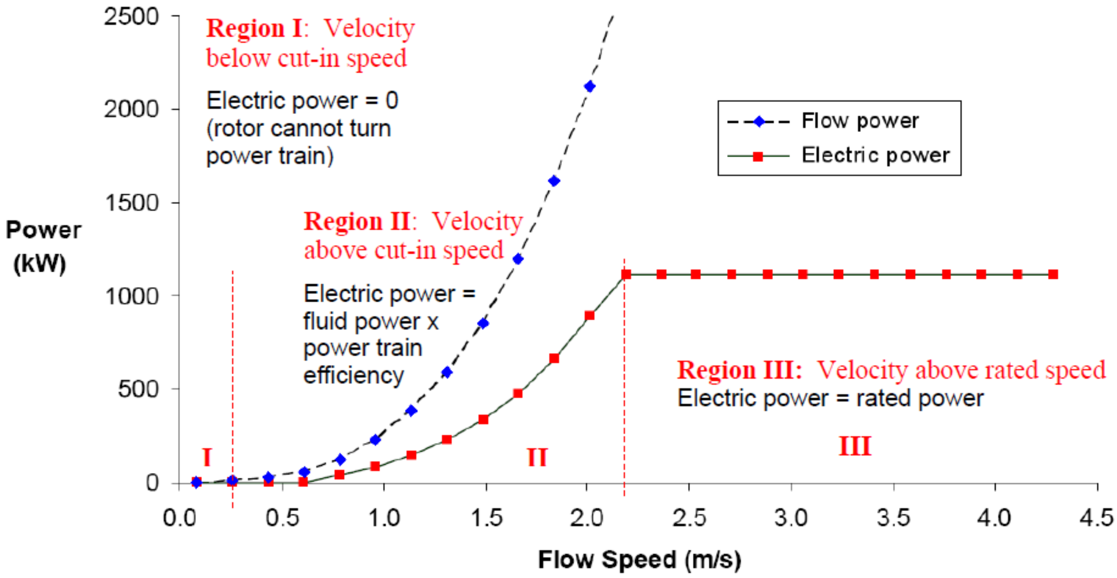


Figure 53: Typical figure of TEC output versus tidal current speed [68].

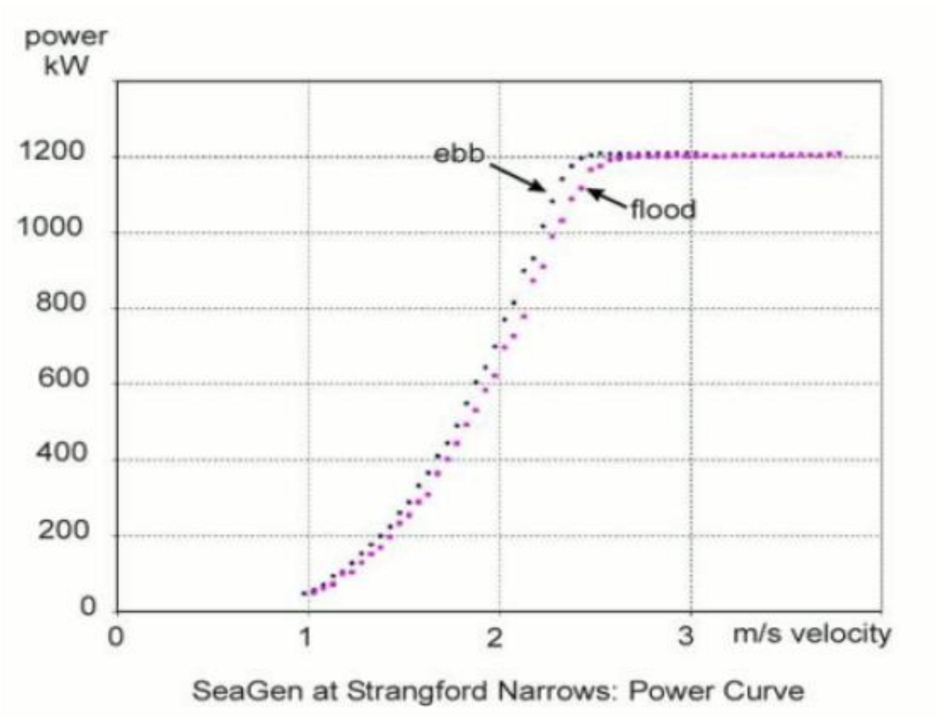


Figure 54: Power curve of the SeaGen TEC tested at the Strangford Narrows [75].

The efficiencies of the different components between the turbine and the electricity network (gear box, generator, power electronic converters etc.) need to be taken into account to obtain the actual electrical power output from the turbine. Different studies have published these efficiencies [77], [76], [67], which can be scaled and used in this work.

The methodology suggested here, to generate the power output of TEC farms is similar to the recommendation made for the same purpose in the EquiMar project [78].

5.1.3 Power characteristics of arrays and farms of TECs

The simplest means by which the power curve of a single TEC can be used to predict the output of arrays and farms of TECs is by multiplying the calculated power output of the single TEC with the number of devices. It is assumed that the tidal current velocity and direction at all the turbines within the TEC farm is the same. Therefore, only one tidal velocity distribution will be necessary for a site where a TEC farm is constructed. A similar approach was used to quantify the output of offshore wind farms used to make a cost-benefit analysis of different electrical connection options in [3].

Finding the real power output time-series of arrays and farms of TECs is more challenging, mainly due to the modification of the tidal current energy flux at the location of a turbine due to the presence of the other neighbouring turbines. This is mainly due to wake losses [79], [80], [77] and due to the modification of the tidal flow caused by energy extracted by the TECs [81], [82], [83]. These phenomena need to be included to make the analysis accurate. Projects like Perawat have studies these effects [84]. An approach that includes these effects will be used in this work using real site data (and/or data from models). Boehme et al. [67] simplifies the calculation of the wake losses, by assuming that this is 5% of the net generated power output obtained from the power curve, while Black and Veatch assumed that the percentage of energy not captured due to the wake effect lies between 5 and 20% [81].

5.1.4 Limitations and assumptions

- Power curves can only be used in cases where the tidal channel is wide and deep, compared to the rotor disc diameter [71]

- Only small changes in the free surface elevation across the turbine location are assumed [71]

5.1.5 Similar techno-economic studies

Similar approaches as those herein described are available in literature. In particular:

- References [67], [68] and [69] with respect to the simulation of time-series of power output from TEC farms;
- Reference [3] for the cost-benefit analysis of different transmission options, even though referred to offshore wind farms;
- Reference [85] for the studies about the power system based on time-series approach with a significant amount of wind penetration.

5.2 Power generation from wave energy converter (WEC) farms

5.2.1 Resource characteristics

Waves in a sea state can be thought of being made up of a spectrum of regular waves with different periods, heights and directions superimposed over each other, and can be represented using spectral means [86]. Characteristics of sea states, including the power density per meter wave front that is relevant when studying the power output from wave energy converter (WEC) farms, can be quantified by using a set of statistical parameters obtained from the spectrum [87]. Two such parameters, the significant wave height H_s and the mean zero-upcrossing wave period T_z, have often been used to quantify the power density in a sea state and also to predict the power output from WECs [69], [88], [89]. How different wave elevation and period measurements are to be made, stored and processed to give these parameters in question have been described in [87]. The energy losses in due to enhanced dissipation in shallow waters can be approximated as a modification of the sea spectra as described in [90], [91], [92], [93].

The directional spreading of the wave and the dominant wave direction also influences, depending on the type of device being considered and the layout of the WECs in the farm [89], the power output of a WEC farm. Therefore a directional spreading function is also needed to fully represent the sea state using spectral means [94], [89]. In many sites in the UK with a significant wave resource, the wave predominantly arrives from one of two particular dominant directions [69]. The directional characteristics will be different at other sites and will be one of the inputs considered in this work.

To obtain the power output from WECs and WEC farms, therefore, a time-series (or a combined distribution) of H_s and T_z with the dominant wave direction and information on the directional spreading needs to be used as input. Figure 55 shows a scatter diagram (frequency distribution) of H_s and T_z at a site off the UK. Similar scatter diagrams of H_s and T_z for other sites in the world are available in [69], [95], [96], [97], [98], [93], [99]. In all these publications these scatter diagrams have been used to calculate the power output from individual WECs and/or WEC farms.

Tz - seconds

Hsig - metres	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0.5	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%								
1.0	1.5%	2.4%	1.3%	0.3%	0.0%	0.0%	0.0%							
1.5	2.1%	5.6%	3.4%	1.2%	0.3%	0.0%	0.0%	0.0%					0.0%	
2.0	0.6%	6.7%	5.3%	2.2%	0.6%	0.1%	0.0%	0.0%					0.0%	0.0%
2.5	0.2%	3.6%	6.0%	2.7%	0.7%	0.1%	0.0%	0.0%	0.0%					
3.0	0.1%	1.2%	6.1%	3.6%	1.2%	0.2%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%
3.5	0.0%	0.3%	3.8%	3.7%	1.5%	0.3%	0.0%	0.0%	0.0%					0.0%
4.0	0.0%	0.1%	1.8%	4.1%	1.9%	0.4%	0.1%	0.0%	0.0%		0.0%			
4.5	0.0%	0.0%	0.4%	3.0%	1.9%	0.6%	0.1%	0.0%						0.0%
5.0		0.0%	0.1%	1.7%	2.2%	0.7%	0.1%	0.0%	0.0%					
5.5		0.0%	0.0%	0.7%	1.7%	0.7%	0.1%	0.0%	0.0%	0.0%				0.0%
6.0				0.2%	1.3%	0.8%	0.2%	0.0%	0.0%	0.0%				
6.5				0.0%	0.7%	0.7%	0.2%	0.0%	0.0%					
7.0			0.0%	0.0%	0.3%	0.7%	0.3%	0.0%	0.0%	0.0%				
7.5		0.0%		0.0%	0.1%	0.5%	0.2%	0.1%	0.0%	0.0%				
8.0			0.0%		0.0%	0.3%	0.2%	0.1%	0.0%	0.0%				
8.5			0.0%		0.0%	0.1%	0.2%	0.1%	0.0%					
9.0				0.0%	0.0%	0.1%	0.1%	0.1%	0.0%					
9.5					0.0%	0.0%	0.1%	0.0%	0.0%					

Figure 55: Scatter diagram of H_s and T_z at a site off the UK [69].

5.2.2 Power characteristics of a single device

The power, in kW, per metre wavefront in a sea state is given by [69], [88]:

$$P = 0.57\, H_s^2 T_z \qquad 7$$

The power extracted by a WEC from a wavefront, depending on the WEC type and the control strategy used, may be many times the key horizontal dimension of the device [100]. Several optimal and suboptimal control strategies for both individual WECs and WEC farms have been researched and applied in real devices, with the aim of maximising the power extracted [101], [102], [103], [104], [105], [106].

The power characteristics of the different types of WECs being tested and deployed today – point absorbers, terminators, attenuators etc., have been represented by normalised power matrices [87], [69]. A power matrix is a bivariate joint probability diagram of H_s and T_z in which each cell in the matrix displays the average power output of the WEC for all the sea states that fall within that cell [89]. Power matrices may be generated using full-scale testing of WECs in the sea [107], [108] or from computer based simulation studies [69], [95], [109], [110]. In the computer modelling approach, analysis may be done either in the time or frequency domain depending on the device type, control strategy and the modelling requirement (e.g. device with constraints etc. cannot be modelled in the frequency domain). Pitt [89] and BSI [87] recommend the use of matrices with cell widths of 0.5 m for H_s and 1.0 s for T_z. Additional parameters like the dominant wave direction or the spectral bandwidth may be added to the matrix to reduce the variability of the average power in each matrix cell [87]. BSI [87] also describes how to generate a normalised power matrix from measurements and recommends procedures to make these measurements. Figure 56 shows the power matrix of the 750 kW Pelamis device. The BSI document [87] explains how the mean annual energy production of a WEC may be calculated using its power matrix.

Significant wave height (H_{sig}, m) \ Power period (T_{pow}, s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Figure 56: The power matrix of the 750 kW Pelamis device [107].

The methodology suggested in this work to generate the power output of WEC farms is similar to the recommendations made for performing a cost analysis of WEC farms in the EquiMar project [104].

5.2.3 Power characteristics of arrays and farms of WECs

The simplest means by which the power matrix of a single WEC can be used to predict the output of arrays and farms of WECs is by multiplying the calculated power output of the single WEC with the number of devices. In this approach it is assumed that the average H_s and T_z seen by all the devices, over a specified period of time, is the same. Therefore, only one set of (H_s, T_z) pair is used as input at an instant of time. A similar approach was used to quantify the output of offshore wind energy converter farms to make a cost-benefit study of different electrical connection options in [3].

Accounting for the interactions between WECs within a farm is different from how interactions are dealt with in TEC farms. The ideal solution in TEC farms, if there were no limitations on the sea bed available, would have been to space the TECs as far apart as possible so as to make the wake effect, affecting the power capture by a downstream TECs, negligible. Within WEC farms, the control applied on the individual WECs, the spacing of the WECs within the farm, the farm layout and the resource characteristics (H_s, T_z and dominant wave direction) determine how each WEC interacts hydrodynamically with the other WECs. This in turn influences the power output of the farm. The motion of each WEC, which can be controlled, determines these hydrodynamic interactions and gives the possibility of applying different control strategies to maximise the net power output of the farm. Several optimal and suboptimal control strategies for WEC farms have been researched and applied in real devices, with the aim of maximising the power extracted [101], [102], [103], [104], [105], [106]. Projects like Perawat have studied the hydrodynamic interactions between WECs in farms and its influence on the net power output [84]. Publications on the hydrodynamic interactions and the park effect in farms of WECs and their influence on the power output of arrays have been reviewed by Babarit [111]. The effects of hydrodynamic interactions will be included in this work and will be supported by both modelled data and some real site data. In some techno-economic analysis with large WEC farms, the interactions between the WECs have been incorporated as 'array losses' that is reduced from the net power output [67]. AMEC [112] describes a simplified alternate method to include the interactions.

The dominant wave direction needs to be accounted for when generating the power matrix. The dominant wave direction and the directional spreading have a direct influence on the power output of WEC farms. One option to include the direction effect would be to have separate power matrices for a range of dominant wave directions. Another option would be to treat directionality using an angular attenuation factor as done by Boehme et al. [67]. Borgarino et al. [95] identify two types of power matrices – omnidirectional power matrices and directionally resolved power matrices. They are to be selected depending on the water depth at the farm site and the type of WEC under consideration [89]. A simplified method to approximate the effects of changing wave directions has been discussed by AMEC [112].

5.2.4 Limitations and assumptions

- The statistics involved in generating power matrices for WECs means there would be some uncertainty involved in the furnished power values [89]

- Using frequency domain analysis enables the use of linear theory, assuming that the wave elevation is small when compared to the wavelength and the water depth.

5.2.5 Similar techno-economic studies

Similar approaches as those herein described are available in literature. In particular:

- References [88] and [93] with respect to the simulation of time-series of power output from a WEC;
- Reference [113] for the generation of a time-series of power output from a WEC farm to be used aimed to the estimation of costs associated with wave energy. See also for WEC farms References [114], [115] and [116];
- Reference [110] for the estimation of average power output over time for different WEC types.

6 Conclusions

The work done within this document represents the introductory review of components, methods and technologies in the field of electrical system architecture all over DTOcean project and more specifically within Work Packages 3 (Electrical System Architecture) and the 7 (Design Tool Development & Operation).

The literature survey of components and offshore and onshore electrical networks has been focused on providing the different technological alternatives, but also some aspects in terms of cost modelling and reliability have been investigated because of their importance in the global targets of DTOcean.

The tasks in WP3 which will be exploiting the results of such documents directly will be:

- Task 3.3: Offshore electrical network layout modelling and design, because at that stage the electrical network layout and technologies considerations studied will be included in a single cost function.
- Task 3.4: Offshore electrical network components selection
- Task 3.5: Offshore substation design
- Task 3.6: Enabling Technologies
- Task 3.7: Robustness/Reliability Assessment

Similarly, the task in WP7 which will take into account the literature review herein included is essentially Task 7.3 (Collection of models for ocean energy arrays). It will deal with distributed parameters algorithms for the calculation of the efficiency of the electrical connection scheme depending on the transmission voltage, cable section and the presence of other hardware (transformer, converter etc.) and reliability and cost models for the electrical components of the connection infrastructure.

7 References

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